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XII ESW BRASIL 2025

2025 IEEE ESW Brazil

Electrical Safety Workshop Brazil (ESW Brazil)

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ORGANIZADORES

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APOIO

DIAGRAMAÇÃO E PROJETO GRÁFICO:
KENNY KENDY KAWAGUCHI

Prefácio

Entre os dias 7 e 9 de outubro de 2025, o Instituto de Energia e Ambiente da Universidade de São Paulo (IEE-USP) sediou a 12ª edição do *Electrical Safety Workshop – ESW BRASIL*, o mais importante evento técnico do país dedicado à segurança em eletricidade.

A conferência reuniu mais de 120 profissionais, entre engenheiros, pesquisadores, gestores e representantes de grandes empresas como Vale e Petrobras, em três dias de intensas trocas de conhecimento e networking qualificado.

O ESW BRASIL é promovido pela *Industry Applications Society (IAS)* do *Institute of Electrical and Electronics Engineers (IEEE)*, a maior organização técnico-científica do mundo voltada ao avanço tecnológico; e a co-organizadora Abracopel, desde 2013. Em 2025, o evento brasileiro reafirmou o compromisso com esse propósito, fortalecendo laços internacionais e elevando o país ao status de referência latino-americana em segurança elétrica.

Programação Técnica e Destaques

O primeiro dia do evento foi dedicado a dois tutoriais técnicos voltados à atualização e capacitação profissional. Pela manhã, ocorreu o Tutorial 1 – “Critérios para Avaliação e Classificação de Riscos Elétricos nas NR10 e NR1”, conduzido por Aguinaldo Bizzo de Almeida e Diego Tognon, ambos da DPST – Desenvolvimento e Planejamento em Segurança do Trabalho, que apresentaram metodologias práticas de análise de risco aplicadas à gestão da segurança elétrica ocupacional.

No período da tarde, o Tutorial 2 – “Roteiro de Elaboração e Avaliação de um Estudo de Energia Incidente” foi ministrado por Cláudio Mardegan (Engepower), Dr. Márcio Bottaro (IEE-USP) e Felipe Resende (Vale), abordando critérios normativos, fundamentos de cálculo e exemplos aplicados à ABNT NBR 17227.

Nos dois dias seguintes, foram apresentadas 40 contribuições científicas, sendo 29 apresentações orais e 11 pôsteres, abordando temas como Arco Elétrico e Energia Incidente, Regulamentação e Conformidade, Segurança e Prevenção, além de Impactos e Tratamento de Acidentes.

Essas discussões refletiram o estado da arte da pesquisa e da prática profissional em segurança elétrica, promovendo integração entre academia, indústria e entidades técnicas.

Internacionalização e Reconhecimento

A conexão entre o ESW BRASIL e o ESW dos Estados Unidos — existente desde as primeiras edições — foi formalmente institucionalizada em 2024, consolidando uma cooperação técnica e científica permanente.

A presença de renomados palestrantes norte-americanos, como Daniel Majano (ESFI), James Cliver (Milliken & Company) e Daleep Mohla (IEEE Fellow), reforçou o caráter internacional do evento e ampliou sua relevância global.

Entre os momentos mais marcantes, destacou-se a homenagem ao engenheiro Luiz Tomiyoshi, idealizador do ESW BRASIL, agraciado com o William C. Jordan Award, a mais alta honraria concedida pelo ESW internacional a profissionais que dedicam sua carreira à promoção da segurança elétrica.

ORGANIZAÇÃO

A 12ª edição do ESW BRASIL foi coordenada por uma equipe multidisciplinar, comprometida em fortalecer a cultura de segurança elétrica no país.

Dr. Marcio Bottaro - *Coordenador Geral ESW Brasil 2025*

Possui graduação em Tecnologia em Saúde pela Faculdade de Tecnologia de Sorocaba (1995), pós-graduação em Engenharia da Qualidade pela Escola Politécnica da Universidade de São Paulo (1999), Mestrado em Tecnologia Nuclear - Aplicações, pelo Instituto de Pesquisas Energéticas Nucleares (IPEN) da Universidade de São Paulo (2007) e Doutorado em Tecnologia Nuclear - Aplicações, pelo Instituto de Pesquisas Energéticas Nucleares (IPEN) da Universidade de São Paulo (2012). Tem experiência nas áreas de Engenharia Elétrica, Automação, Engenharia Biomédica e Física Médica. Concentra suas atividades em pesquisas relacionadas a segurança e desempenho essencial de equipamentos e materiais elétricos, desenvolvendo instrumentos, dispositivos, métodos e programas nesta área. Atua junto a ABNT CB26 nas áreas de Diagnóstico por Imagem e Dosimetria das Radiações e no CB32 na área de Energias Térmicas provenientes de Arcos Elétricos.

Eng. Edson Martinho - *Coordenação Financeira - ESW 2025*

Engenheiro eletricista formado pela Universidade de Mogi das Cruzes-SP, Pós-Graduação em Engenharia em Segurança do Trabalho, Marketing e Docência do Ensino Superior. É especialista na área de qualidade da energia elétrica e segurança com eletricidade em baixa tensão. Fundador, ex-presidente e diretor executivo na ABRACOPEL. Sócio-diretor da Lambda Consultoria. Coordenador da CE003-064:012 da ABNT, Coordenador Pedagógico da Fluke Academy, onde é também instrutor e palestrante nacional e internacional.

Prof. Dr. Helio Eiji Sueta - *Coordenação de infraestrutura ESW 2025*

Possui mestrado em Engenharia Elétrica pela Universidade de São Paulo (1998) e doutorado em Engenharia Elétrica pela Universidade de São Paulo (2005). Foi diretor da Divisão de Potência do Instituto de Energia e Ambiente da Universidade de São Paulo de 2001 a 2011 e atualmente ocupa o cargo de Chefe substituto da Divisão Científica de Planejamento, Análise e Desenvolvimento Energético no mesmo Instituto. Tem experiência na área de Engenharia Elétrica, com ênfase em Técnicas de Medição e Ensaios Elétricos de Altas Correntes, atuando principalmente nos seguintes temas: descargas atmosféricas, raios, ensaios elétricos, proteção e aterramento.

Prof. Dr. Danilo Ferreira de Souza -
Coordenador do Programa Técnico ESW 2025

Danilo de Souza possui graduação em Engenharia Elétrica pela Universidade Federal de Mato Grosso (2011). Também é especialista em Engenharia de Segurança do Trabalho pela FAUC (2014), e em Energia e Sociedade pela Universidade Federal do Rio de Janeiro (2015). De Souza é Doutor em Energia (Summa Cum Laude) pelo Instituto de Energia e Ambiente/IEE da Universidade de São Paulo/USP (2024) e professor adjunto na Universidade Federal de Mato Grosso. De Souza já foi Coordenador de Curso de Graduação em Engenharia Elétrica da UFMT no Biênio 2018-2020 e é membro do Comitê Brasileiro de Eletricidade (ABNT/CB-003). Tem experiência na área de energia, atuando em instalações elétricas, proteção contra descargas atmosféricas, segurança com eletricidade, planejamento energético, energia na sociedade e eficiência energética. Danilo é vice-presidente de Abracopel – Associação Brasileira de Conscientização para os Perigos da Eletricidade. Danilo também é membro do Centro de Estudos em Descargas Atmosféricas e Alta Tensão (CENDAT/USP) do Grupo de Desempenho e Segurança de Equipamentos e Materiais Elétricos da Universidade de São Paulo.

Dr Milton Shigihara - *Comissão de Infraestrutura*

Graduado em Engenharia Elétrica - Ênfase em Energia e Automação pela Escola Politécnica da Universidade de São Paulo (2001), mestrado em Energia pelo Programa Interunidades de Pós-graduação em Energia da USP (2005) e doutorado em Ciências pelo Programa de Pós-graduação em Energia da USP (2015). Atualmente é engenheiro eletricista e pesquisador do Laboratório de Altas Tensões do Instituto e Energia e Ambiente da USP. Tem experiência na área de engenharia elétrica, com ênfase em proteção de sistemas elétricos de potência, atuando principalmente nos seguintes temas: descargas atmosféricas, curto-circuito, sobretensões atmosféricas e proteção.

M.Sc. Sergio Roberto Santos - *Comissão Organizadora*

Engenheiro eletricista formado pela Universidade Federal do Rio de Janeiro, com especialização em economia e negócios pela Universidade Federal de São Carlos e Mestre em tecnologia da energia pelo Instituto de Energia e Ambiente da Universidade de São Paulo. Engenheiro da Lambda Consultoria, colunista da revista Eletricidade Moderna, consultor da Embrastec e membro de comissões de estudo do Cobei/ABNT há mais de 20 anos. Atua nas áreas de proteção contra descargas atmosféricas, proteção contra arcos elétricos e equipamentos de proteção coletiva e individual.

Agradecimentos

A edição de 2025 contou com o apoio e patrocínio de Vale, Santista, Leal, Westex, Grace, Etap e Magvatech, além dos apoios de mídia das revistas Eletricidade Moderna, O Setor Elétrico, Fotovolt e Unipotência.

Palavra do Coordenador Geral

É com grande satisfação que celebramos a realização do **XII Electrical Safety Workshop – ESW Brasil 2025**, sediado no Instituto de Energia e Ambiente da Universidade de São Paulo. Esta edição reafirmou o compromisso do evento com a **excelência técnica, a integração entre academia e indústria** e a **promoção de uma cultura sólida de segurança em eletricidade**. Reunindo especialistas de todo o país e convidados internacionais, o ESW Brasil consolidou-se como um fórum de referência na **disseminação de conhecimento científico e prático**, fortalecendo o papel do Brasil no cenário global da segurança elétrica.Os debates, tutoriais e apresentações técnicas refletiram o avanço contínuo das normas, metodologias e tecnologias voltadas à **proteção da vida e à gestão de riscos elétricos**.Agradeço a todos os palestrantes, autores, instituições e patrocinadores que tornaram possível este encontro, e em especial à IEEE IAS pelo apoio e confiança renovados.Que os resultados aqui compartilhados inspirem novas pesquisas, políticas e práticas que garantam ambientes de trabalho cada vez mais seguros e sustentáveis.

Dr. Márcio Bottaro

Coordenador Geral – XII ESW Brasil 2025

História do Electrical Safety Workshop Brasil

Apoiado pela Industry Applications Society (IAS) do Institute of Electrical and Electronics Engineers (IEEE), o IEEE IAS Electrical Safety Workshop (ESW) é um fórum técnico transnacional estruturado em 1991 pelo Subcomitê de Segurança em Eletricidade do IAS Petroleum and Chemical Industry Committee (PCIC), que realizou o primeiro ESW em 1992. Em 2012, o Conselho Executivo do IAS aprovou a criação do IAS Electrical Safety Committee (ESafeC) e transferiu a responsabilidade pelo ESW para este novo comitê técnico. Desde sua fundação, o ESW tem como lema “Mudando a cultura da segurança em eletricidade” visando promover melhorias contínuas na prevenção de lesões e acidentes devidos à eletricidade.

A ideia de fazer uma edição brasileira partiu de Luiz Tomiyoshi, um engenheiro eletricista entusiasta da segurança em eletricidade, que mantinha contato próximo com os organizadores do ESW nos Estados Unidos e buscava formas de realizar o evento no Brasil. Com a iniciativa de Tomiyoshi, o apoio da Seção IEEE Sul Brasil e de profissionais da DuPont e da Union Carbide, o primeiro ESW Brasil foi realizado em 2003, reunindo profissionais interessados na segurança em eletricidade dos Estados Unidos e com a participação de importantes colaboradores do ESW-USA, como Lanny Floyd, Dan Doan, Bruce McClung e a Dra. Mary Capelli-Schellpfeffer. Desde então, a realização do ESW Brasil tem sido bienal.

A ligação entre os eventos ESW Brasil e ESW EUA era mantida por meio de colaborações informais, com membros do comitê do ESW-EUA participando do evento brasileiro em algumas ocasiões. No entanto, essa conexão nunca havia sido formalmente oficializada, dependendo de contatos pessoais. Com a aposentadoria de alguns desses colaboradores, o vínculo acabou enfraquecendo.

Contudo, em 2024, os esforços da equipe organizadora foram voltados para a formalização da conexão com o ESW nos Estados Unidos, elevando ainda mais o patamar do evento brasileiro.

Até o momento, já foram realizadas 11 edições de forma bienal do ESW Brasil, ocorrendo em cidades distintas, incluindo uma edição on-line, tendo sido a última edição, em 2023 realizada nas instalações do Instituto de Energia e Ambiente da USP.

Em outubro de 2025, aconteceu a 12ª edição do evento, também na USP. Graças aos esforços de colaboradores dedicados à segurança no uso da eletricidade, juntamente com a ABRACOPEL (Associação Brasileira de Conscientização para os Perigos da Eletricidade), o ESW Brasil segue sendo a principal conferência dedicada à prevenção de acidentes de origem elétrica na América Latina.

Ano	Local	Chair(s)
2025	São Paulo, SP, Brasil	Márcio Bottaro
2023	São Paulo, SP, Brasil	Márcio Bottaro
2021	Virtual	Edson Martinho
2019	Salto, SP, Brasil	Edson Martinho
2017	Salto, SP, Brasil	Luiz K. Tomiyoshi, Edson Martinho,
2015	Rio de Janeiro, RJ, Brasil	Edson Martinho
2013	Recife, PE, Brasil	Luiz K. Tomiyoshi, Edson Martinho
2011	São Paulo, SP, Brasil	Luiz Tomiyoshi, Mario Ogava; Daniela Leal
2009	Blumenau, SC, Brasil	Luiz Tomiyoshi, Fernando Bernardes
2007	Rio de Janeiro, RJ, Brasil	Luiz Tomiyoshi,Ricardo Mattos
2005	São Paulo, SP, Brasil	Luiz Tomiyoshi, Estellito Rangel Jr.
2003	Guararema, SP, Brasil	Luiz Tomiyoshi, Estellito Rangel Jr.

https://www.ieee.org.br/eswbrasil/

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10:10 - 10:35		Trabalho 3	
10:35 - 11:00	Intervalo	Visita aos Pôsteres e Patrocinadores	Visita aos Pôsteres e Patrocinadores
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11:25 - 11:50		Trabalho 5	Trabalho 20
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XII IEEE ESW-Brasil 2025
A Engenharia Elétrica na Segurança do Trabalho
7 a 9 de outubro de 2025 – São Paulo - SP

ELIM – An analysis of the impact of variability in the new IEC arc rating parameter compared to the well-known ATPV

Luis Eduardo Caires
Institute of Energy and Environment
University of São Paulo
São Paulo, Brasil
luis@iee.usp.br

Márcio Bottaro
Institute of Energy and Environment
University of São Paulo
São Paulo, Brasil
marcio@iee.usp.br

Thais Ohara de Carvalho
Institute of Energy and Environment
University of São Paulo
São Paulo, Brasil
thais@iee.usp.br

Paulo Futoshi Obase
Institute of Energy and Environment
University of São Paulo
São Paulo, Brasil
obase@usp.br

Rogerio Masaro
Institute of Energy and Environment
University of São Paulo
São Paulo, Brasil
rogerio@iee.usp.br

Hédio Tatizawa
Institute of Energy and Environment
University of São Paulo
São Paulo, Brasil
hedio@iee.usp.br

***Abstract*— Arc rating is a fundamental parameter for characterizing any personal protective equipment, with the most well-known indicators being ATPV and EBT, both based on a 50% probability of second-degree burns. Since 2018, the ELIM parameter has been introduced internationally, assuming a zero likelihood of second-degree burns. With the extensive use of the IEC 61482-2 standard to certify PPE worldwide, ELIM became an arc rating parameter considered conservative. Based on a single test, ELIM is always more conservative, which is why the European Community chose it for characterizing thermal protective clothing. However, characterizing a fabric based on a single test is controversial and can be prone to errors. International research shows up to 40% variability when analyzing parameters such as ATPV in the same fabric and comparing different tests, laboratories, and time periods. Additionally, a tendency to report ATPV values higher than the average or most probable value has been observed—a practice with significant commercial impact, even though highly not recommended. As for ELIM, which is still not widely studied in laboratories, its behavior and actual contribution to a more conservative approach to thermal protection remain uncertain. In this study, we analyzed the variability of ELIM across different test sets for various thermal protective fabric technologies. By assessing the probability of burn occurrences within these sample groups, we found that burns can occur within ELIM's confidence interval, reaching up to 16.9 % under a students' distribution approximation, raising questions about its actual conception of zero probability of skin burns. Additionally, the study shows that ELIM's variability is considerably high, influenced by various factors, which may lead to ELIM historical mean values being sometimes equivalent to the ATPV historical mean, or even values of ELIM can overlap ATPV's confidence interval. This finding raises further doubts about the conservative protection philosophy associated with this parameter.**

Keywords—ELIM, ATPV, variability, arc flash burns, Personal Protective Equipment

I. INTRODUCTION

The current process to assign an arc rating to a material that will be part of thermal protective clothing is based on a mathematical technique consisting of a logistic regression fit applied to incident energy data (independent variable) and second-degree burn evaluation (binary response dependent variable) on an open arc standard test arrangement [1, 2].

$$p = \frac{1}{1+e^{(-a-bx)}} \quad (1)$$

where p is the probability of the logit, a is the intercept, b is the slope of the function's linear portion, and x represents the independent variable.

The dependent variable binary response compares the transmitted energy on materials under test with an empirical model based on the studies of second-degree burns with different heat sources [3]. The empirical model is the Stoll curve by international standards [1,2]. Any transmitted energy equal to or over the Stoll curve is recognized as reaching the Stoll Criteria, which means 100 % skin second-degree burn probability. Transmitted energies under the Stoll curve are considered to have a 0 % skin second-degree burn probability.

The test consists of submitting at least 20 samples to AC electric arcs generated and controlled to be within 8 kA ± 0.5 kA in a 305 cm electrode gap, mechanically sustained by a current bus cage. Each arc can be simultaneously applied to three sample holding panels, which usually confers 21 samples to the test results. Those panels are positioned at 305 cm from the arc vertical center line and are 120°

horizontally equidistant over the vertical center of the cage [1, 2].

The main parameter of the arc rating test is the ATPV (Arc Thermal Performance Value), which in practice is the mean value of the logistic regression, mathematically representing 50 % of the probability of occurrence. Away from the mean value, the logistic regression percentiles show low confidence values, meaning that ATPV is the most stable result for the arc rating determination in this procedure.

The arc rating method using ATPV is considered efficient in characterizing materials that will be applied on protective clothing [4]. Although related to a parameter obtained by a logistic regression, the procedure is considered conservative as the panel methodology subjects samples to a more severe application, with almost no air interfaces within fabrics and sensors and a stricter positioning of samples that are static during the arc test. In the real use of protective clothing, the garments have more components that add protection, such as pockets and closing coverings, and air in the body interfaces. Additionally, human response to an arc flash is not static; however, risks can also be enlarged for some working places, as it is confined.

Due to the origin of the ATPV being related to the logistic regression and consequently associated with a 50% probability of second-degree skin burn, a new arc rating parameter was proposed by the International Electrotechnical Commission (IEC) in 2018 [5], the Incident Energy Limit – ELIM. The ELIM is an arithmetic mean of incident energies of the three test values with no indication of Stoll curve second-degree burn just before the first burn prediction in the test's incident energy range – lower energy point of the so-called mix zone [1].

In principle, there's no data point below the ELIM value with the amount of heat transmitted through the material reaching the Stoll Criteria [5]. This is evident for a single test; however, for a historical of tests, how does ELIM behave? Recent studies show that ATPV has a considerable variation within tests [6-8], which is attributed not only to the intrinsic properties of fabric but also to the test arrangements, measuring, and statistical criteria.

To investigate their correlation, the present study evaluates a historical of ATPV and ELIM tests in different fabric compositions and arc flash laboratories from 2018 to 2024. The repeatability and reliability of ELIM, when not only a single fabric test is taken under consideration, give a comprehensive result of the effectiveness of this parameter as an indicator of zero probability of skin burn injuries.

II. Arc Rating Overview

A. *ATPV and ELIM primary relationship*

All open arc rating standard tests are conducted to find the ATPV, even though a fabric manufacturer or any other interested party demands ELIM. It means that the test procedure will mainly look for the ATPV criteria that can be summarized according to [1]:

- 3 points under mix zone (0 % burn evidence);
- 3 points over mix zone (100 % burn evidence);
- At least 10 points within 20 % of the final arc rating value.

One observes that the way the test is conducted can influence the 3 points under the mix zone, which means that the test conduction can influence the ELIM as it's not the main parameter of the test procedure.

After at least 20 valid sample results within the test criteria, also respecting electrical parameters tolerances, logistic regression is fitted to data points, and ATPV is calculated. Within those data, ELIM is secondly determined. Figure 1 shows a test example in the graph with a graphical indication of ATPV and ELIM.

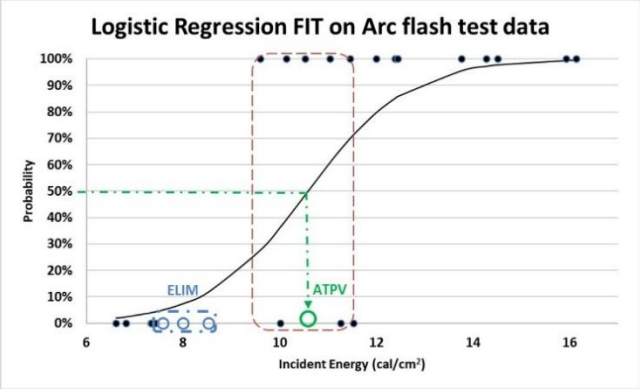

Fig. 1. An arc rating test with ATPV and ELIM is indicated on the incident energy independent variable axis.

For the example in Figure 1, ATPV is 11 cal/cm², while ELIM is 8 cal/cm². The test was conducted with incident energies from 6.6 to 16.1 cal/cm², where 6.6 cal/cm² has a probability near 0 % to occur and 16.1 a probability near 100 %. Interestingly, ELIM in this specific case is close to 8 % occurrence if we look at the logistic fitting, a fact that is often observed during practical tests. As mentioned before, the confidence of fitting results always comes from the mean value of the logistic regression. The sample size adopted in the arc rating test, which is small if we look at the most accurate applications [9], can be considered very poor.

If the test was conducted differently, exploring more incident energies from 8.5 to 9.5 cal/cm², a higher ELIM, or even a shift in the logistic regression and, consequently, the ATPV could be obtained. However, with such a small sampling [9], it is impossible to affirm such behavior, and a new test is mandatory to evaluate such assumptions.

B. *Importance of the historical data*

Due to the process limitation, as already observed with a single example of the ATPV and ELIM determination, it's clear that, although a single test shows that ELIM will always be lower than ATPV, variations in the arc rating procedure are expected to happen and can also be considerably relevant.

Recent studies reported ATPV values within the same material varied by 41 % with an 81 % confidence interval [6], and in Brazil, a 38 % variation with a 68 % confidence interval was found for nine different fabrics. Such variations are much higher than the expected uncertainties in a single process [10], triggering a warning regarding which values are being selected to produce and certify garments, as a single arc rating test can be used in this sense [8].

If ELIM is never higher than ATPV in a single arc rating test in historical data for the same fabric, it's essential to understand their correlation. Moreover, as ELIM is based on a simple arithmetic mean of 3 results and depends on arc rating

test conduction, where ATPV is the main target, that's supposed to have a considerable variation within tests and time.

Although ELIM represents a conservative parameter concerned with ATPV use, its variation can reveal concerns about its effectiveness and proper use to state a final PPE arc rating.

III. Analyzing Arc Rating History Data

A. *ELIM and ATPV historical rating*

Five fabric brands were analyzed to evaluate arc rating data variations, with three different compositions and a history of at least five tests in one or more standard open arc test laboratories from 2018 to 2024. Table I shows the fabric composition and number of tests with respective periods of tests. All tests were performed with one layer of material. Fabric and Laboratory names are not presented for confidentiality reasons.

TABLE I. Fabric and Arc Rating Data

Fabric	Material and Historical Data			
	Composition	*Nominal Weight (g/m²)*	*Test Period*	*Number of Tests*
F1	88 % Cotton 12 % Polyamide	260	2018 – 2024	12
F2	100 % Cotton	290	2018 – 2023	9
F3	88 % Cotton 12 % Polyamide	237	2018 – 2024	18
F4	98% Aramid 2% Antistatic	200	2020 – 2024	9
F5	88 % Cotton 12 % Polyamide	250	2021 – 2024	6

Figures 2 to 6 show the fabrics in t-distribution approximation results, which are more realistic than a normal distribution if we consider the number of tests involved in each evaluation.

One observes that ELIM and ATPV areas overlap, meaning that ELIM values can coincide with ATPV values when we evaluate an arc rating historical data that, in truth, is more representative of fabric real characterization [6,7].

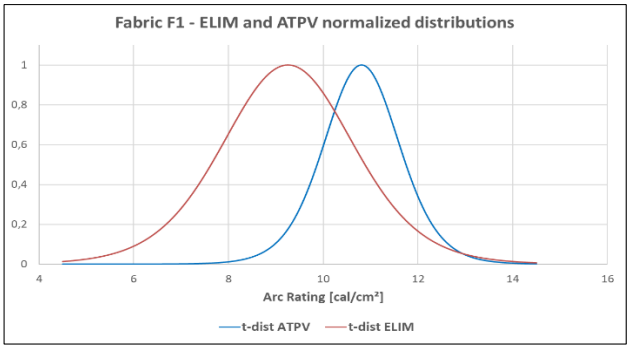

Fig. 2. ELIM and ATPV normalized t-distributions for Fabric F1.

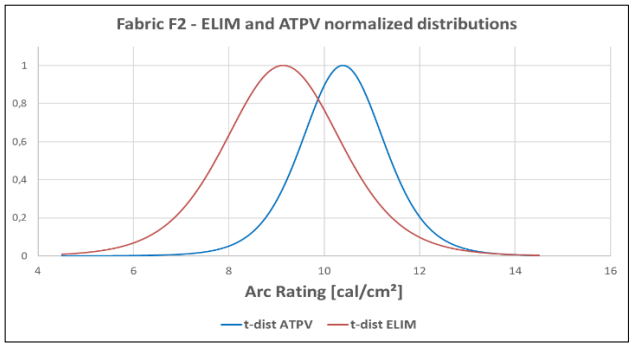

Fig. 3. ELIM and ATPV normalized t-distributions for Fabric F2.

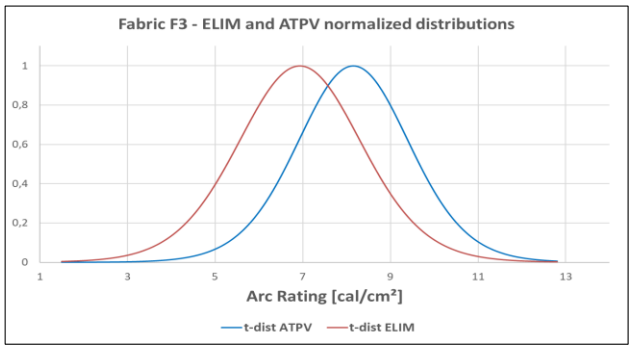

Fig. 4. ELIM and ATPV normalized t-distributions for Fabric F3.

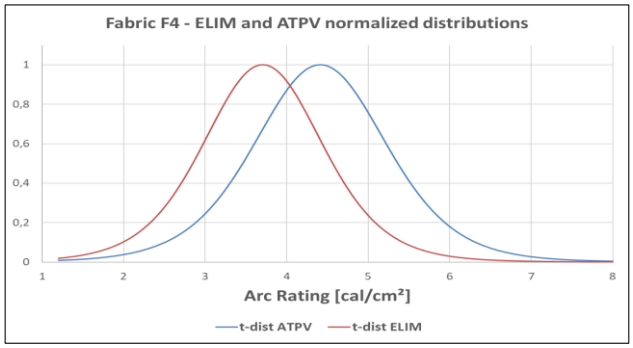

Fig. 5. ELIM and ATPV normalized t-distributions for Fabric F4.

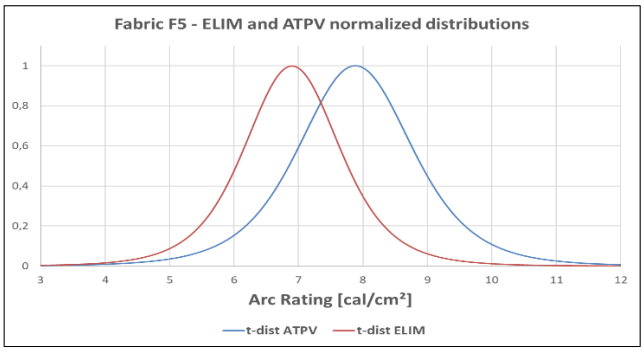

Fig. 6. ELIM and ATPV normalized t-distributions for Fabric F5.

ELIM and ATPV assumed different distributions depending on the material. With the ELIM characteristics of a simple mean value within three samples and also not being the main target on the arc rating procedure, its variation was expected to be wide in all cases. However, as recent studies [6-8] reported, ATPV also has considerable variations.

B. *ELIM and ATPV variations – an arc rating concern*

Table II summarizes ELIM and ATPV maximum variations related to mean historical values, with the respective confidence levels (CL) considering a student's t-distribution.

TABLE II. FABRIC AND ARC RATING DATA VARIATIONS AND CONFIDENCE INTERVALS

Fabric	$ELIM_{MEAN}$ [cal/cm²]	ELIM Variation *(CL)*	$ATPV_{MEAN}$ [cal/cm²]	ATPV Variation *(CL)*
F1	**9.3**	**52 %** (*83 %*)	**10.8**	**31 %** (*91 %*)
F2	**9.1**	**40 %** (*82 %*)	**10.4**	**27 %** (*80 %*)
F3	**6.9**	**95 %** (*97 %*)	**8.2**	**66 %** (*95 %*)
F4	**3.7**	**59 %** (*81 %*)	**4.4**	**57 %** (*79 %*)
F5	**6.9**	**26 %** (*72 %*)	**7.9**	**27 %** (*69 %*)

An impressive ELIM variation of 95 %, with a respective ATPV variation of 66 %, was observed for an 88 % Cotton and 12 %, Polyamide fabric (F3). However, a similar material (F1) presented a 52 % variation in ELIM and 31 % in ATPV, and F5 presented 26 % in ELIM and 27 % in ATPV. Aramid-based material showed an ELIM variation of 59 % and ATPV variation of 57 %. Fabric with 100 % cotton (F2) presented variations of 40 % on ELIM and 27 % on ATPV.

Correlation with materials is complex, but all tests showed considerable historical variations, posing questions on methodology and materials real arc rating repeatability and reproducibility, a real challenge for protection development [8].

IV. STATISTICAL TESTS ON ELIM AND ATPV RESULTS

A. *Applying the student's t-test*

To evaluate whether ELIM and ATPV are consistently different, a student's t-test [11] was applied for every fabric under consideration.

The student's t-test consists of a comparison of means within two groups in an aleatory sampling process. Here, one can consider ELIM, and ATPV means to be independent. The combined variance for the two results can be summarized as:

$$s_{\overline{X1}-\overline{X2}} = \sqrt{\left(\frac{N_1 \cdot s_1^2 + N_2 \cdot s_2^2}{N_1 + N_2 - 2}\right) \cdot \left(\frac{N_1 + N_2}{N_1 \cdot N_2}\right)} \qquad (2)$$

where $\overline{Xi}$ represents the mean value of the parameters' groups (ELIM – 1 or ATPV – 2), N_i the number of samples for each parameter, and s_i^2 the variance for the parameter group of data.

The *t* parameter is defined by:

$$t = \frac{\overline{X1}-\overline{X2}}{s_{\overline{X1}-\overline{X2}}} \qquad (3)$$

This parameter can be directly compared in a convenient t-distribution probability function or table, in an appropriate confidence level, where values within ± *t* limits are considered equivalent means and out of this range, independent means.

A summary of the student's t-test results for each evaluated fabric results are presented in the Table III.

TABLE III. STUDENT'S T-TEST ON ELIM AND ATPV HISTORICAL RESULTS

Fabric	*t-test limit*	ELI-ATPV *t*	ELIM and ATPV means
F1	**2.07**	**3.33**	**Statistically Different**
F2	**2.12**	**2.49**	**Statistically Different**
F3	**2.03**	**2.69**	**Statistically Different**
F4	**2.12**	**1.91**	**Statiscally Equivalent**
F5	**2.23**	**2.23**	**Statiscally Equivalent**

Although Figures 2 to 6 show a significant overlap within ELIM and ATPV distributions in the five fabric samples, the student's t-test shows the independence of means within a 95 % confidence level for the Fabrics F1, F2, and F3, which in principle indicates that ELIM and ATPV means are statistically different for the respective groups or fabrics under test, Fabrics F4 and F5 on the other hand, presented ELIM and ATPV means considered equivalent in the students' t-test within 95 % confidence level, and so, can be considered statistically not independent.

B. *Can ELIM be higher than ATPV, or can ATPV be lower than ELIM?*

As mentioned, it's impossible in a single arc rating test to have an ELIM higher than the ATPV or an ATPV lower than an ELIM. However, using the student's t-distribution, it is possible to estimate the probability of such cases in historical data of arc rating tests.

Table IV presents data of probabilities of ELIM to be higher than ATPV and ATPV to be lower than ELIM, considering historical data of fabrics under test in a student's t distribution.

TABLE IV. PROBABILITY OF ELIM AND ATPV VALUES TO BE SUPERPOSED

Fabric	$P_{ELIM>ATPV}$	$P_{ATPV<ELIM}$
F1	**14.5 %**	**4.1 %**
F2	**16.6 %**	**9.0 %**
F3	**20.5 %**	**18.3 %**
F4	**18.5 %**	**20.8 %**
F5	**12.6 %**	**16.3 %**

Contrary to the expectation of a zero probability of second-degree burns, a broader look at a set of tests for the same material shows that the ELIM can be higher than the historical average of ATPV values, even with probabilities exceeding 20 %. The latter, in turn, may have a value lower than the historical average of ELIM, with probabilities also exceeding 20 %, depending on the material. That's controversial for the idea of a more conservative arc rating parameter.

V. SECOND-DEGREE SKIN BURNS WITHIN ELIM

A fundamental aspect of the ELIM concept is the condition that no events meet the Stoll criterion in the analysis of energy transmitted through the materials or even the absence of breakopen in that energy.

A point-by-point search of Stoll Events was performed for each fabric, and each test under the ELIM mean value for each fabric historical data to evaluate such events within the historical data. The expected result should be zero, as under ELIM, according to its definition [1, 5], no prediction of skin burn would be present, which is mandatory and true in a single arc rating test.

A critical remark is that no breakopen occurrences were evidenced within the ELIM intervals in the historical data, which, in principle, would compromise the ELIM acceptance criteria according to [1].

Table V illustrates the Stoll events under ELIM mean value and percentual of such events within the total arc shots in the historical arc rating tests for each material.

One observes that Stoll events under ELIM mean value for all fabrics, which a historical approach can evidence. This confirms that a prediction of zero skin burn according to the standards' prediction model [1-3] is not real in principle; however, values are all under 5 %.

TABLE V. SKIN BURN PREDICTION POINTS UNDER ELIM MEAN HISTORICAL VALUE

Fabric	$ELIM_{MEAN}$ [cal/cm²]	STOLL events under ELIM	Historical number of Electric Arcs	Percentual within a total of arcs
F1	**9.3**	**10**	**253**	**4.0 %**
F2	**9.1**	**5**	**186**	**2.7 %**
F3	**6.9**	**19**	**436**	**4.4 %**
F4	**3.7**	**7**	**189**	**3.7 %**
F5	**6.9**	**3**	**126**	**2.4 %**

Table VI illustrates the same analysis regarding the ATPV, comparing the total percentual of arcs with Stoll events at incident energies under this arc rating parameter, which has been extensively used in the last decades.

Although events under ATPV are expected to be near a 50 % probability, Stoll events under this mean value are always evidenced under 17 %.

TABLE VI. SKIN BURN PREDICTION POINTS UNDER ATPV MEAN HISTORICAL VALUE

Fabric	$ATPV_{MEAN}$ [cal/cm²]	STOLL events under ATPV	Historical number of Electric Arcs	Percentual within a total of arcs
F1	**10.8**	**25**	**253**	**9.9 %**
F2	**10.4**	**19**	**186**	**10.2 %**
F3	**8.2**	**55**	**436**	**12.6 %**
F4	**4.4**	**32**	**189**	**16.9 %**
F5	**7.9**	**19**	**126**	**15.1 %**

VI. CONCLUSIONS

Although idealized to be a zero-odd probability indicator, ELIM, when evaluated in a population of Stoll second-degree skin-burn prediction, based on analysis of material historical data, falls in a questionable concern related to such a conservative aspect.

Due to the different aspects of the arc rating test procedure and considerable variation in results, some materials can also exhibit a statistical equivalence within ELIM and ATPV historical means, as demonstrated for materials F4 and F5 on students' t-tests. Even when such tests show the independence of these parameters on arc rating historical data, the probability of ELIM being higher than the ATPV historical mean and of the ATPV values under the ELIM historical mean cannot be neglected.

Test results showing Stoll skin-burn events under ELIM mean values reached up to 5 % and under ATPV mean values were close to 17 %, and variations of more than 66 % on ATPV or of 95 % on ELIM are paramount concern points to be discussed on standardization groups, as it's observed that not only materials are contributing to such historical deviations but also test procedure.

The test data distribution according to the test requirements stated by the international requirements regarding a single test raises a considerable number of questions regarding the data distribution, test arrangement, test uncertainties [10], as well as historical data and global results have many points that need to be revisited to enhance procedure and reduce test variations [6-8].

Different or optimized arrangements or even a reduction of non-linearities would contribute to the procedure [12], as it's evident that the test contributes to a considerable part of the variations reported. The proposal of an enhancement on the actual arc rating method, looking for a more robust method or statistical-based data approach, or even a new or complementary arc rating parameter would be interesting in a way to reduce test variations.

ACKNOWLEDGMENT

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Aterramento elétrico temporário para manutenção em usinas e subestações

Luiz Henrique Zaparoli
Gerência de Saúde, Segurança e Bem Estar no Trabalho
Eletrobrás
Poços de Caldas , Brazil
zaparoli@eletrobras.com

***Abstract*— This work aims to define safety procedures and requirements for the use of temporary electrical grounding in the maintenance of substations and power plants. These requirements include equipment tests, installation and removal procedures and controls for low, medium and high voltage equipment and systems.**

Keywords — Temporary electrical grounding, safety, de-energization

I. INTRODUÇÃO

As intervenções de manutenção em equipamentos desenergizados representam a maior parte das atividades de manutenção em usinas de geração de energia elétrica e subestações. Para realização destas atividades é imprescindível, para segurança dos trabalhadores e do sistema, que se realize corretamente o processo de desenergização que inclue obrigatoriamente, seccionamento, bloqueio, constatação da ausência de tensão e instalação de aterramento elétrico temporário entre outras ações.

O histórico de acidentes no setor elétrico nos mostra que todo processo de desenergização e reenergização são pontos de atenção que devem ser padronizados e controlados de modo a evitarmos acidentes durante o procedimento de instalação e retirada dos conjuntos de aterramento temporários. Não obstante deve – se garantir a eficácia da proteção dos trabalhadores tanto para as tensões induzidas, quanto para possíveis reenergizações acidentais no ponto de intervenção.

Este trabalho se propõe a identificar estes parâmetros e controles para utilização de aterramento elétrico temporário em subestações e usinas desde a baixa tensão até a alta e extra alta tensão sendo aplicável a todos equipamentos e sistemas com tensão superior a 50 volts em corrente contínua ou 120 volts em corrente alternada, entre fases ou entre fase e terra.

A base deste trabalho está no texto que vem sendo formulado junto a Associação Brasileira de Normas Técnicas (ABNT), em sua comissão de segurança em eletricidade, para uma NBR de procedimentos para execução de Aterramento Elétrico Temporário (AET), bem como no escopo do normativo Eletrobrás recentemente revisado e atualizado.

II. REQUISITOS DE TREINAMENTO

A. *Treinamento de AET*

A instalação e remoção de aterramento elétrico temporário deve ser considerada ação com alto risco de acidente e faz-se necessária a correta especialização de seus executantes. Desta forma é imprescindível que os trabalhadores que executem esta tarefa, bem como as demais referentes ao procedimento de desenergização, participem de treinamento específico do assunto. É desejável que este treinamento seja objeto de reciclagem periódica ou por demanda quando da modificação de processos sistemas, equipamentos etc.

B. *Outros treinamentos*

Além do treinamento específico os trabalhadores devem realizar treinamentos de reciclagens de segurança em eletricidade conforme legislação vigente, estar com o atestado de saúde ocupacional em dia e ter a autorização para acesso a áreas de risco e intervenção em eletricidade

.

III. TESTES EM ENSAIOS EM SISTEMAS E EQUIPAMENTOS

Os sistemas e equipamentos a serem utilizados durante o procedimento de instalação e retirada dos AET deve passar por inspeções e testes de forma a garantir sua integridade conforme mostrado nos itens a seguir:

A. *Pontos de Afloramento da malha de terra*

Os pontos de afloramento da malha de terra em subestações e usinas que são utilizados para conexão do aterramento elétrico temporário devem ser ensaiados, em sua

resistência ôhmica, como forma de se garantir a integridade de suas conexões.

Estes ensaios devem ter periodicidade máxima de dez anos ou serem realizados por demanda, quando ocorrerem modificações/ obras na instalação.

Todos os pontos de afloramento ensaiados e aprovados devem ser identificados com codificação própria de forma a garantir a rastreabilidade dos ensaios. Para este ensaio são indicados dois procedimentos sendo o ensaio de medição de resistência ôhmica com micro ohmímetro ou o ensaio com o equipamento Terrômetro.

B. Conjuntos de aterramento temporário

Os conjuntos de AET devem ser inspecionados antes de sua utilização com, no mínimo os seguintes itens:

- Verificar a condição dos cabos, atentando para possível rompimento dos fios formadores, principalmente na região dos terminais prensados.
- Verificar os grampos que devem estar livres de impurezas, com o parafuso de aperto girando livremente e as roscas lubrificadas.
- Verificar a condição das conexões dos grampos que devem estar limpas e firmemente conectadas ao cabo. No caso do grampo multiangular, deve-se verificar a pressão da mola e a presença de impurezas e ferrugem.
- Verificar o aperto de todos os parafusos dos grampos
- Verificar a presença de oxidação nos cabos e na interface terminal-cabo;
- Verificar se a identificação do conjunto de aterramento está legível;
- Verificar a existência de trincas ou danos nos grampos e terminais
- Verificar a validade dos ensaios elétricos.

Além da inspeção antes da utilização os conjuntos de AET devem ser anualmente ensaiados em suas resistências ôhmicas sendo os resultados máximos esperados indicados em (1) segundo a ASTM F2294-24 [1]:

$$Rm = 1{,}05\ RL + 0{,}32\ m\Omega \quad (1)$$

Onde Rm é a máxima resistência elétrica admitida dos cabos juntamente com os terminais prensados e grampos de aterramento, R é a resistência ôhmica do cabo conforme ABNT NBR NM280 (IEC 60228) [2] e L é o comprimento do cabo em metros.

C. Bastões e Varas de manobras utilizados para detecção de tensão e instalação e retirada de conjuntos de AET

Na inspeção antes da utilização, os bastões e varas de manobra devem ser verificados quanto à uniformidade de cor e brilho, ausência de arranhões, trincas, rebarbas, empenamentos, condições das conexões e sujeira.

Deve-se dar atenção especial às junções entre os bastões e as partes metálicas, garantindo que estejam em perfeito estado para uso seguro.

Recomenda-se o teste com o testador portátil diariamente antes do uso do bastão para constatação de ausência de tensão e/ou instalação dos conjuntos de aterramento temporário pelos agentes de manutenção.

O teste antes da utilização com o testador portátil deve atender o seguinte procedimento para realização do teste:

- Realizar a higienização do bastão utilizando produto indicado pelo fabricante
- Aferir o testador portátil
- Realizar o teste em toda extensão do bastão/vara de manobra utilizando o testador portátil, e verificar a indicação de aprovado/reprovado
- Caso qualquer parte do bastão indique reprovação o mesmo não poderá ser utilizado.

Os bastões isolantes devem ser submetidos, a cada dois anos, ao ensaio de tensão aplicada em laboratório de acordo com a norma IEC 60832 [3]

Quando da realização do aterramento temporário, deve ser observada a quantidade mínima de segmentos ou tamanho do bastão/vara de manobra a serem utilizados, considerando:

- O nível de tensão do circuito a ser trabalhado
- A distância mínima de segurança que garanta a proteção contra choque elétrico.
- A energia incidente do arco elétrico para o equipamento/sistema em questão na distância de trabalho em relação a especificação da vestimenta de proteção térmica conforme NBR 17227[4].

D. Luvas isolantes de Borracha

As luvas isolantes devem ser ensaiadas quanto à isolação elétrica, conforme critérios definidos pela NBR16295[5], em periodicidade indicada pelo fabricante e na falta desta com periodicidade máxima de um ano.

Deve se realizar a inspeção da integridade da luva isolante e de sua luva de cobertura bem como a realização do teste de insuflação diariamente antes do início das atividades.

E. Detectores de tensão

Recomenda-se o ensaio dos detectores de tensão em laboratório com periodicidade máxima de um ano.

É obrigatório o envio para reparos e ensaios laboratoriais sempre que apresente qualquer problema de falha do botão teste ou falha na utilização. O teste sonoro e luminoso do detector de tensão deve ser realizado sempre antes da sua utilização.

IV. . UTILIZAÇAO DE EQUIPAMENTOS DE PROTEÇÃO INDIVIDUAL (EPI) NA INSTALAÇÃO E RETIRADADE DE AET

Para execução das atividades de aterramento elétrico temporário deve se utilizar no mínimo calçado de segurança isolante, vestimenta de proteção térmica conforme estudo de energia incidente atendendo os requisitos da NBR 17227, capacete, óculos de segurança e luvas isolantes com suas respectivas luvas de cobertura conforme análise de risco da atividade. A luva isolante com suas respectivas luvas de cobertura deve ser utilizada na etapa da constatação de ausência de tensão, na etapa de conexões e desconexões dos grampos (conectores) de terra e fase.

Os parâmetros mínimos para utilização de luva isolante, com suas respectivas luvas de cobertura, para execução de atividades vinculadas ao aterramento elétrico temporário são descritos na tabela abaixo:

TABELA 1 . UTILIZAÇÃO DE LUVA ISOLANTE PARA ATERRAMENTO ELÉTRICO TEMPORÁRIO

Nível de tensão nominal	**Classe mínima da luva NBR16295**		
	Constatação de ausência de tensão com bastão isolante	***Instalação e retirada do conector de terra (classe)***	***instalação e retirada do conector de fase com bastão isolante***
Até 1 kV	0	0	0
Até de 15 kV	2	2	2
Até de 25 kV	2	2	2
Até de 36,2 kV	3	3	3
Acima de 36,2 kV	2	*	*

Recomenda -se a utilização de luva isolante classe 2 para instalação e retirada do conector de terra e de fase com bastão isolante para tensões acima de 36,2 kV. Esta utilização da luva pode ser objeto de análise de risco e nos casos em que se verificar a inviabilidade técnica desta utilização esta poderá ser revista desde que registrada e garantida a condição de segurança para execução da tarefa e que a condição seja descrita e registrada na análise de risco da atividade.

V. DIMENSIONAMENTO DOS CONJUNTOS DE ATERRAMENTO TEMPORÁRIO

Os conjuntos de aterramento elétrico temporários devem ter a capacidade para conduzir a máxima corrente de curto pelo tempo necessário à atuação do sistema de proteção, garantindo a segurança da equipe de manutenção, no caso de energização inadvertida da linha ou equipamento, além disso, devem conduzir correntes induzidas de estado permanente.

Desta forma, o dimensionamento dos conjuntos de aterramento elétrico temporário deve ser realizado considerando o valor da maior corrente de curto-circuito calculada para o ponto de aterramento e o tempo de atuação da proteção adicionando o tempo de eliminação da falta (tempo de sensibilização e atuação da proteção, tempo dos contatos auxiliares, tempo de abertura do disjuntor ou dispositivo de proteção). A capacidade da condução de corrente do conjunto ou da soma das capacidades dos conjuntos, quando houver mais de um instalado por fase, para o tempo mínimo, deve ser de, no mínimo, 1,05 vezes o valor da maior corrente de curto calculada no tempo considerado para eliminação da falta.

Para efeito de especificação da seção transversal do condutor do conjunto de aterramento elétrico temporário considera-se como tempo para atuação da proteção, no mínimo 500ms para tensões nominais iguais ou acima de 138 kV, e no mínimo, 1000ms para tensões abaixo de 138 kV. Tempo maiores podem ser considerados a depender de estudos da proteção, bem como de definições específicas de cada empresa/instalação.

Para verificação da capacidade de condução dos conjuntos de aterramento, deve ser utilizada a tabela 2 a seguir, baseada em recomendação de catálogo de fabricantes e nas normas ASTMF855 [6] e IEC 61230 [7].

TABELA 2 . VALORES DE CORRENTE DE CURTO-CIRCUITO POR SEÇÃO TRANSVERSAL DE CABO

Seção Nominal (mm²)	**Capacidade de condução de Corrente elétrica (kA)**	
	30 Ciclos (0,5 Seg.)	***60 Ciclos (1 Seg.)***
25	7	5
35	10	7
50	15	10
70	20	14
95	30	21
120	39	26

Deve se atentar também para a capacidade de condução de corrente dos conectores e terminais prensados. A capacidade de condução de corrente do conjunto de aterramento temporário será a menor dentre os cabos, conectores e terminais que o compõe.

Os cabos, grampos e conectores além da capacidade de condução de corrente deverão suportar os esforços mecânicos criados pelas correntes de curto, sem se desprenderem nas conexões, nem se romperem.

VI. CONTROLES DE ISNTALAÇÃO E RETIRADA DOS CONJUNTOS DE ATERRAMENTO ELÉTRICO TEMPORARIOS

Para o controle de instalação e retirada, devem ser utilizados, no mínimo, o formulário de controle e identificação dos pontos de aterramento temporário e o croqui de aterramento, juntamente com a inspeção visual em campo antes e depois da retirada dos conjuntos de aterramento temporário.

É recomendável também a utilização de cartões de controle de aterramento que podem complementar os controles do formulário de controle e identificação dos pontos de aterramento temporário e o croqui de aterramento e ainda

servir como sinalização. A tabela 3 e a figura 1 mostram exemplos deste formulário e do croqui supracitados.

TABELA 3 . FORMULÁRIO DE CONTROLE E IDENTIFICAÇÃO DOS PONTOS DE ATERRAMENTO TEMPORÁRIO

Controle e identificação dos pontos de aterramento temporário											
Instalação dos conjuntos de aterramento temporário							Retirada dos conjuntos de aterramento temporário				
Identificação conjunto de aterramento temporário	Local de instalação conector de fase	Identificação do ponto de aforamento da malha de terra para instalação conector de fase	Número do documento de intervenção	Data	Responsável	Assinatura	Confirmação de retirada	Data	Responsável	Assinatura

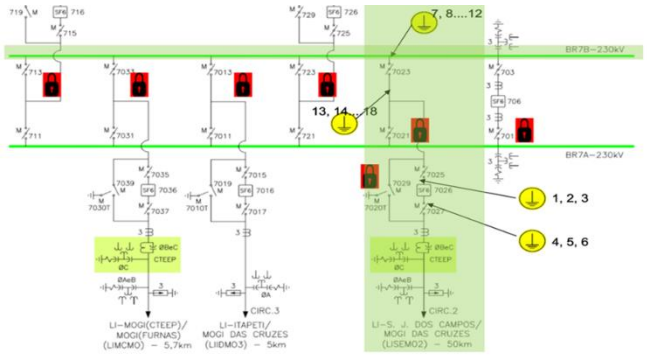

Fig. 1. Exemplo de croqui de aterramento

Os cartões de controle de aterramento podem ser utilizados como forma de identificação e complemento no controle de instalação e retirada. É recomendado a instalação de 2 cartões por cabo de aterramento temporário um em cada extremidade, um próximo ao conector de terra e outro próximo ao conector de fase. Os dois cartões instalados em um mesmo cabo de aterramento temporário deverão ter a mesma numeração prevenindo a desconexão indevida do conector de terra antes do conector de fase quando da instalação de vários conjuntos de aterramento temporário para uma mesma intervenção.

A figura 2 mostra exemplos dos cartões de aterramento a serem instalados nos conectores de fase e terra

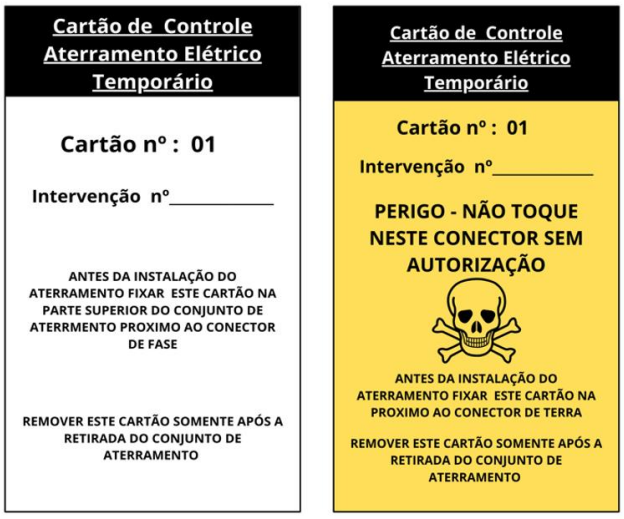

Fig. 2. Exemplo cartões de aterramento

VII. ATERRAMENTO ELÉTRICO TEMPORÁRIO NA REALIZAÇÃO DE ENSAIOS EM EQUIPAMENTOS

Nas tarefas de testes de equipamentos como disjuntores, onde existe somente a interação com a parte de comando e controle com abertura e fechamento do equipamento, poderá ser dispensado o uso do conjunto de aterramento temporário desde que respeitadas as distâncias de segurança contra choque elétrico e o limite seguro de aproximação do arco elétrico ou utilização de vestimentas de proteção térmica com proteção superior a energia incidente do arco elétrico calculado para o equipamento a ser aterrado na distância de trabalho necessária para execução destas tarefas. Nesse caso, a sinalização da área de trabalho deve considerar a área energizada, não podendo haver interação com a parte de potência. Também nesse caso, deve constar na análise de risco uma observação acerca dessa condição

O conjunto de aterramento temporário poderá ser removido, momentaneamente, nas tarefas onde seja necessária a realização de ensaios em equipamentos e estes não possam estar aterrados. Nesse caso, todos os profissionais envolvidos na tarefa devem estar cientes e atentos com tensão aplicada por instrumento ou indução que o equipamento possa ser submetido. Durante o período sem o aterramento elétrico temporário o equipamento deve ser considerado energizado sendo o procedimento correto para o teste/ensaio a seguinte sequência após a todo processo de isolação, bloqueio, impedimento de reenergização e constatação de ausência de tensão já terem sido realizados:

- Aterrar o equipamento
- Conectar os terminais do equipamento de teste”
- Afastar do equipamento sob teste mantendo distância de segurança ao choque e arco elétrico
- Desaterrar o equipamento
- Executar o teste em distância de segurança de choque e arco elétrico
- Aterrar o equipamento
- Desconectar” o terminais de teste”

VIII. DISPOSIÇÕES GERAIS

A instalação e a retirada dos aterramentos elétricos temporários somente devem ser realizadas em condições meteorológicas adequadas, considerando risco de descargas atmosféricas

Dentro de instalações energizadas devem ser aterrados máquinas e equipamentos de grande porte, guinchos, andaimes (não isolantes) e estruturas metálicas em construção, bem como plataforma elevatória móvel de trabalho (PEMT) ou qualquer estrutura que tenha proximidade com as instalações energizadas.

Antes da instalação dos aterramentos temporários devem ser verificadas as isolações elétricas e o bloqueio físico dos pontos de isolação bem como a instalação de sinalização de impedimento de reenergização.

Os cabos de aterramento temporário não devem ser instalados em locais frágeis que não suportem os esforços elétricos e mecânicos oriundos dos curtos-circuitos, como os anéis anti-corona e centelhadores.

É terminantemente proibida a execução de qualquer tipo de atividade em instalações consideradas desenergizadas sem a devida instalação do conjunto de aterramento temporário.

As chaves de aterramento das linhas aéreas instaladas nas subestações não devem ser consideradas como conjunto de aterramento temporário, sendo obrigatório o uso do conjunto de aterramento temporário no local da tarefa para intervenções de manutenção.

Sempre que o conjunto de aterramento temporário for submetido à uma corrente elétrica por uma energização acidental do sistema ou por uma descarga atmosférica, todo o conjunto deve ser retirado de uso e ser descartado completamente.

Os conectores de fase e de terra dos conjuntos de aterramento temporários devem ser utilizados somente para o tipo de conexão que foram projetados (afloramento da malha de terra, estrutura, cabo, barramento etc)

Durante a execução da constatação de ausência de tensão bem como na instalação e retirada dos aterramentos elétricos temporários devem ser respeitadas as distâncias de segurança contra choque elétrico bem como deve se garantir a utilização de todos os EPI´s necessários segundo análise de risco.

As vestimentas de proteção térmica devem prover proteção superior a energia incidente do arco elétrico calculado para o equipamento a ser aterrado na distância de trabalho necessária para execução destas tarefas conforme NBR 17227[4].

A constatação de ausência de tensão deve ser realizada com equipamento projetado e destinado para tal atividade. Para tensões acima de 1 kV devem atender os requisitos da ABNT NBR IEC 61243-1 Para tensões entre 0,05 a 0,99 kV AC devem ser utilizados detectores de tensão para baixa tensão.

A constatação de ausência de tensão deverá ser realizada localmente em todos os pontos onde serão instalados os conjuntos de aterramento temporários e não poderá ser substituída pela verificação da medição de voltímetros nem por medições realizadas com medidores de tensão portátil.

IX. Conclusões

O aterramento elétrico temporário é uma parte essencial do processo de intervenção em sistemas elétricos uma vez que só é possível realizar trabalhos em equipamentos desenergizados através da instalação destes dispositivos. Desta forma é imprescindível que se possa garantir a eficiência e segurança deste processo sendo que isso só é possível quando se definem procedimentos e controles específicos.

Estes procedimentos e controles devem assegurar a confiabilidade dos sistemas de aterramento permanente, de todos EPI e EPC utilizados no processo de instalação e retirada dos conjuntos de AET, bem como a confiabilidade dos próprios conjuntos. Esta confiabilidade é possível de ser verificada com as inspeções e testes sugeridos no escopo deste trabalho

Além da confiabilidade dos conjuntos é indispensável a correta especificação desses principalmente no que se refere a capacidade de condução de corrente.

Outro fator essencial é a implementação de mecanismos de controle para a correta instalação de retirada dos conjuntos de AET no que diz respeito tanto ao “passo a passo” destes procedimentos bem como evitar o “esquecimento” de conjuntos de AET instalados durante uma reenergização. A utilização do Formulário de Controle, Croqui de aterramento e cartões de aterramento visa mitigar a probabilidade de ocorrência destas falhas.

Dado ao exposto, fica clara a necessidade de padronização destes procedimentos e controles via normatização oficial com vistas a implementar melhorias e condições mínimas de segurança no processo

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Accidents Involving Telecommunication Cables on Power Poles: Global Challenges and Evidence-Based Solutions

Arileide Cristina Alves
Institute of Technology for Development-Lactec
Curitiba, Brazil
arileide.alves@lactec.com.br

Gilberto Dias de Melo
Regional Council of Engineering and Agronomy of Paraná (CREA-PR) Curitiba, Brazil
gilberto@sercomtel.com.br

***Abstract*—Pole sharing between the energy and telecommunication sectors, while economically advantageous, constitutes a significant global safety concern. Data from the International Energy Agency (IEA) report over 30,000 annual fatalities linked to accidents involving overhead infrastructure. In Brazil, between 2009 and 2024, 36,000 incidents and 4,000 deaths were recorded, a scenario comparable to nations such as India and Mexico. This article synthesizes global statistics, evaluates successful international frameworks (e.g., Germany's underground cabling initiatives and AI-driven inspections in the United States), and proposes context-specific adaptations for Brazil. Recommendations include strengthening regulatory oversight through intelligent monitoring technologies, implementing targeted underground cabling in critical areas, and establishing mandatory technical standards for the installation and maintenance of telecommunication cables on shared utility infrastructure.**

Keywords*—Utility Pole Sharing, Public Safety, Underground Cables, Smart Grids, International Standards.

I. Introduction

Accidents associated with overhead cable networks constitute an endemic issue on a global scale, with a marked exacerbation in emerging economies. In Brazil, the disorderly expansion of telecommunications networks, coupled with insufficient oversight and the absence of systematic predictive and corrective maintenance programs, has resulted in approximately 4,100 fatalities over the past 15 years [1]. This study integrates historical data series from the International Energy Agency (IEA), a comparative analysis of international regulatory protocols, and national normative practices. The aim is to propose technical-regulatory guidelines based on asset management principles (such as those defined in ISO 55000) and ISO/IEC standards, with a focus on mitigating operational risks and maximizing public safety.

In the Brazilian context, the tangled cables on utility poles undermine both urban infrastructure and collective safety, leading to numerous annual incidents. Fig. 1, which depicts downtown Curitiba, highlights the chaotic overlap of wiring, presenting imminent risks of falls, short circuits, and pedestrian accidents. Furthermore, there is an evident lack of standardized protocols for the management of overhead cables, resulting in critical situations such as exposed wiring and structural overload, significantly increasing the likelihood of electrical failures and accidents.

Fig. 1. Chaotic overhead distribution of power and telecommunication cables on utility poles in central Curitiba, demonstrating imminent risks of structural collapse due to mechanical overload, electrical failures from conductor abrasion, and pedestrian electrocution hazards from degraded insulation.

II. Global and National Statistical Data

A. Global Overview

According to the International Energy Agency (IEA, 2023), accidents involving telecommunication cables and

wires cause approximately 30,000 annual fatalities worldwide. In absolute terms, India accounts for around 12,000 deaths, followed by Mexico (3,500) and Brazil (4,100) [1]. Mortality rate analysis reveals stark disparities: in low-income countries, the rate reaches 230 deaths per million inhabitants, while in developed economies, it remains below 2 per million [2]. In Brazil, the specific mortality rate is 19 deaths per million inhabitants, estimated based on the 4,100 annual fatalities reported by the IEA (2023) and the Brazilian population of 214.3 million (World Bank, 2023) [3].

B. Representative Cases in the Brazilian Context

The national landscape underscores the critical nature of accidents involving aerial telecommunication infrastructures, with emblematic episodes illustrating both the severity of consequences and potential advancements arising from structural interventions. To visualize the national scenario, a graph is presented in Fig. 2, based exclusively on official Brazilian data sources.

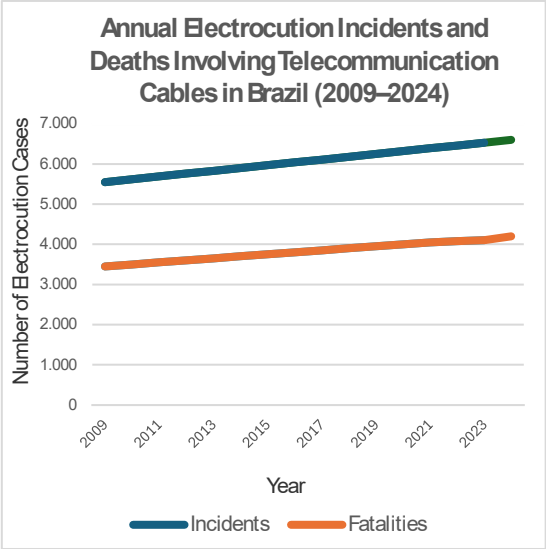

Fig. 2. Electrocution-Related Incidents and Deaths Associated with Telecommunication Infrastructure in Brazil (ICD-10 W85–W87).

Mortality statistics were extracted from the Mortality Information System (*Sistema de Informações sobre Mortalidade* – SIM) of DATASUS (Brazilian National Health Data System), applying a temporal filter spanning 2004 to 2024 and ICD-10 codes for electrocution (W85, W86, W87). Similarly, non-fatal incident data were collected from the Hospital Information System (*Sistema de Informações Hospitalares* – SIH/SUS) of the Unified Health System (*Sistema Único de Saúde* – SUS), using identical temporal and classification filters.

These codes were selected to represent electrocution cases linked to exposed cables in urban environments, as they encompass exposures to unspecified electrical currents, per coding manuals and technical studies on urban accidents. Although the codes do not explicitly distinguish the type of conductor involved (energy or telecommunications), W86 and W87 cover typical incidents of accidental contact with energized wiring in public spaces.

The raw data were obtained directly from the DATASUS platform, which provides public access to national health information systems maintained by the Brazilian Ministry of Health. After download in tabular format, the datasets were subjected to primary processing, including data cleaning, column standardization, removal of duplicate entries, and year-by-year aggregation. This treatment enabled the construction of a consistent historical series focused on electrocution cases plausibly related to telecommunication infrastructure. All data handling procedures were conducted using spreadsheet software and statistical tools, ensuring reproducibility, transparency, and fidelity to the original records.

This methodological approach was supplemented by consulting annual reports on third-party accidents and related fatalities (*Núcleo de Acidentes com Terceiros e Óbitos Relacionados* – NACTER/NMOTER), available on the Open Data Portal of the Brazilian Electricity Regulatory Agency (*Agência Nacional de Energia Elétrica*, ANEEL). Specifically selected were events classified as “accidents in aerial power networks,” frequently associated with infrastructure shared between electric power distribution utilities and telecommunication operators. All records pertain to the national scope and were accessed in April 2025, forming an integrated database for analyzing the issues addressed in this study. In addition to the quantitative analysis presented in Fig. 2, the following sections describe emblematic cases that qualitatively illustrate both the severity of impacts resulting from failures in aerial telecommunication infrastructures and the potential gains derived from structural and managerial interventions. Each case highlights distinct aspects, ranging from gaps in preventive monitoring to innovative mitigation solutions, contributing to a more comprehensive and evidence-based understanding of risk dynamics and control strategies at the national level.

- **São Paulo (2022)** – A fatal incident in São Paulo’s capital involved the electrocution of a pedestrian due to accidental contact with a ruptured and damaged telecommunication cable abandoned in a public thoroughfare. The case garnered widespread attention, exposing systemic gaps in monitoring installed networks and failures in identifying and neutralizing immediate risks to the population.
- **Cascavel (2023)** – In the municipality of Cascavel (Paraná), a utility pole shared between an energy distributor and multiple telecommunication operators collapsed due to structural overload and overheating, resulting in a large-scale fire. Subsequent technical analysis identified excessive occupancy, lack of load control at fixation points, and incompatibility between grounded systems.
- **Curitiba (2023)** – Em In contrast to critical events, the capital of Paraná launched a pilot project for selective underground cabling in areas with high population density and accident incidence. After six months of implementation, a 40% reduction in cable-related incidents in public spaces was recorded [3]. This initiative, a collaboration between municipal authorities, local utilities, and regulatory agencies, has been recognized as a national benchmark for risk mitigation best practices.

These examples reflect the challenges posed by the heterogeneity of regional approaches and reinforce the necessity for integrated public policies, underpinned by

technical data, robust regulatory frameworks, and incentives to modernize urban infrastructure.

III. Successful International Models

The analysis of successful international frameworks reveals distinct yet complementary strategies. These strategies were adopted by countries that faced challenges analogous to Brazil's in securing aerial telecommunication infrastructure. These experiences demonstrate that mitigating risks associated with overhead networks requires a triad of: (i) stringent technical standardization, (ii) deployment of smart monitoring technologies, and (iii) regulatory frameworks with effective enforcement capabilities. The coordinated adoption of these elements can serve as a strategic reference for the Brazilian context.

A. Germany: Underground Cabling and Technical Standards

In Germany, the focus lies on structural modernization and technical standardization. The regulatory agency Bundesnetzagentur (BNetzA) coordinated an ambitious program to migrate aerial networks to underground systems, resulting in an 85% cumulative reduction in accidents between 2010 and 2023 [4]. This success is anchored in precise technical guidelines, such as the DIN 4131:2010 standard, which mandates minimum distances between power conductors and telecommunication cables, significantly reducing risks of electromagnetic interference and contact-induced failures [5].

B. United States: AI-Driven Inspections

In the United States, the approach combines regulatory advancements with emerging technologies. The National Electrical Safety Code (NESC) has integrated artificial intelligence (AI)-based systems to predict critical failure points in shared infrastructure. Organizations like the Electric Power Research Institute (EPRI) have developed machine learning algorithms capable of identifying risk patterns through automated visual inspections, contributing to a 60% reduction in incidents in regions such as California [6]. The integration of predictive tools into regulatory processes marks a significant advancement in urban asset management.

C. Australia: Centralized Database

Australia's regulatory model emphasizes accountability and data centralization. The Australian Energy Regulator (AER) operates a national database consolidating records of pole occupancy and maintenance, enabling real-time traceability and oversight. Additionally, the country imposes severe penalties fines of up to AUD 500,000 per violation and mandates compliance with the AS/NZS 3000:2018 standard, which requires the use of flame-retardant cables to contain hazards and protect public safety [7].

Table 1 outlines the primary strategies adopted by Germany, the United States, and Australia to address accidents associated with unauthorized occupation of utility poles. It provides a comparative analysis of the technical and regulatory instruments employed, the percentage reduction observed in incident rates, and the bibliographic sources supporting the data.

This synthesis highlights the potential replicability of these initiatives within the Brazilian context, provided local regulatory and operational specificities are duly considered. The 85% accident reduction reported for Germany specifically refers to the implementation of underground cabling in urban areas, as documented in references [4] and [5].

TABLE 1. COMPARISON OF INTERNATIONAL ACCIDENT-REDUCTION STRATEGIES: QUANTITATIVE DATA SUMMARY

Country	***Strategya***	***Accident Reduction***	***References***
Germany	Underground Cabling	85 %	[4], [5]
United States	NESC + AI Integration	60 %	[6]
Australia	Centralized Database + Penalties	70 %	[7]

IV. Recommendations for Brazil

The mitigation of accidents caused by aerial telecommunication infrastructure requires the coordinated adoption of advanced technical measures and robust regulatory actions to address both structural and operational root causes of the issue. This integrated approach has been validated in international contexts, and its application to the Brazilian scenario represents a technically viable and socially urgent pathway.

A. Technical Measures

Prioritizing the underground installation of telecommunication networks in high-density urban areas is a critical measure for risk reduction and public space enhancement. European experience (particularly in Germany) demonstrates up to an 85% reduction in incidents related to exposed cables [4]. While the initial investment is substantial, life cycle analysis (LCA) studies confirm tangible gains in safety, reliability, and property value: for example, EPE (2023) estimated a 15-year return on investment (ROI) for undergrounding projects in São Paulo [5].

The implementation of IoT-based smart sensors for continuous monitoring of critical variables—voltage, temperature, and vibration has proven equally effective. Case studies from Texas (USA) show that this technology enables early fault detection, fire prevention, and mitigation of structural overloads in shared or heavily occupied utility poles [8], facilitating a shift from reactive to predictive asset management models. For implementation in Brazil, recommended sensor configurations include: (a) thermographic infrared sensors for contactless thermal monitoring of conductor joints, with alert thresholds aligned with applicable standards; (b) accelerometers for structural fatigue detection; (c) precision transducers combined with optimized protocols for leakage current measurement. Additionally, field validations serve to establish vibration baselines and thermal reference profiles under Brazilian climatic conditions.

Finally, the mandatory adoption of fire-resistant cables compliant with the AS/NZS 3000 standard (Australia) adds an essential layer of safety. These conductors withstand high temperatures, resist flame propagation, and reduce toxic gas emissions during short circuits or cable ruptures, a particularly critical feature in dense urban environments.

B. *Regulatory Actions*

From an institutional standpoint, it is imperative to integrate regulatory and oversight bodies, such as ANEEL, ANATEL, and state and municipal Civil Defense agencies, into a coordinated system for monitoring, licensing, and inspection. Isolated efforts by individual agencies have proven ineffective in addressing the complexities of shared infrastructure. Integrated governance models, such as those implemented in the European Union, underscore the necessity of unified digital data platforms and joint operational protocols. Furthermore, the introduction of penalties proportional to incurred damages, inspired by the Australian Energy Regulator (AER), should be considered as a mechanism to incentivize compliance with established norms.

Substantial fines, levied based on technical criteria (e.g., risk potential, recurrence, and damage severity), not only penalize but also deter negligent practices. In Brazil, adopting such a framework would require revising regulatory statutes and updating joint ANEEL/ANATEL resolutions. A recent legislative initiative in Paraná exemplifies this integrative approach. Three state-level bills (PL 33/2024, PL 294/2024, and PL 306/2024) propose standardized norms for cable organization, mandatory removal of obsolete wiring, and penalties for non-compliance.

These proposals seek to operationalize and elaborate, at the state level, the safety and infrastructure-sharing principles enshrined in Joint Resolution 390/2009, thereby creating technical and regulatory synergies. Notably, PL 33/2024 integrates aesthetic and safety objectives, mirroring Germany's success in reducing visual pollution while enhancing urban safety. Developed in collaboration with technical bodies such as CREA-PR (Regional Council of Engineering and Agronomy of Paraná) and the Parliamentary Front for Infrastructure, these initiatives demonstrate how subnational frameworks can implement internationally recommended practices within Brazil's regulatory context.

Initial reports indicate significant compliance hurdles among service providers and limited public awareness, though coordinated enforcement and stipulated penalties are expected to enhance effectiveness. In summary, the synergy between technological innovation and regulatory rigor establishes the foundation for a public policy on telecommunication network safety that is efficient, adaptable, and socially responsible.

V. Conclusion

The safety of aerial infrastructure installed on shared utility poles can no longer be treated as a negligible externality of urban growth and telecommunication network expansion. This constitutes a systemic challenge demanding a multidimensional response grounded in the convergence of cutting-edge technology, effective regulation, and institutional and international cooperation.

Brazil's experience demonstrates that the absence of integrated governance, regulatory fragmentation, and low adoption of technological solutions have cost human lives and undermined the reliability of essential services. However, the data analyzed in this study indicate that reversing this trend is achievable. Estimates suggest Brazil could reduce accidents involving aerial cables and wiring by up to 70% by adaptively and incrementally incorporating internationally proven practices.

Selective undergrounding, as implemented in Germany, proves effective in dense urban contexts, yielding not only safety improvements but also aesthetic enhancements and increased property values. Meanwhile, AI-driven inspection systems, successfully deployed in the United States, demonstrate the feasibility of preempting failures and optimizing inspection resource allocation with high precision. Regulatory transparency and operational data centralization, as exemplified by Australia, complement this framework with efficient traceability and accountability mechanisms.

"Together we can save lives" is not merely an expression of possibility; rather, it constitutes an imperative demanding immediate implementation and effective institutional coordination. The urgency of adopting these measures transcends sectoral agendas and necessitates the establishment of a federative pact to safeguard urban infrastructure. Failure to act risks perpetuating a dysfunctional model that transforms negligence into fatality. This urgency demands immediate implementation. And with the available technical knowledge, we can no longer plead ignorance.

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Engineer Melo played a key role in the technical drafting of the proposal that supported Bill No. 33/2024, submitted in 2023 as part of CREA-PR's Parliamentary Agenda to the Legislative Assembly of the State of Paraná (ALEP). Entitled *State Policy for the Reduction of Visual Pollution and Prevention of Accidents Caused by Irregularly Installed Telecommunications Cables and Wires on Utility Poles*, the proposal was grounded in safety principles, technical regulations, and engineering best practices. Although not formally listed as an author of the legislative proposal, Eng. Melo was instrumental in its technical foundation, ensuring rigorous adherence to applicable regulatory standards and exemplifying the integration of engineering knowledge within legislative frameworks for urban safety.

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[2] ARCPRO, a commercially available software program developed by Kinectrics, Toronto, ON, CA.

[3] NFPA, NFPA 70E: Standard For Electrical Safety In The Workplace. National Fire Protection Association (NFPA), 2021

[4] ND 4.15 CEMIG, Proteção de Sobrecorrentes do Sistema de Distribuição de Média Tensão da Cemig, 2017.

[5] ABNT - NBR 7282:2023, Dispositivos fusíveis de alta-tensão – Dispositivos tipo expulsão – Requisitos e métodos de ensaio, 2023.

[6] IEC 61850, Communication Networks and Systems in Substations, 2003.

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A tensão de contato na proteção contra choques elétricos

João Gilberto Cunha
Instituto Mi Omega
São José dos Campos-SP
jcunha@miomega.com.br

A tensão de contato é um parâmetro crítico na proteção contra choques elétricos em instalações de baixa e média tensão. Ela é definida como a diferença de potencial que surge entre dois pontos que, em condições normais, estão em equipotencialidade, durante uma falta à terra. Este artigo aborda os fundamentos teóricos da tensão de contato, sua análise em instalações de baixa tensão (esquemas TN, TT e IT) e em instalações de média tensão, além de discutir medidas de proteção como o seccionamento automático da alimentação e a transferência de potencial. O objetivo é garantir a segurança dos usuários, prevenindo choques elétricos perigosos.

I. INTRODUÇÃO

A segurança elétrica é um aspecto fundamental em instalações elétricas, especialmente quando se trata de prevenir choques elétricos. Os choques elétricos podem causar desde reações fisiológicas leves até eventos graves, como a fibrilação ventricular, levando a fatalidades. A tensão de contato, um conceito essencial na proteção contra choques elétricos por contatos indiretos, é influenciada por diversos fatores, incluindo o esquema de aterramento, a impedância do percurso de falta e a presença de dispositivos de proteção.

A preocupação com a segurança elétrica é refletida nas normas técnicas, como a ABNT NBR5410 [1] para baixa tensão e a ABNT NBR 14039 [2] para média tensão, que estabelecem limites para a tensão de contato e diretrizes para a proteção contra choques elétricos. No entanto, a aplicação prática dessas normas pode ser complexa, especialmente em instalações existentes ou em situações onde a segurança elétrica é comprometida.

Este artigo visa explorar os aspectos teóricos e práticos da tensão de contato em instalações de baixa e média tensão, destacando a importância de medidas adequadas de proteção para garantir a segurança dos usuários. Serão abordados os fundamentos teóricos da tensão de contato, a análise de sua ocorrência em diferentes esquemas de aterramento e a discussão de medidas de proteção, como o seccionamento automático da alimentação e a equipotencialização das massas. O objetivo é fornecer uma visão abrangente da tensão de contato e sua importância na segurança elétrica, contribuindo para a prevenção de choques elétricos e a proteção da integridade física dos usuários.

II. FUNDAMENTOS TEÓRICOS

A tensão de contato é um conceito central na proteção contra choques elétricos por contatos indiretos. As normas de instalações elétricas – tanto a ABNT NBR 5410 [1] para baixa tensão quanto a ABNT NBR 14039 [2] para média tensão – estabelecem que a tensão de contato máxima admissível é aquela que um ser humano pode suportar sem comprometer sua integridade física. No contexto brasileiro, tais normas encontram alinhamento com os padrões internacionais, destacando-se as recomendações da Comissão Eletrotécnica Internacional (IEC), especialmente por meio da série IEC TS 60479 [3].

Frequentemente, ouve-se ou lê-se a afirmação de que, desde que um equipamento elétrico esteja devidamente aterrado, não é possível que uma pessoa receba um choque elétrico em caso de falha. O conceito de tensão de contato demonstra que tal afirmação é totalmente incorreta.

A compreensão do conceito de tensão de contato, que é um conceito muito simples, proporciona ao projetista da instalação e a outros envolvidos com instalações elétricas uma compreensão mais completa dos requisitos estabelecidos nas normas de instalações elétricas para proteção contra contato indireto.

A tensão de contato pode ser definida como a diferença de potencial que se estabelece, durante uma falta a terra, entre dois pontos que, em condições normais de operação, se encontrariam em equipotencialidade.

Em uma instalação elétrica, quando ocorre uma falta – devido a falha do isolamento – uma massa condutiva pode elevar-se a um potencial, devido a circulação da corrente de falta pelo circuito de retorno da corrente de falta, expondo os usuários a riscos graves de choque elétrico. Essa condição pode surgir devido à degradação do material isolante, ocasionada por fatores como envelhecimento, exposição a agentes químicos, sobretensões ou elevações excessivas de temperatura, os quais comprometem a integridade dos componentes elétricos.

Quando as partes acessíveis se energizam, os efeitos do choque elétrico podem variar desde reações fisiológicas leves, como contrações musculares involuntárias, até eventos de alta periculosidade, como a fibrilação ventricular, que podem resultar em fatalidades. Dessa forma, a magnitude e a duração da tensão de contato emergem como fatores determinantes no impacto sobre o organismo humano. O critério de proteção contra choques elétricos é, portanto, fundamentado no limite admissível da tensão de contato – que, de forma simplificada, corresponde ao produto entre a corrente que atravessa o corpo humano e sua impedância total em função do tempo. Ressalta-se que a relação entre tensão e corrente não é linear, uma vez que a impedância do corpo humano varia conforme o nível da própria tensão de contato.

Por fim, a definição de tensão de contato-limite emerge como o valor máximo da tensão de contato que pode se manifestar em condições de falta. Essa definição é crucial para o dimensionamento dos dispositivos de proteção, contribuindo de maneira significativa para a segurança de usuários e operadores em instalações elétricas.

Adicionalmente, distingue-se a tensão de contato – que refere à diferença de potencial efetivamente mensurada no momento do contato – da tensão de contato presumida, a qual diz respeito à diferença de potencial entre partes condutoras acessíveis, mas que não estão sendo tocadas simultaneamente. Enquanto a tensão de contato é um parâmetro importante para a proteção contra contatos indiretos, a tensão de contato presumida é um parâmetro mais usado no dimensionamento das malhas de aterramento de média tensão. A diferença fundamental das duas tensões é a queda de tensão que ocorre devido a passagem da corrente de choque.

Cabe destacar que os valores da tensão de contato limite apresentam abordagens específicas conforme o nível de tensão da instalação. Para instalações de baixa tensão, a ABNT NBR 5410 [1] define os limites de tensão de contato para três situações distintas, levando em consideração influências externas, tais como a resistência elétrica do corpo humano e o contato das pessoas com o potencial da terra. Essa abordagem visa contemplar variáveis que influenciam a segurança em ambientes residenciais, comerciais e industriais, onde fatores como estado da pele, área e pressão de contato são determinantes para a dissipação da corrente elétrica. Em contrapartida, para instalações de média tensão, a ABNT NBR 14039 [2] adota uma metodologia diferenciada: a tensão de contato-limite é estabelecida com base exclusivamente na resistência elétrica do corpo humano, considerando as condições de pele normal e molhada. Assim, são apresentadas duas curvas de tensão de contato-limite em função do tempo, refletindo as variações da impedância humana conforme as condições ambientais e fisiológicas.

III. ANÁLISE DE TENSÃO DE CONTATO EM INSTALAÇÕES BT

A tensão de contato deve ser rigorosamente controlada para garantir a segurança dos usuários, em conformidade com as especificações das normas técnicas, como a NBR 5410 [1]. Este item apresenta uma análise detalhada dos principais esquemas de aterramento empregados em instalações de baixa tensão – TN, TT e IT –, enfatizando os mecanismos intrínsecos que asseguram a redução da tensão de contato e os desafios técnicos associados a cada configuração.

A. Esquema TN

O esquema TN possui um ponto da alimentação diretamente aterrado – geralmente o neutro do secundário do transformador – é aterrado diretamente, sendo as massas dos equipamentos conectadas a esse mesmo ponto ou a um condutor de proteção interligado ao neutro. Neste contexto, as principais características que contribuem para o controle da tensão de contato são: redução da impedância do percurso de falta e equipotencialização das massas.

Durante uma falta fase-massa, a corrente de falta circula por condutores de baixa impedância (fases, neutro e condutor de proteção), o que propicia correntes elevadas e, consequentemente, uma rápida atuação dos dispositivos de proteção, como disjuntores, fusíveis e dispositivos DR. Essa dinâmica permite manter a tensão de contato em níveis seguros – usualmente inferiores a 50 V em corrente alternada para aplicações residenciais e comerciais.

A interligação dos condutores de proteção, realizada por meio de ligações equipotenciais, reduz as diferenças de potencial entre as partes acessíveis da instalação, reduzindo o risco de choques elétricos.

B. Esquema TT

No esquema TT, há uma distinção clara entre o aterramento fornecido pela fonte (realizado no transformador, via aterramento do neutro) e o aterramento das massas da instalação, que se dá por meio de eletrodos independentes ou grupos de eletrodos distribuídos na edificação. Essa configuração impõe um desafio específico que é o efeito dos eletrodos de aterramento na tensão de contato.

Os eletrodos podem apresentar elevados valores de resistência, dependendo das condições do solo e do dimensionamento adotado. Durante uma falta fase-massa, a tensão de contato é diretamente influenciada pela queda de tensão no eletrodo, que é o produto da resistência de aterramento pela corrente de falta.

A eficácia do esquema TT depende crucialmente do adequado dimensionamento dos eletrodos e da implementação correta das interligações equipotenciais. Um projeto bem elaborado, aliado à manutenção periódica, é fundamental para manter os valores de resistência de aterramento dentro dos limites seguros e, assim, proporcionar a proteção contra choques elétricos.

C. Esquema IT

Embora menos comum em instalações de baixa tensão convencionais, o esquema IT é adotado em ambientes que exigem alta continuidade do fornecimento, como hospitais e determinadas instalações industriais. Sua principal característica é o não desligamento na primeira falta, o que implica necessariamente no não aparecimento de tensão de contato perigosa nesta falta.

No esquema IT, nenhuma parte viva (fase ou, em certas configurações, o neutro) é diretamente conectada à terra; somente as massas são aterradas. Em uma primeira falta fase-massa, a elevada impedância do percurso para a terra limita a corrente de falta, prevenindo a imediata elevação crítica da tensão de contato.

A continuidade operacional é uma característica marcante do sistema IT, na qual o primeiro defeito não resulta no seccionamento automático da alimentação. Contudo, se ocorrer uma segunda falta, a redução abrupta da impedância

do percurso pode elevar significativamente a tensão de contato. Por essa razão, a implementação de dispositivos supervisórios de isolamento (DSI) e a intervenção imediata são imperativas para manter a segurança.

D. Considerações finais

A análise dos esquemas TN, TT e IT evidencia que a mitigação da tensão de contato em instalações de baixa tensão depende de três fatores inter-relacionados:

a. Minimização da impedância do percurso de falha:

Sistemas que proporcionam caminhos de baixa impedância (como o TN) favorecem a rápida atuação dos dispositivos de proteção, mantendo a tensão de contato em níveis aceitáveis.

b. Equipotencialização das massas:

A integração dos condutores de proteção, por meio de ligações equipotenciais, é essencial para eliminar diferenças de potencial entre partes acessíveis, reduzindo os riscos de choque elétrico.

c. Uso adequado de dispositivos de proteção e monitoramento:

Especialmente nos esquemas TT e IT, a correta seleção e sensibilidade dos dispositivos DR, juntamente com a implementação de sistemas de monitoramento, como os dispositivos supervisórios de isolamento (DSI), são fundamentais para a detecção precoce de falhas e a prevenção de elevações críticas da tensão de contato.

Em conclusão, a segurança dos usuários em instalações de baixa tensão depende da combinação de um projeto de aterramento, da manutenção regular dos sistemas e da utilização eficiente dos dispositivos de proteção, sempre em consonância com as normas técnicas vigentes.

IV. ANÁLISE DE TENSÃO DE CONTATO EM INSTALAÇÕES MT

Quando ocorre uma falha em uma instalação de média tensão, uma corrente significativa é injetada no sistema de aterramento, originando uma variação de potencial à medida que a corrente de falha se propaga pelo solo. A queda de tensão ao longo desse percurso depende tanto da magnitude da corrente quanto das propriedades elétricas do terreno, tais como resistividade e distribuição da impedância. Consequentemente, quanto maior a corrente injetada, mais acentuada será a variação do potencial entre dois pontos, evidenciando o risco de tensão de contato. Esse cenário se agrava se uma pessoa entrar em contato com uma estrutura metálica energizada, estando seus pés apoiados em regiões do solo com potenciais significativamente divergentes, o que pode gerar uma diferença de potencial perigosa.

A Figura 1 mostra as tensões que pode ocorrer em uma subestação durante a ocorrência de uma falta.

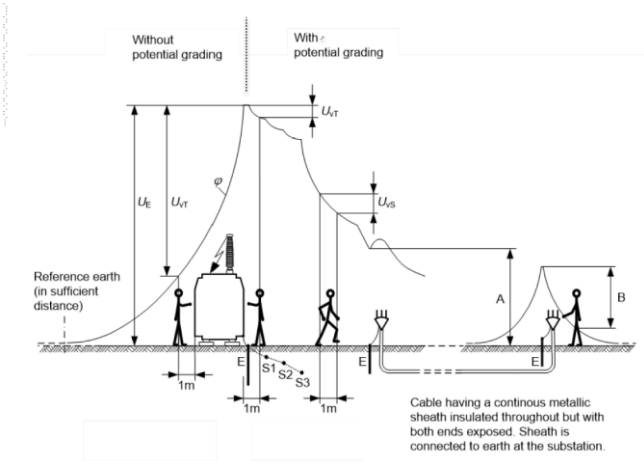

Fig. 1. Tensões notáveis em uma SE durante uma falta.

Para mitigar esse risco, recomenda-se a utilização de eletrodos de aterramento dispostos em forma de malha, pois eles promovem uma melhor equalização dos potenciais no solo, reduzindo de forma efetiva a diferença de potencial entre os diversos pontos. De acordo com a ABNT NBR 14039 [2], o eletrodo de aterramento deve ser implementado sob o piso da subestação ou da carga de média tensão, ou, no mínimo, configurado como um anel circundante ao perímetro da área. O critério para a especificação desse eletrodo baseia-se na tensão de contato máxima admissível, sendo que o parâmetro mais relevante para o dimensionamento da malha de aterramento é a tensão de contato presumida. Essa tensão leva em consideração o tipo de revestimento do solo (por exemplo, brita ou asfalto), pois determina a queda de tensão entre o solo e os pés de uma pessoa durante a circulação da corrente de falha.

Embora a ABNT NBR 14039 [2] não imponha um valor específico para a resistência de aterramento — os tradicionais 10 Ω, por exemplo, ainda que possam ser exigidos por algumas distribuidoras de energia — tal parâmetro remete a práticas históricas que carecem de fundamentação técnica atualizada.

Atualmente, não há uma norma internacional da IEC específica para o projeto de malhas de aterramento em instalações com tensões superiores a 1 kV. Em contrapartida, destacam-se a norma americana IEEE 80 e a norma europeia EN 50522 [5]. A principal diferença entre essas metodologias reside na determinação do limite para provocar a fibrilação cardíaca: enquanto a IEEE 80 adota a equação de Dalziel para o cálculo da corrente crítica, considerando uma impedância fixa de 1000 Ω, a EN 50522 [5] utiliza dados tabelados que relacionam a corrente em função do tempo e a impedância corporal em função da tensão de toque, baseando-se na IEC/TS 60479-1 [3], o que torna o processo iterativo.

Por fim, a norma brasileira ABNT NBR 15751 [6] define os requisitos para o dimensionamento dos sistemas de aterramento em instalações alimentadas com tensões superiores a 1 kV, considerando as condições de frequência industrial, e orienta o projeto quanto tanto aos critérios de segurança quanto às especificidades operacionais das instalações.

V. SECCIONAMENTO AUTOMÁTICO DA ALIMENTAÇÃO

Quando o aterramento e a equipotencialização não são suficientes para impedir o surgimento de tensões de contato perigosas, torna-se necessário desligar o circuito no qual essa tensão se manifesta. Por esse motivo, a equipotencialização e o seccionamento automático da alimentação são medidas complementares e indissociáveis, tanto em instalações elétricas de baixa quanto de média tensão.

Quando as normas técnicas afirmam que o aterramento de um equipamento elétrico, por si só, não é suficiente para evitar que uma pessoa receba um choque elétrico perigoso em caso de falta, isso se deve ao fato de que mesmo um aterramento adequado não garante, por si só, que a tensão de contato permanecerá abaixo do limite de segurança. Assim, a única forma de assegurar a proteção das pessoas é por meio do desligamento automático do circuito que alimenta a carga.

Nas instalações de baixa tensão, essa relação é mais facilmente compreendida, especialmente devido ao uso do dispositivo DR. No entanto, em sistemas de média tensão, essa complementaridade também se aplica, uma vez que a tensão de contato admissível é função do tempo durante o qual essa tensão está presente. Dessa forma, a alimentação deve ser desligada em um tempo igual ou inferior ao considerado no projeto da malha de aterramento.

Os dispositivos de proteção utilizados no seccionamento automático da alimentação devem ser sensíveis à corrente de falta, pois é essa corrente que os aciona. Como a magnitude da corrente de falta depende do esquema de aterramento adotado, os dispositivos empregados devem ser compatíveis com esse esquema.

No contexto do seccionamento automático, quando ocorre uma falta à terra, a corrente que circula pelo caminho de retorno deve ser capaz de desligar automaticamente o dispositivo de proteção em um tempo suficientemente curto para evitar a ocorrência de fibrilação cardíaca. Esse tempo é determinado pela curva de tensão de contato limite (ou tensão de contato admissível) em função do tempo de exposição.

Ou seja, conhecendo-se o valor da tensão de contato que pode surgir durante uma falta, é possível estabelecer o tempo máximo de seccionamento necessário para garantir a segurança das pessoas expostas.

Nos esquemas TN — aplicáveis tanto à baixa quanto à média tensão — as impedâncias de percurso da corrente de falta são baixas, uma vez que esse percurso é composto exclusivamente por condutores metálicos. Nesses casos, a corrente de falta é da mesma ordem de grandeza da corrente de curto-circuito, permitindo o uso de dispositivos de sobrecorrente no seccionamento automático da alimentação.

Já nos esquemas TT, também válidos para ambas as faixas de tensão, o percurso da corrente de falta inclui o solo, o que introduz um componente de alta resistividade. Isso reduz significativamente a corrente de falta em relação à corrente de curto-circuito, exigindo o uso de dispositivos sensíveis à corrente de sequência zero para garantir a atuação eficaz do seccionamento automático.

VI. TRANSFERÊNCIA DE POTENCIAL

É comum que muitos profissionais assumam que se um componente se encontra devidamente aterrado a instalação elétrica está completamente segura. Essa premissa pode levar à falsa impressão de que o condutor de proteção ou o eletrodo de aterramento não apresentam tensões perigosas. Todavia, é importante ressaltar que, durante uma condição de falta, a tensão de contato pode alcançar valores que oferecem riscos significativos à integridade das pessoas.

Em uma instalação projetada de forma adequada, o risco associado à tensão de contato permanece confinado ao circuito onde a falta ocorre. Entretanto, se essa tensão for transferida para outros pontos da instalação, a proteção pode ser comprometida. Um aspecto fundamental, endossado pelas normas técnicas, é justamente a prevenção da transferência de potencial. Dessa forma, torna-se imperativo adotar medidas que evitem a propagação do potencial entre áreas sob condições controladas (por exemplo, ambientes com baixa umidade) e regiões onde esses riscos não foram considerados. As normas técnicas preveem diretrizes específicas para situações em que essa transferência se torna particularmente perigosa.

No âmbito das instalações de baixa tensão (BT), os profissionais devem estar atentos ao fato de que o condutor de proteção (popularmente denominado “fio terra”) pode, durante uma falta à terra, apresentar tensões de contato superiores aos limites estabelecidos. Por exemplo, em uma instalação de 380/220 V, o condutor de proteção no ponto da falta pode atingir aproximadamente 110 V, valor que excede os limites de 50 V (situação 1), 25 V (situação 2) e 12 V (situação 3) definidos pela NBR 5410 [1]. Em virtude desse risco, para a situação 3 (corpo imerso), a norma impõe a obrigatoriedade do uso de circuitos SELV (extra baixa tensão de segurança), pois as cargas não podem ser conectadas diretamente ao condutor de proteção ou aterradas. Um exemplo prático ocorre na iluminação subaquática, cuja massa não deve ser ligada ao condutor de proteção, a fim de evitar a transferência de potencial decorrente de uma falta em outro circuito.

Em instalações de média tensão (MT), os desafios se ampliam. A malha de aterramento de uma subestação pode apresentar tensões na ordem de alguns milhares de volts em relação ao terra de referência. Como é o caso, de condutores ou cercas metálicas conectados à malha, por meio da interligação com a cerca perimetral da subestação, que podem propagar esse potencial para pontos distantes, transferindo o risco e aumentando a possibilidade de acidentes em áreas remotas da instalação durante uma falta.

VII. CONCLUSÃO

A tensão de contato é um fator crucial na segurança elétrica de instalações de baixa e média tensão. A compreensão de seus fundamentos teóricos e a análise de sua ocorrência em diferentes esquemas de aterramento são essenciais para o projeto e a manutenção de instalações elétricas seguras. A implementação de medidas de proteção, como o seccionamento automático da alimentação e a equipotencialização das massas, é fundamental para prevenir choques elétricos perigosos. Além disso, a consideração da transferência de potencial em instalações elétricas é vital para evitar riscos à segurança. Em resumo, a gestão adequada da tensão de contato é indispensável para assegurar a integridade física dos usuários e a confiabilidade das instalações elétricas.

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Estratégia de adequação de energia incidente aplicada em plantas industriais da VALE no Corredor Sul

Gabriel Figueiredo
Ger. Eng. Elétrica, Automação e Instrumentação
Vale S.A.
Nova Lima, Minas Gerais
gabriel.figueiredo22@vale.com

Filipe Resende
Ger. Téc. Atividades Críticas
Vale S.A.
Belo Horizonte, Minas Gerais
filipe.resende@vale.com

Helberth Gonçalves
Ger. Eng. Elétrica, Automação e Instrumentação
Vale S.A.
Contagem, Minas Gerais
helberth.goncalves@vale.com

Ataliba Júnior
Ger. Serviços de Campo
SM&A Service
Belo Horizonte, Minas Gerais
ataliba.junior@sma-eng.com.br

RESUMO

Diante do elevado risco associado ao arco elétrico, a Vale S.A. estabeleceu um procedimento interno que limita a energia incidente máxima permitida em seus painéis elétricos a 8 cal/cm². Este limite visa elevar o nível de segurança dos profissionais que realizam intervenções em painéis elétricos energizados, assim como permitir a utilização de vestimentas padrões resistentes aos efeitos térmicos de arcos elétricos (10 cal/cm²) utilizadas pela empresa.

Este cenário implica em um grande desafio quando consideramos instalações elétricas existentes. Desta forma, este artigo apresenta a estratégia de adequação de energia incidente aplicada em plantas industriais da Vale S.A. no Corredor Sul. Neste contexto, serão detalhadas as soluções utilizadas no processo de adequação: alteração de ajustes em relés de proteção, instalação de relés de arco com fibras de detecção de arco e/ou sensores pontuais, substituição de elos-fusíveis, instalação de religadores a montante de subestações secundárias e transfer-trip entre subestações.

No artigo também serão abordados os aprendizados e desafios envolvendo cada tipo de solução, assim como evidenciar a priorização de cada solução em função do custo-benefício de cada uma.

Palavras-chave — Energia incidente, arco elétrico e relés de proteção.

I. INTRODUÇÃO

A Vale S.A. é uma empresa mineradora que possui um enorme parque de ativos elétricos. As operações da Vale S.A. representam cerca de 1,5% do consumo de energia elétrica do Brasil. As suas instalações elétricas possuem porte similar às grandes concessionárias do Brasil. Seu sistema elétrico é composto por diversos níveis de tensão, por exemplo, 13,8 *kV*, 34,5 *kV*, 69 *kV*, 138 *kV*, 230 *kV* e 345 *kV*. Apenas no estado de Minas Gerais, Brasil, a empresa possui mais de 720 subestações industriais instaladas.

Neste contexto, torna-se essencial uma gestão robusta dos riscos associados aos trabalhos com eletricidade, principalmente o risco associado ao arco elétrico. Para a vestimenta de 10 cal/cm² da Vale, o ELIM (*Energy Limit Value*) é de 8,8 cal/cm². O ELIM é definido como um valor numérico de energia incidente, expresso em cal/cm², que não provocou a ruptura das vestimentas durante os testes de fábrica. Como medida de segurança adicional , a Vale S.A. estabeleceu um procedimento interno que limita a energia incidente máxima em seus painéis elétricos a 8 *cal/cm²* com o objetivo principal de elevar o nível de segurança dos profissionais que realizam intervenções em painéis elétricos energizados.

Este limite estabelecido torna-se um grande desafio, principalmente no cenário de instalações elétricas existentes. Desta forma, este trabalho tem o objetivo de mostrar a estratégia de adequação de energia incidente destas instalações na Vale S.A. Corredor Sul, passando pela elaboração do estudo de energia incidente, soluções utilizadas nos processos de adequação e aprendizados obtidos neste processo, principalmente no que se refere a escolha de soluções que apresentam melhor custo-benefício.

II. ESTUDO DE ENERGIA INCIDENTE

O estudo de energia incidente tem por objetivo determinar os valores de parte da energia térmica, em *cal/cm²*, emitida por um arco elétrico, que incide sobre uma superfície de interesse

(cabeça e tronco). Esta informação é extremamente útil para definir o valor do ATPV da vestimenta resistente aos efeitos térmicos de arcos elétricos, proteções faciais, luvas e demais acessórios. Os cálculos utilizados para a obtenção do valor da energia incidente foram padronizados conforme a norma internacional IEEE Std 1584 [1] (instalações até 15 *kV*) e a metodologia estabelecida no software ArcPro® [2] (instalações acima de 15 *kV*).

É importante destacar que o estudo de energia incidente da instalação só pode ser emitido após completadas as fases do estudo de curto-circuito e estudo de seletividade. Além disto, é um estudo que demanda um levantamento de campo extremamente detalhado para que se obtenha os níveis de energia incidente mais precisos possíveis.

A energia incidente máxima nas instalações elétricas da Vale S.A. foi limitada em 8 *cal/cm²*. Desta forma, o estudo de energia incidente deve destacar todos os painéis que apresentam energia incidente acima de 8 *cal/cm²*, assim como estabelecer as medidas para a adequação de energia incidente destes painéis.

Outro produto relevante do estudo de energia incidente é a emissão das etiquetas de energia incidente para serem instaladas nos painéis elétricos. Esta sinalização nos painéis é de extrema importância, pois permite ao profissional tomar conhecimento do nível de energia incidente do painel elétrico em que ele irá atuar possibilitando o uso de vestimenta resistente aos efeitos térmicos de arcos elétricos adequada. A Figura 1 a seguir apresenta um exemplo de etiqueta de energia incidente utilizada na Vale S.A. Corredor Sul:

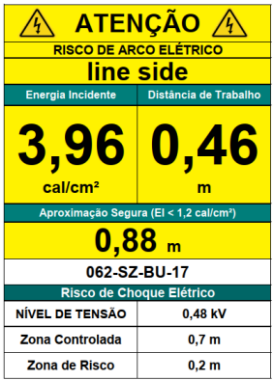


Figura 1 - Exemplo de etiqueta de energia incidente.

III. ESTRATÉGIAS DE ADEQUAÇÃO

A energia incidente possui relação direta com a corrente de curto-circuito do sistema e o tempo de duração de arco elétrico. Neste contexto, ações de engenharia que exploram maneiras de reduzir essas variáveis (tempo e corrente) surgem como interessantes alternativas para mitigação dos níveis de energia e também reforçam a importância dos estudos de curto-circuito e de seletividade do sistema elétrico como premissas básicas para a realização do estudo de energia incidente.

Conforme NFPA 70E [3], deve-se priorizar a eliminação do risco existente nas instalações elétricas e, na impossibilidade, atuar na redução do risco. Desta forma, definiu-se em procedimento interno as alternativas a serem adotadas em instalações existentes para a redução do nível de energia incidente. As principais formas de atuação aplicadas na Vale S.A Corredor Sul são detalhadas nos itens a seguir.

A. Alteração de ajustes em relés de proteção

Esta alternativa consiste em reduzir o tempo de atuação do relé de proteção, dispositivo responsável por comandar a abertura do disjuntor que irá extinguir, eletricamente, a fonte de energia que gerou o arco elétrico. Esta alternativa é uma das mais viáveis econômica e operacionalmente, visto que não implica em substituição de equipamentos ou mesmo paradas de manutenção para que seja implementada.

A alteração de ajustes nos relés de proteção consiste, principalmente, na diminuição do ajuste da função de sobrecorrente instantânea, ANSI 50, em algumas ordens de milissegundos. Como a energia incidente é diretamente proporcional ao tempo de extinção do arco elétrico, esta redução promove, por consequência, a redução do nível de energia. Esta solução é tipicamente aplicada na Vale S.A Corredor Sul para circuitos que envolvem relés localizados no primário e secundário de transformadores, em subestações próximas, pois ainda que a redução do ajuste provoque descoordenação, entende-se que não há perda de seletividade, visto que ambos os relés eliminam o mesmo trecho de circuito.

No Corredor Sul – Complexo Vargem Grande, após a emissão da última revisão do estudo de energia incidente em 2022, 46 pontos que apresentavam energia incidente acima de 8 *cal/cm²* foram mitigados através de alteração nos ajustes dos dispositivos de proteção à montante. Desta forma, comprovando-se a eficácia deste tipo de solução, além do excelente custo-benefício deste tipo de alternativa.

A Figura 2 apresenta um exemplo de mitigação de energia incidente obtida no line side de painel 220V de uma subestação secundária do Corredor Sul através de mudança de ajuste de um disjuntor de baixa tensão.

Painel	Tensão [V]	$I_{CC3\varphi}$ [kA]	I_{ARC} [kA]	t_{trip} [s]	EI $_{line\ side}$ [cal/cm²]
QDG-AUT-01	220	20,63	11,19	2,000	40,5 (antes)
QDG-AUT-01	220	20,63	11,19	0,050	1,72 (depois)

Figura 2 - Exemplo de adequação através de mudança de ajuste.

Apesar de ser uma das primeiras alternativas de engenharia a ser buscada, há cenários em que a redução no tempo de atuação da proteção mostra-se insuficiente para mitigação do risco, seja por não ser capaz de reduzir para níveis inferiores a 8 *cal/cm²* ou por mostrar-se inviável operacionalmente, ou seja, provocaria perda de seletividade não desejada.

B. Instalação de relés de arco com fibras ópticas de detecção de arco e/ou sensores pontuais

O fenômeno do arco elétrico caracteriza-se, principalmente, por uma intensa emissão de luz provocada pela ionização do meio dielétrico. O princípio de funcionamento dos sensores de luminosidade consiste na captura da luz (por fibra óptica ou sensor pontual), a qual é convertida em sinal elétrico e processada pelo relé de proteção, o qual decide de acordo com o pick-up definido, se a condição é de trip ou não trip.

Os sensores pontuais possuem atuação direcionada, com um ângulo definido para a captura de luminosidade e normalmente dedicados a um só compartimento do painel ou ativo. Em contrapartida, a fibra óptica atua como sensor, mas também como meio de transporte para o sinal luminoso. As

fibras ópticas descobertas conseguem capturar o sinal de luz ao longo de toda sua extensão, atuando como sensor compartilhado e cobrindo vários trechos no interior do painel.

A instalação de relés de arco com fibras de detecção de arco e/ou sensores pontuais é uma medida de engenharia utilizada com frequência no Corredor Sul, principalmente nos cenários em que a redução no tempo de atuação da proteção mostra-se insuficiente para mitigação. Como o tempo de detecção e atuação do relé de arco é usualmente menor que 10 ms, o tempo de extinção do arco torna-se da mesma ordem de grandeza do tempo de abertura do dispositivo responsável pela eliminação da falta, em torno de 83 ms para disjuntores de média tensão.

Ressalta-se, entretanto, a importância da atuação do relé de arco sob o princípio de zonas de proteção, em que são definidas regiões de atuação para cada situação de arco elétrico: em caso de um arco no line side (entrada de cabos) o relé de arco atua enviando o comando para o disjuntor à montante (transfer trip), enquanto um arco no load side provoca um sinal de trip no disjuntor principal do painel, conforme ilustrado na Figura 3.

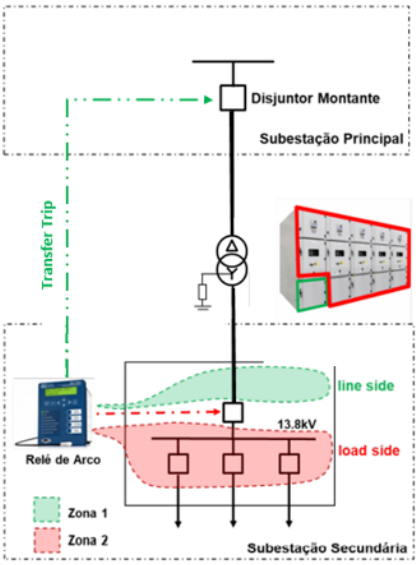


Figura 3 - Exemplo de zonas de proteção.

A Figura 4 apresenta uma solução implementada no Corredor Sul com relé de arco elétrico. Para o caso apresentado, foi feita passagem de fibra óptica na entrada de cabos do painel de baixa tensão com a realização de transfer trip para o disjuntor de média tensão.

Este método de solução é muito aplicado em painéis de baixa tensão alimentados por transformadores que apresentam potência acima de 1 MVA: nestes casos, o curto-circuito apresenta valores elevados e é necessário uma redução drástica no tempo de duração do arco elétrico para que a energia incidente fique abaixo do limite de 8 *cal/cm²*.

Painel	Tensão [V]	$I_{CC3\varphi}$ [kA]	I_{ARC} [kA]	t_{trip} [s]	EI $_{line\ side}$ [cal/cm²]
33-TC-17	480	28,73	20,00	0,483	24,1 (antes)
33-TC-17	480	28,73	20,00	0,088	5,34 (depois)

Figura 4 - Instalação de relé de arco para mitigação.

O relé de arco pode ser usado também em conjunto com o religador, aplicável nos casos em que somente o religador com seu relé de controle integrado não é suficiente para mitigação da energia incidente (ver item D). De forma análoga ao exemplificado na Figura 3, para assegurar a extinção da fonte de energia que alimenta o arco elétrico é importante a definição de zonas de atuação, de forma que um arco elétrico na entrada de cabos do painel deve desligar o religador por meio da implementação do *transfer trip,* conforme apresentado na Figura 5.

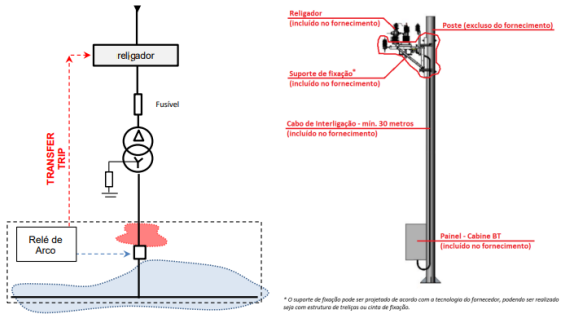


Figura 5 - Esquemático típico envolvendo relé de arco com transfer-trip para religador.

C. *Substituição de elos fusíveis*

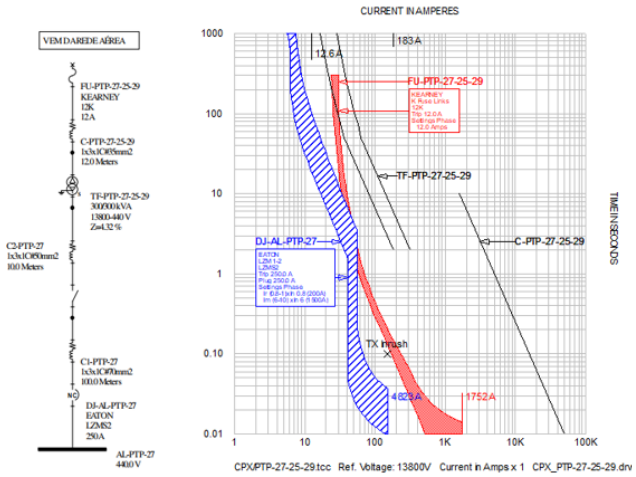
Os elos-fusíveis são a parte ativa da chave-fusível, os elementos sensores que detectam a sobrecorrente e juntamente com o cartucho interrompem o circuito em condições de sobrecorrente. Usualmente classificados em rápidos e lentos, designados como tipo K ou tipo T respectivamente, suportam correntes de até 150% do valor de sua corrente nominal sem fundirem [4]. Existem também os elos fusíveis tipo H, que suportam corrente de surto em períodos de curta duração, evitando interrupções desnecessárias. Cada tipo de elo conta com sua respectiva curva característica de interrupção Tempo x Corrente definidas de acordo com a norma ABNT NBR 7282 [5], atuando de forma mais rápida ou mais lenta a depender da aplicação em que foram utilizados.

A Vale S.A como companhia atuante no ramo da mineração, possui diversos ativos em áreas de mina, cujo fornecimento de energia é proveniente de redes de média tensão, principalmente em 13,8 *kV*. Os painéis localizados em

áreas de mina são predominantemente alimentados por transformadores de média para baixa tensão, localizados em poste, com sua proteção realizada por elos fusíveis.

Um curto-circuito com arco elétrico entre um transformador de média para baixa tensão e o disjuntor de entrada de um painel resultaria na atuação do fusível para eliminação da falta. A extinção do curto pelo fusível, entretanto, pode atingir tempos elevados e aumentar de maneira significativa o nível de energia incidente daquele painel.

Para redução do nível de energia incidente nestes casos, adota-se a prática de substituir o elo fusível existente por outro de menor corrente nominal: desta forma o elo fundirá mais rápido e o tempo de duração do arco será menor. No exemplo da Figura 6 aplicado em um dos ativos do Corredor Sul, fez-se a substituição do elo fusível de 15k para 12k, com consequente redução da energia incidente para níveis inferior a 8 *cal/cm²*, limite estipulado em procedimento interno pela Vale.



Painel	Tensão [V]	$I_{CC3\varphi}$ [kA]	I_{ARC} [kA]	Elo utilizado	t_{trip} [s]	EI $_{line\ side}$ [cal/cm²]
AL-PTP-27	440	3,83	2,34	15k	2	10,0 (antes)
AL-PTP-27	440	3,83	2,34	12k	0,906	4,54 (depois)

Figura 6 - Mitigação de energia incidente pela redução do elo fusível.

Deve-se atentar para que a redução da corrente nominal do elo fusível respeite, sempre que possível, a corrente nominal do transformador o qual está protegendo: por regra, deve-se evitar incluir um elo inferior à corrente nominal do circuito.

D. Instalação de religadores a montante de subestações secundárias

Os religadores são dispositivos capazes de realizar operações de energização e interrupção de circuitos, por um número pré-determinado de vezes, quando em condições de sobrecorrente. Na ocorrência de faltas o religador é sensibilizado pela sobrecorrente e inicia seu ciclo de operação: se a falta for temporária o religador executa operações de abertura e religamento sem completar o ciclo programado, mantendo assim a continuidade do circuito. Se a falta é permanente, o ciclo é completo e o religador abre o circuito de forma definitiva.

A Vale S.A Corredor Sul possui suas subestações divididas entre Subestações Principais e Secundárias. As Subestações Principais recebem energia da concessionária local, rebaixam o nível de tensão e fazem a distribuição de energia por meio de redes e linhas aéreas para as Subestações Secundárias (usina, área de mina, bombeamento, etc.) que, por sua vez, alimentam cargas de processo na planta. A Figura 7 apresenta um esquema ilustrativo da divisão de subestações.

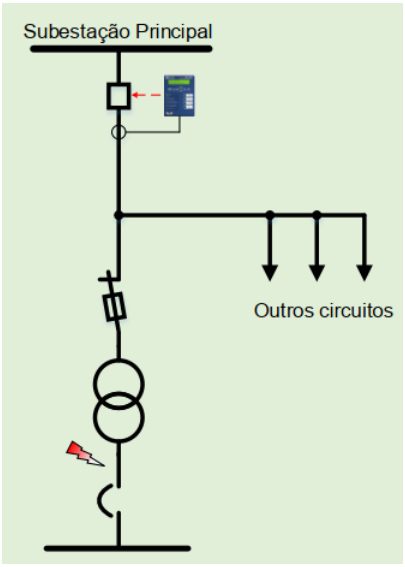


Figura 7 - Subestações Secundárias.

A instalação de religadores à montante de subestações secundárias tem por objetivo principal reduzir o nível de energia incidente na entrada dos painéis (*line side*) sem perder a seletividade do sistema, conforme esquemático da Figura 8. Esta prática torna-se viável em subestações secundárias distantes de subestação principal, em que a redução nos ajustes do relé à montante poderia provocar descoordenações indesejadas, agregando também como vantagem a eliminação da falta o mais próximo da carga.

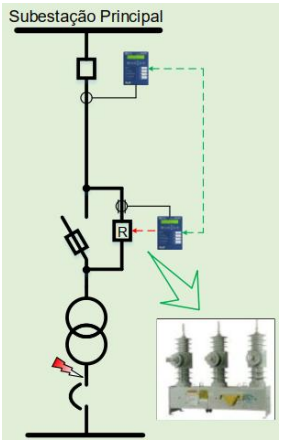
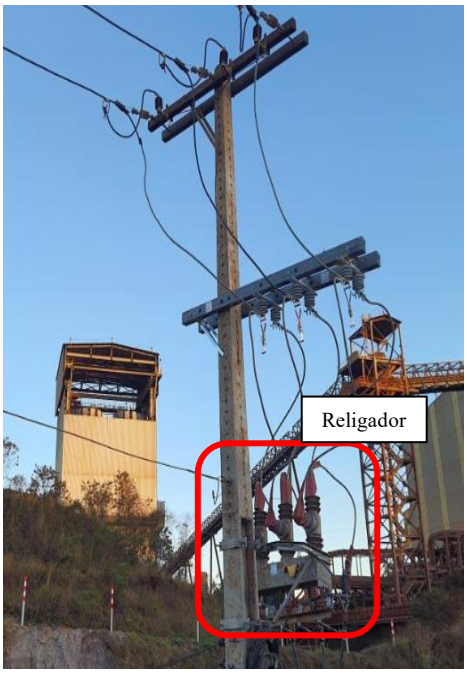


Figura 8 - Esquemático típico de aplicação envolvendo religador.

A Figura 9 apresenta caso real de religador instalado à montante de subestação secundária na Vale S.A. Corredor Sul para mitigação de energia incidente no line side de painel 13,8 *kV*.



Painel	Tensão [kV]	$I_{CC3\varphi}$ [kA]	I_{ARC} [kA]	t_{trip} [s]	EI $_{line\ side}$ [cal/cm²]
QD-8025VG-01	13,8	18,2	16,5	0,383	10,3 (antes)
QD-8025VG-01	13,8	18,2	16,5	0,090	4,28 (depois)

Figura 9 - Aplicação de religador à montante de subestação secundária.

E. *Transfer trip entre subestações*

O *transfer trip* refere-se a um sistema de proteção no qual utiliza-se fibra ótica (ou outro meio de comunicação) para permitir a transmissão de informações entre diferentes unidades de proteção. Quando um evento de falha é detectado em uma parte do sistema, para isolar a falha rapidamente o esquema de transfer trip envia um sinal de desligamento para outras partes do sistema, com o objetivo de extinguir a fonte de energia e eliminar o defeito.

Na Vale S.A Corredor Sul, além dos esquemas de transfer trip já apresentados em [B] e [D] é aplicado também o transfer trip entre subestações. Esta solução é aplicada em casos onde temos um elevado nível de energia incidente no *line side* dos painéis 13,8 *kV* das subestações secundárias, principalmente em casos onde não é viável a aplicação de religador, seja devido a elevado nível de curto-circuito da instalação ou devido a alimentação subterrânea entre subestações.

Para viabilizar o *transfer-trip* entre subestações é necessário um sistema robusto de comunicação entre o relé da entrada 13,8 *kV* da subestação secundária e o relé instalado no cubículo alimentador à montante da subestação principal. Neste contexto, prioriza-se a utilização do protocolo de comunicação GOOSE definido na Norma IEC-61850 [6].

Este tipo de solução é particularmente desafiadora quando não temos uma infraestrutura de rede pronta entre as subestações. Nestes casos, a implantação da solução torna-se mais complexa, devido a necessidade de instalação de infraestrutura e lançamento de fibra óptica passando por diversas partes da planta que estão em operação.

A Figura 10 exemplifica uma mitigação de energia incidente em line side de painel 13,8 k*V* em uma subestação secundária do Corredor Sul obtida através de transfer-trip entre subestações.

Painel	Tensão [kV]	$I_{CC3\varphi}$ [kA]	I_{ARC} [kA]	t_{trip} [s]	EI $_{line\ side}$ [cal/cm²]
075-QD-10	13,8	18,00	16,28	0,683	18,5 (antes)
075-QD-10	13,8	18,00	16,28	0,088	4,10 (depois)

Figura 10 - Exemplo de adequação através transfer trip entre subestações.

IV. CONCLUSÕES

Diante de plantas industriais com grande quantidade de ativos elétricos instalados, torna-se necessária uma gestão extremamente robusta para controle adequado do risco associado ao arco elétrico. É preciso um conhecimento profundo da instalação e um levantamento de campo detalhado, para que as soluções com melhor custo-benefício sejam escolhidas durante o processo de adequação de energia incidente das instalações.

Conforme explanado neste artigo, sempre que possível deve-se priorizar a mitigação dos pontos através da mudança nos ajustes dos dispositivos de proteção, claramente sendo a solução com melhor custo-benefício. No entanto, esta solução pode não ser viável de ser implementada, nestes casos é necessária a adoção de uma das outras soluções listadas neste documento.

No processo de adequação, é importante priorizar a mitigação das instalações que apresentam os maiores valores de energia incidente que consequentemente implicam em maior risco aos profissionais que atuam nestes ativos. No contexto da Vale S.A. Corredor Sul, priorizou-se a adequação das instalações que apresentavam energia incidente superior a 40 *cal/cm²*. Em procedimentos internos da empresa, foi estabelecido que em painéis com nível de energia incidente superior a este valor é proibida a intervenção de profissionais nestas instalações energizadas. Desta forma, foi feito um amplo trabalho de adequação, sendo que todas as instalações que apresentavam energia incidente acima de 40 *cal/cm²* já tiveram o seu nível de energia incidente reduzido para abaixo de 8 *cal/cm²*.

Nas instalações que já apresentam um nível de energia incidente abaixo de 8 *cal/cm²*, é necessária uma forte disciplina operacional para que estes valores sejam mantidos. Qualquer necessidade de mudança de ajustes em dispositivos de proteção deve passar pelo crivo do time de engenharia de proteção e, em caso de substituição de elos-fusíveis, é preciso respeitar o modelo do respectivo elo daquela instalação.

Em resumo, o processo de adequação de energia incidente é um processo que demanda conhecimento profundo das instalações, equipe fortemente qualificada na liderança deste processo, gestão robusta na priorização das adequações, disciplina operacional e engajamento dos profissionais que atuam nas instalações elétricas.

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Review of Electric Arc Tests on Cables Used in Fast Charging of Electric Vehicles

1st João Paulo Costa Lima
Graduate Program in Electrical Engineering (PPGEE)
Federal University of Santa Maria
Santa Maria, Brasil
limajoaoege@gmail.com

2nd Lucas Vizzotto Bellinaso
Graduate Program in Electrical Engineering (PPGEE)
Federal University of Santa Maria
Santa Maria, Brasil
lucas@gepoc.ufsm.br

3rd Leandro Michels
Graduate Program in Electrical Engineering (PPGEE)
Federal University of Santa Maria
Santa Maria, Brasil
michels@inriufsm.com.br

***Abstract*— The phenomenon of electric arc represents a critical challenge to the safety and reliability of electrical systems, especially in DC applications such as fast charging of electric vehicles. This paper presents an analysis of the physics involved in electric arc formation, considering the energetic conditions inherent to the phenomenon. Furthermore, it offers an analytical review of existing standards for electric arc testing and proposes a new testing protocol focused exclusively on conductor cables used in fast charging of electric vehicles, including a suggested protocol for conductor rupture simulations. The proposal considers aspects such as temperature and energy dissipation, providing a foundation for understanding the practical implications of these phenomena on the performance and safety of fast charging cables. The results highlight the differences between standardized tests and real operating conditions, emphasizing the need to revise testing parameters to better reflect actual applications.**

Keywords*— *electric arc, direct current, electric vehicle, fast charging.

I. Introduction

The introduction and commercialization of electric vehicles (EVs) have accelerated in the global market in response to worldwide concerns regarding CO_2 reduction and energy security. As a result, the growing adoption of EVs has driven the development of technologies associated with charging infrastructure, and DC charging is seen as an effective and complementary solution to AC charging, enhancing the viability of electric vehicles [1]. In this context, electrical safety is a fundamental aspect, especially concerning the risk of electric arc occurrence, which is considered one of the most dangerous failures in power systems.

Currently, standards such as ABNT NBR IEC 61851, IEC 62196, and UL 2251 establish criteria for the construction, safety, and performance of cables and connectors used in EV conductive charging. These standards generally address requirements to prevent the formation of electric arcs under normal operating conditions, such as disconnection under load, insulation failures, or poor contact at terminals. Mechanical resistance tests such as tensile strength, bending, and electrical durability are also performed, which indirectly contribute to mitigating risks related to electric arcs [1]-[4].

At present, no standard defines a unique and comprehensive standardized procedure for testing for arc flash resulting from physical cable rupture, as illustrated in Figure 1. This means that situations where the conductor, which is a major component of conductive load infrastructure, may be accidentally cut or ruptured while energized and in operation are being overlooked. Although rare, this type of event can generate a significant arc flash and therefore poses a real safety concern.

Specialized laboratories and manufacturers develop customized tests, based on internal protocols, to simulate extreme scenarios such as conductor rupture under load.

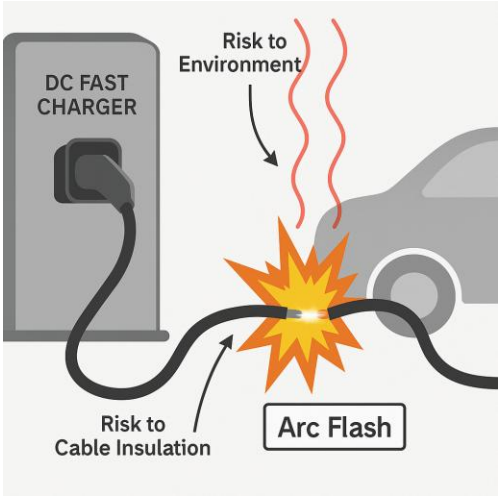

Fig. 1 Arc flash damage to cable insulation and the environment.

These tests are generally conducted as part of research and development (R&D) programs or to meet specific quality and safety certification requirements. However, the cables used for electric vehicle charging, especially for fast charging, are not currently covered by the requirements set forth in existing standards.

Considering the ongoing evolution in the pursuit of fast charging, the current absence of a standardized test specifically aimed at this condition reveals a technical gap in normative publications. Professionals involved in the design, certification, or risk assessment of cables for fast electric vehicle charging must be aware of this aspect and, if necessary, propose their own destructive testing protocols, based on principles derived from existing standards and references from industrial arc flash standards, such as IEEE 1584 (incident energy calculation) or IEC 61482-1-1 (protective clothing against the thermal hazards of an electric arc) [6].

Despite normative advances regarding the safety of charging systems, this article aims to draw the special attention of the professionals and certification bodies to the critical issue of the lack of a specific normative test for electric arcs resulting from the physical rupture of fast charging cables for EVs and finally to suggest premises for such practices. To this end, standards that can serve as a basis for the development of such tests are listed, as well as the risks involved in this type of situation.

II. Electric Arc Physics

The electric arc is a visually striking and physically complex phenomenon that occurs when an intense electric current passes through an ionized gas between two electrodes, as can be seen in Figure 2. Despite its various industrial applications, such as welding, metal cutting, lighting, and material testing under extreme conditions, the electric arc is generally undesirable in electrical systems, as it can cause damage and equipment failures, and in more severe cases, lead to explosions and fatalities. Understanding the electric arc is not trivial, since the term "arc" has been used to describe different types of discharges that may look similar but exhibit distinct physical behaviors. In general, there is a consensus among plasma physicists that the electric arc should be defined by its electrical characteristics, especially the current and voltage involved [7]-[8].

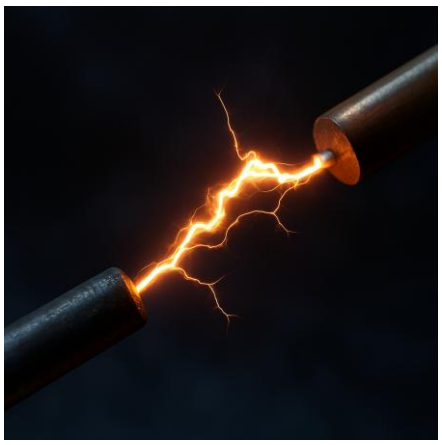

Fig. 2 Representation of an electric arc between two electrodes.

The typical voltage versus current curve of an electric discharge reveals three main regimes:

- Dark discharge (or Townsend discharge).
- Glow discharge.
- Arc discharge.

The transitions between these regions are illustrated in Figure 3. They occur in an unstable manner, but the overall shape of the curve remains similar, even under varying experimental conditions, provided the electrodes do not have sharp edges or tips (thus avoiding corona discharges). This curve is illustrated in Figure 3. Within the electric arc discharge regime, it is possible to distinguish two fundamental categories: high-pressure arcs and low-pressure arcs. The difference between these two classes becomes evident when analyzing the temperature behavior of the various plasma components (electrons, ions, and neutral atoms) as a function of gas pressure. This analysis shows that, despite the different operating conditions, similar curves can be observed, reflecting the complexity and robustness of the phenomena associated with electric arcs. These temperatures are defined based on experimental facts about the macroscopic behavior of gases, in which temperature is a direct measure of the average molecular kinetic energy, defined by equation (1):

$$\frac{1}{2}m_0C^2 = \frac{3}{2}k_BT \qquad (1)$$

where k_B is the Boltzmann constant, T is the temperature of the relevant type of particles, m_0 is their mass, and C is the root mean square velocity [7]-[9].

In high-pressure electric arcs, the various plasma particles mentioned above tend to have very similar temperatures, which allows the system to be treated as if it were in "local thermodynamic equilibrium", that is, it is possible to define a single temperature at each point in the plasma, although this temperature may vary from one point to another. This simplifies the study of the electric arc, as it allows the use of heat equations and theoretical models to understand how temperature is distributed and how it affects plasma density. In more complex cases, small deviations from this equilibrium can still be considered to obtain more accurate results [7]-[8].

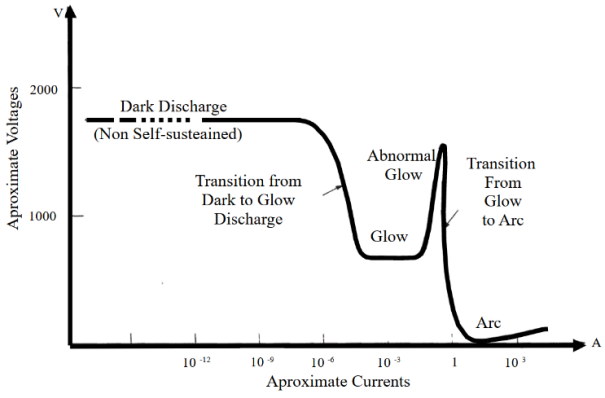

Fig. 3 Approximate voltage vs. current characteristic of an electrical discharge.

In low-pressure electric arcs, electrons reach much higher temperatures than ions and neutral atoms, as they travel longer distances without collisions and absorb more energy from the electric field. Since they lose little energy in collisions with heavier particles, the temperature difference is maintained, and the temperature of the neutral gas remains close to ambient. The arc's behavior depends on whether the electron mean free path is shorter or longer than the tube radius: this determines different mathematical models to describe how particles are distributed in space. These models mainly consider how the "hot" electrons generate new particles and how those particles disappear upon reaching the tube walls. Despite differences in approach, the two main models show good agreement when the physical dimensions involved are similar and can be refined further for greater accuracy [7]-[8].

Physically, the electric arc consists of three regions: the cathode region, the plasma column, and the anode region. In the cathode region, a small voltage drops forms to ensure a stable flow of current from the electrons into the plasma. In the column, current is mainly carried by electrons due to their high mobility, while the ion and electron densities remain nearly equal because of electric forces that maintain the system nearly neutral. At the anode, the main challenge is replenishing the ions continuously absorbed by the column. This structure provides the minimum stability necessary to sustain the electric arc in direct current DC [7]-[8].

In practice, DC electric arcs that occur in power system faults are highly dynamic. The arc length changes over time, and the plasma shape can bend due to thermal convection and electromagnetic forces. The actual geometry of a free (unconfined) electric arc is often larger than the space between the electrodes, as the plasma tends to expand and move constantly. These arcs can also extinguish and reignite repeatedly, and interactions with the electrode material make the phenomenon even more complex. Most electric arc studies are conducted with opposing electrodes, where current flows directly from one side to the other, and this configuration is especially useful in the development of safety devices such as circuit breakers and fuses [7]-[10].

Thus, although it may appear simple, at first glance, just a thread of fire between two points, the electric arc is the result of an intricate combination of thermal, electrical, and physical effects that make it a subject of great interest for both engineering and basic science, including fields such as astrophysics [7]-[10].

III. On Fast Charging And Conductive Cables

As the adoption of EVs accelerates, the development of charging infrastructure for electric vehicles is also expanding. As a complement to AC charging systems, DC charging is recognized as an effective solution to meet the needs of the available range of electric vehicles. The international standardization of charging infrastructure is essential for the widespread adoption of electric vehicles, and new standards are being developed for the convenience of manufacturers, providing general requirements and guidelines for DC charging stations for EVs with conductive connection to the vehicle [1].

Fast charging for EVs is in a phase of growth and development, and the conductive cables used in this charging mode may have a complex internal structure. They must be designed to safely and thermally efficiently handle the required high currents, as fast-charging stations operate at high power levels. Such cables must be made from high-quality materials and subjected to rigorous testing to ensure durability and resistance. However, despite all the engineering involved and quality control measures, they are not infallible and are subject to failure, especially when not used properly or when exposed to unfavorable conditions.

Typically made of copper, these conductors are responsible for carrying large electric currents. The higher the current capacity of the charger, the larger the diameter of the conductors must be, significantly increased to reduce electrical resistance and, consequently, heat generation. To manage the heat produced during fast charging, some cables incorporate internal channels through which a cooling liquid circulates. This system helps keep the cable temperature within safe limits, allowing higher currents without overheating. Layers of insulating materials must surround the conductors and cooling channels, providing electrical safety and thermal resistance, along with a robust outer layer that protects the cable against mechanical damage and adverse weather conditions. Integrated sensors monitor the cable's temperature in real time, allowing adjustments to the cooling system and ensuring safe operation even under extreme conditions.

Among the factors that can compromise the durability of these cables over time are excessive use and natural wear due to repeated bending, exposure to extreme temperatures, moisture, and dust. These factors accelerate the degradation of materials. Another critical point is improper handling, such as excessive pulling, sharp bends, or incorrect storage, which can cause mechanical damage. Manufacturing defects or the use of substandard materials may also contribute to premature failures. In addition, poor compatibility between the cable, the vehicle, and the charging station is another factor that cannot be overlooked.

If there is damage to the insulation or the outer jacket, protection against electric shock and environmental conditions will be compromised. Connectivity or contact issues between the cable and the connectors can also result in failures in power transfer. Furthermore, conductor wear or breakage may be partial or complete, as the cable is generally composed of a bundle of copper wires, and such ruptures can lead to electric arcs or localized overheating. In such critical scenarios, high temperatures can degrade the conductor’s insulation and render the cable unusable.

To ensure safety and extend the lifespan of fast-charging cables, it is essential to adopt a series of precautions. Strictly following the manufacturer's instructions for use and maintenance is the first step. Conducting regular inspections to identify signs of wear, physical damage, or malfunction allows for preventive action, avoiding accidents. Proper cable storage, in dry places, protected from sunlight, and without sharp bends, also significantly contributes to their preservation. Finally, choosing cables certified by current standards and compatible with both the vehicle and the charging station is fundamental to ensuring efficiency and safety during charging.

Although fast-charging cables for electric vehicles are designed to provide reliability and performance, careful use and maintenance are crucial to prevent failures and ensure longevity. Adopting good practices can make all the

difference in the safety of the charging system and even ensure the proper operation of the EV.

Given the reported issues, the idea emerges to develop a specific testing protocol for conductor ruptures, since, after conducting a search for such tests based on normative systems, no existing standard was found to govern this type of situation.

IV. Standards Related To This Type Of Test

Currently, some Brazilian and international standards that regulate the safety and performance of conductive charging systems for electric vehicles can serve as a basis for new guidelines and standards for arc flash testing on fast-charging EV conductors. These standards include:

A. ABNT NBR IEC 61851

The ABNT NBR IEC 61851 standard, especially parts 1 and 23, is fundamental for conductive charging systems of electric vehicles. ABNT NBR IEC 61851-1:2021 addresses general requirements for conductive EV charging systems, while ABNT NBR IEC 61851-23:2020 establishes specific requirements for DC charging stations and includes parts focused exclusively on fast chargers (referred to as Mode 4). Although it does not directly address conductor ruptures with electric arcs in cables, ABNT NBR IEC 61851 provides technical parameters, operational limits, and electrical safety requirements that serve as a normative basis to structure a simulated arc rupture testing protocol. The standard can contribute to key areas for defining the protocol:

1) Definition of Realistic Test Conditions

ABNT NBR IEC 61851 specifies:

- Rated operating voltage for DC chargers.
- Maximum currents in DC connectors.
- Types of charging (Mode 3 and Mode 4), where Mode 4 (DC) involves high currents and greater risks.

Application in the new testing protocol:

- Defines current/voltage limits to be used in the electric arc test (e.g., simulate rupture at 400 V and 500 A).
- Allows simulation of failure scenarios during charging under full load.

2) Cable and Connector Architecture

The standard defines:

- Construction requirements for cables and connectors (IEC 62196 combined with 61851).
- The presence of temperature detection and signal conductors for communication and safety.

Application in the new protocol allows structuring tests considering:

- Total rupture (power conductor broken).
- Partial rupture (signal or ground conductor interrupted).
- Arc simulation in cases of insulation failure between adjacent conductors.

3) Safety Requirements and Circuit Interruption

ABNT NBR IEC 61851 requires that:

- Systems include protection devices against overcurrent and ground faults.
- The system must automatically interrupt charging in the event of abnormality.

Application in the new protocol:

- The protocol can simulate fault conditions where these devices fail to act in time, resulting in an electric arc.
- It allows verification of actual vs. expected interruption time.

4) Functional and Durability Tests

The standard includes tests such as:

- Verification of insulation resistance.
- Connection/disconnection cycles.
- Operating temperatures under rated load.

Application in the new protocol:

- Prior to the arc flash testing, accelerated aging tests or disconnection cycles can be performed to simulate mechanical fatigue, which contributes to conductor ruptures.

B. IEC 62196-1:2022

The standard defines the constructional, electrical, thermal, and mechanical aspects of connectors, which are critical points where failures can result in electric arcs, especially in high-power DC systems.

Main Contributions to a Test Protocol:

1) Standardization of Electromechanical Interfaces

IEC 62196 describes the types of connectors used globally:

- Type 1 (SAE J1772 – North America).
- Type 2 (Mennekes – Europe).
- Type 3 (with shutter).
- Combo Type (CCS): combines AC + DC in a single connector.

Application in the proposed test allows simulation of ruptures between cable and connector, such as:

- Partial contact under load.
- Disconnection under current (which can cause arcing).
- Insulation failure or thermal fatigue at the terminals.

2) Design Specifications for Current and Voltage
The standard defines:

- Rated current (up to 400 A for DC).
- Maximum voltage (up to 1000 V DC).
- Maximum allowable temperature rise at the pins.

Application in the new test defines the actual operating limits to simulate failures such as:

- Connector overload.
- Localized heating leads to insulation breakdown.
- Electric arc generation during abnormal disconnection.

3) Electrical, Thermal, and Mechanical Resistance Requirements
The standard includes tests such as:

- Electrical durability testing (repeated connections under load).
- Heating test under rated current.
- Mechanical tests for tensile and torsional stress on cables and connectors.

These tests simulate progressive degradation that precedes or contributes to the formation of electric arcs, especially:

- Cracks in the housing.
- Deformations in the pins.
- Loosening of connections.

4) Safety Against Accidental Contact and Insulation Failures
The standard establishes protection degrees (IPXXD, IPXXB) and tests for:

- Insulation between conductors.
- Insulation resistance under voltage.
- Protection against live contact.

Application in the proposed test protocol:

- These requirements help simulate partial insulation failures that can generate electrical arcs between positive and negative DC poles or with the metallic casing (ground).

C. UL 2251

UL 2251, *Standard for Plugs, Receptacles, and Couplers for Electric Vehicles* (Underwriters Laboratories) is an American standard focused on the safety of connectors and couplers used in electric vehicle charging, primarily in DC and high-power environments.

Although it is not a standard specifically designed for electric arc testing, UL 2251 directly contributes to the development of a simulated test protocol for total or partial conductor rupture with electric arc generation, by establishing:

1) Realistic Electrical Failure Scenarios
UL 2251 includes:

- Load break tests (disconnection under load).
- Insulation failure tests.
- Sparking/arc tests under overload conditions.

Application in the new protocol:

- It enables the simulation of partial ruptures or forced disconnections while the system is still conducting DC current, leading to real electric arc generation.

2) Tests under Overcurrent and Overvoltage Conditions
The standard requires connectors to withstand:

- Momentary overcurrent.
- Elevated voltages for short durations.
- Surge voltages.

Application in the new protocol:

These requirements can be used to induce conditions that precede or cause electrical arcs, especially:

- Thermal fatigue.
- Insulation degradation.
- Local overvoltage at rupture points.

3) Electric Arc Resistance and Ignition Tests
UL 2251 includes criteria for:

- Non-arcing capability.
- Ignition and flame propagation tests.
- Assessment of connector behavior under insulation failure.

Application in the new protocol:

It provides parameters and limits for the expected behavior of materials under electric arc conditions, such as:

- Carbon tracking formation on dielectric surfaces.
- Flame propagation after electric arc occurrence.
- Material self-extinguishing capability.

4) Durability and Repeated Disconnection Tests
The standard requires connectors to withstand:

- Multiple connection and disconnection cycles under load.
- Cable flex and tensile stress tests.
- Evaluation of contact resistance over time.

Application in the new protocol:

It helps simulate scenarios in which mechanical fatigue leads to partial or intermittent failures, creating ideal conditions for internal electrical arcs.

UL 2251 provides a practical and safety-oriented foundation for structuring a test protocol involving partial or total rupture that may generate electric arcs in fast charging cables for electric vehicles. Its most relevant contributions include:

- Load break testing under real operating conditions.
- Assessment of ignition and thermal propagation during arc flash events.
- Definition of electrical and mechanical operating limits.
- Objective failure and acceptance criteria.

D. IEEE 1584

The IEEE 1584 - *Guide for Performing Arc-Flash Hazard Calculations* is one of the most comprehensive international references for arc flash hazard analysis, particularly in alternating current (AC) power systems. However, there are specific aspects of IEEE 1584 that can be leveraged even when the focus is a simulated electric arc rupture test in DC fast-charging cables for electric vehicles (EVs).

Although IEEE 1584 primarily addresses 50/60 Hz AC systems, it provides standardized, empirically based methods for testing and calculating incident energy, which can be adapted or serve as inspiration for DC protocols, including for EV cable systems.

The standard specifies critical variables that influence arc flash severity:

- Arc current.
- Arc duration.
- Working distance.
- Electrode configuration.

These parameters can be used to design a controlled laboratory test setup.

Even though it does not directly apply to DC systems, IEEE 1584 serves as a robust technical foundation and can be adapted for real testing, especially when used in conjunction with other standards such as NFPA 70E (which addresses DC hazards) and the previously mentioned IEC and UL standards.

E. UL 1699B

UL 1699B - *Outline of Investigation for Photovoltaic (PV) DC Arc-Fault Circuit Protection* was specifically developed to address devices for arc fault detection and interruption in DC, particularly in photovoltaic systems. However, its technical content can be partially applicable to other DC applications, such as fast charging of EVs.

The UL 1699B electric arc generator is designed to:

- Produce simulated DC arc fault conditions.
- Evaluate the detection and response capabilities of DC Arc-Fault Circuit Interrupters (AFCIs).
- Simulate real arc faults with repeatability and safety.

The UL 1699B electric arc generator can be used as a basis for arc rupture testing in EV fast-charging cables, if adaptations are made to the electrodes, fault conditions, and test criteria. Figure 4 shows the electric arc generator with the electrode model used in UL 1699B, which should be replaced with a conductor cable for EV cable testing. The original model consists of tungsten alloy sphere electrodes and a movable blade, as illustrated in Figure 4. The test is initiated with the electrodes in contact and then separated at a controlled rate of speed. The positive pole of the test circuit must be connected to the ring of the assembly shown. This type of generator provides a robust structure for DC arc generation, is technically compatible with the voltage and current levels used in EV fast chargers (400 V, 600 V, 800 V) and ensures repeatability and safety. It enables the simulation of critical faults and the evaluation of the thermal, electrical, and mechanical protection of charging cables.

F. IEC 63027

IEC 63027 – DC Arc Detection and Interruption in Photovoltaic Power Systems defines performance requirements and tests such as DC arc detection, safe arc interruption methods, reliability requirements, and false positive prevention.

Both photovoltaic (PV) systems and fast charging systems for electric vehicles operate in DC, at potentially high voltage and current levels (400–1000 V, 100 A or more). Therefore, DC arc phenomena behave similarly in both contexts.

Main Contributions to a Test Protocol:

1) Similarity of the Electrical Environment

- Both systems operate in DC.
- Both systems operate with potentially high voltage and current levels.

2) Practices That Enhance Safety and Quality of Testing

- Establishment of criteria to consider the electric arc a real risk in DC.

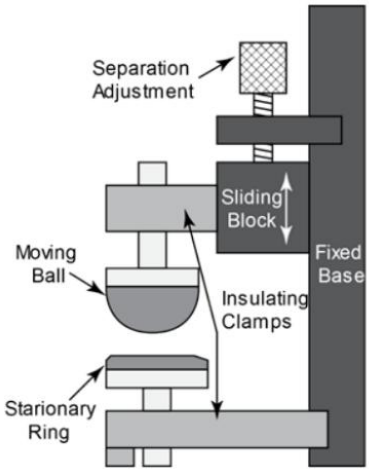

Fig. 4 Schematic of the arc generator (as derived from UL 1699 B).

- Inspiration for creating a safe bench for arc generation and control.
- Electric Arc detection and extinction criteria may be applicable to fault detection in EV cables.
- Guidance on realistic and repeatable test limits.
- Definition of the number of test cycles to validate robustness.
- Requirements for reliable protection mechanisms.

Therefore, the test structure, the equipment used, the detection and protection response times (when applicable), and the current/energy limits are all relevant and adaptable to the context of DC fast charging for electric vehicles.

G. IEC 62606

IEC 62606: Arc Fault Detection Devices (AFDDs) – General Requirements establishes technical criteria and test methods for arc fault detection devices, primarily used in low-voltage AC installations (< 440 V) to detect hazardous arcs and disconnect circuits. Although focused on AC systems and building installations, the standard provides essential foundations for arc fault testing protocols.

Key contributions include:

1) Definition of Test Parameters

- Operating voltage.
- Minimum current required to initiate the electric arc.
- Gap (separation distance) between conductors.
- Type of load (resistive, inductive).
- Test duration.
- Electric arc interruption criteria.

These parameters can be adapted to the DC environment of fast chargers, using voltages and currents typical of the target system.

V. Proposed Testing Practices

Due to the identified regulatory gap, some manufacturers and testing laboratories have developed their own protocols to assess the behavior of cables and connectors under extreme failure conditions, such as the intentional rupture of an energized conductor. These tests are typically conducted in a controlled research and development (R&D) environment and are not part of mandatory compliance requirements.

Furthermore, standards like those previously mentioned can be used as complementary references for assessing the severity of electric arcs, even though their scope is directed toward other specific purposes.

1) Objective of Creating a Specific Protocol

To evaluate the electrical and thermal behavior of a fast-charging electric vehicle cable under failure conditions caused by the physical rupture of an energized conductor, simulating a real-world scenario with the potential for arc flash formation. The goal is to determine the associated risks, the severity of the electric arc, and the effectiveness of the system's built-in protective measures.

2) Required Equipment and Materials

- Fast-charging cable (Mode 3 or Mode 4), including connectors and plugs.
- Adjustable power supply: current and voltage matching real application conditions.
- Protective circuit breaker rated according to the typical system curve.
- High-speed camera for visual recording of the electric arc.
- Current and voltage sensors with data acquisition.
- Electric arc containment test chamber.
- Remote cutting tool (heated blade or automated mechanical system, e.g., arc generator similar to UL 1699B).
- Thermocouples or thermal imaging camera.

3) Initial Conditions

- The cable must be in its original application configuration, connected to a simulated or real charging system.
- Voltage and current must match the cable's rated operating conditions.
- Current, voltage, and temperature sensors must be calibrated and properly installed.
- The automatic shutdown system (relay or connector auxiliary contact) must be enabled, if applicable.

4) Test Procedure

a) Preparation:

- Position the cable inside the containment chamber with direct line of sight to the high-speed camera.
- Apply electrical load (rated current and voltage) to the primary conductor to be tested.
- Activate the cutting tool at a defined point (preferably the middle of the cable).

b) Test Execution

- Perform the cut or rupture of the conductor while the circuit is energized using electric arc generator.
- Record: arc voltage (abrupt drop), arc current, arc duration until extinction, local temperature, and activation (or not) of protection devices.

c) Post-Test

- Check the integrity of other components.

- Assess thermal damage to the insulation.
- Verify the operation of the protection system.
- Inspect for visual signs of the electric arc (carbonization, melting, copper splatter).

5) Evaluation Criteria

TABLE I. CRITERIA TABLE

Parameter	Acceptable
Arc time	<100 ms (ideal)
Estimated incident energy	<1.2 cal/cm²
Protection system actuation	Yes (automatic shutdown in milliseconds
Physical damage to insulation	Localized, no propagation
Plug integrity	No structural damage

VI. CONCLUSION

The growing adoption of electric vehicles and the evolution of fast DC charging systems present new challenges to electrical safety, particularly regarding the mitigation of risks associated with arc faults during failure conditions. Although consolidated standards such as ABNT NBR IEC 61851, IEC 62196, UL 2251, and IEEE 1584 exist, there remains a specific regulatory gap concerning test protocols dedicated to the controlled simulation of arc faults in charging cables.

The aforementioned standards include criteria related to the prevention of electric arcs under normal operation or foreseeable fault conditions, such as connector disconnection under load, dielectric insulation failure, overheating, degradation of insulating materials, and mechanical wear through bending and tensile tests. However, after a detailed analysis of these standards, it becomes evident that there is no clear and specific normative definition for a test solely dedicated to simulating arc faults caused by the physical rupture of an energized conductor. This type of failure, though not frequent, can occur due to improper handling, accidents, or vandalism, representing a serious arc hazard with the potential for material damage and personal injury.

In this context, the development of a specific experimental protocol proved essential to support the advancement of safer and more reliable cables, connectors, and protection devices. The protocol proposed in this document focuses on assessing the thermal and electrical behavior of conductors used in fast EV charging under extreme fault conditions, enabling the identification of critical failure points, validation of existing protections, and guidance for the revision or creation of technical standards for the sector.

The practical application of such tests in a controlled research environment significantly contributes to accident prevention in the field, expands technical understanding of the underlying phenomena, and enhances the safety of users and electrical infrastructure. Furthermore, the data obtained can support manufacturers, certification bodies, and regulatory agencies in defining objective criteria for compliance and performance, thereby strengthening the reliability of fast charging systems for EVs.

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Analysis and Impact of Arc-Flash Hazard Studies in Low-Voltage Panels

Sarah Vieira Galdino
DEE –Department of Electrical Engineering
CEFET-MG Federal Center for Technological Education of Minas Gerais
Belo Horizonte, Brasil
sarahgaldinoo11@gmail.com

Fernando Venâncio Amaral
DEEB: Department of Electronics and Biomedical Engineering
CEFET-MG Federal Center for Technological Education of Minas Gerais
Belo Horizonte, Brasil
famaral@cefetmg.br

Eduardo Gonzaga da Silveira
DEE –Department of Electrical Engineering
CEFET-MG Federal Center for Technological Education of Minas Gerais
Belo Horizonte, Brasil
eduardo@cefetmg.br

***Abstract*—This study analyzed incident energy and safe approach distance in low-voltage panels, applying the IEEE Std 1584-2018 methodology and a Microsoft Excel-developed spreadsheet. The work underscores the critical need for precise preliminary calculations to ensure appropriate Personal Protective Equipment selection and efficient control measures, given the severe hazards of arc flash accidents. Results from simulations under various conditions corroborated the empirical nature of the IEEE Std 1584-2018 model, revealing that relationships between input variables and the resulting incident energy and safe approach distance are neither linear nor intuitively proportional, often defying simple expectations.**

Keywords—Arc-Flash Hazard, Arc Flash Boundary, IEEE Std 1584-2018, Personal Protective Equipment, Electrical Safety, Arc Flash Boundary

I. Introduction

Until 1950, all overcurrent protection devices were of the magnetic trip type, consisting of a coil (electromagnet) that attracts an articulated piece (armature) when the current reaches a certain value [1], instantly eliminating the fault. However, after this period, the electromechanical induction disk relay emerged, which introduced a time delay in fault clearing. Consequently, selectivity became an essential component of protection studies.

Due to the delayed fault clearing time, the destruction of equipment such as switchgear assemblies, Motors Control Center (MCCs), and panels became a major concern. Additionally, during the same period, the continuous increase in transformer power ratings and their secondary nominal voltages led to the emergence of low-voltage arc faults, which also proved to be highly destructive [2].

In 1967, Shields published a paper analyzing several "unexplained" cases of equipment destruction caused by arc flash in low-voltage systems. He emphasized the severity of the issue, pointing out that arc flash events are more dangerous than conventional short circuits. He also noted the industry's lack of awareness—among designers and users alike—regarding the need to implement measures to reduce the likelihood of such destructive failures [3].

Arc flash, also known as arc fault, is an electrical phenomenon that occurs when the dielectric strength of an insulating medium, such as air, is broken down, allowing the passage of electric current through an ionized channel (plasma). This process can release a large amount of thermal energy and cause significant damage to equipment and people [4]. It can also occur when two terminals in a circuit separate, such as during switching, due to the interruption of load current, overload, or a fault. Arcs are typically initiated by a discharge caused by some type of conductor that then vaporizes, forming an arc [5].

In the 1980s, Ralph Lee, a pioneer in studies related to arc flash explosions and known as the father of incident energy, published the article “The Other Electrical Hazard: Electrical Arc Blast Burns.” In it, he demonstrated that electric shock is not the only hazard concerning personal protection for workers, emphasizing burns caused by arc flash explosions. His work revolutionized the understanding of incident energy calculations and protection methods against arc flash hazards. He proposed an equation for calculating the incident energy resulting from arc flash above 600 V [6]. As a result, arc flash began to be studied not only for its elevated risks to electrical systems and equipment but also for the severe injuries and fatalities it could cause to workers, due to the large amount of energy released in a short time.

Figure 1 illustrates some of the effects associated with arc flash events. Among these, burns—ranging from first to third degree—stand out due to the high temperatures from the expansion of hot air, plasma, and vapor, as well as contact with molten or ejected solid fragments. While other hazards are concerning, thermal effects are especially critical, as they are responsible for most cases of disability and death [7].

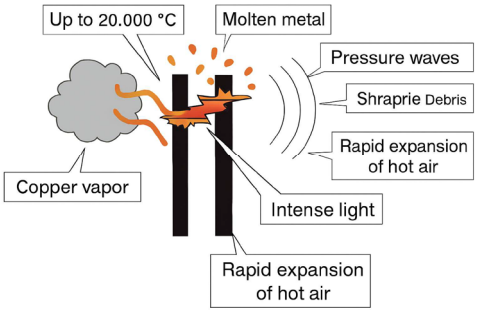


Fig. 1. Arc flash effects [8]

In response to these new concerns regarding arc flash hazards, the IEEE published in 2002 the IEEE Std 1584: IEEE Guide for Performing Arc-Flash Hazard Calculations. This was a significant milestone, as the methods proposed by Ralph Lee often resulted in excessively high incident energy values, requiring uncomfortable protective clothing [1]. IEEE Std 1584 uses statistical methods based on the arc's unstable characteristics and defines the main variables influencing arc current and energy. It determines the equations for these quantities using sample data and curve fitting. An update was released in 2018, with a new model producing more accurate results for configurations shared with the previous version, as well as expanding the model to evaluate incident energy for previously unaddressed setups, such as vertical conductors in enclosures with barriers, and horizontal conductors in and out of enclosures [9].

The IEEE 1584 guide provides models and an analytical process that allows for the calculation of predicted incident energy and arc flash boundary. Applications include electrical equipment and conductors for three-phase alternating current (AC) voltages from 208 V to 15 kV. The purpose of the guide is to enable qualified persons to calculate the incident energy to which employees may be exposed during operations and maintenance work. The incident energy calculation model was empirically developed based on more than 1,860 tests conducted at various voltage levels. It is considered reliable when applied within the recommended parameter ranges [9].

Despite the known importance of incident energy studies, many companies and industries either fail to perform these calculations during the design phase or do so incorrectly, using outdated or inappropriate methods. This results in the selection of improper Personal Protective Equipment (PPE), either under-protective or overly restrictive, compromising both safety and comfort. In other words, although arc flash incidents are highly dangerous and increasingly frequent, negligence still prevails, particularly in comparison to electric shock risks. This is evidenced by insufficient investments in specialized training and equipment aimed at reducing incident energy exposure.

Moreover, there is often improper use of PPE against arc flash effects, which can worsen the severity of burns depending on the clothing worn at the time of the arc event.

Given this scenario, the objective of this study is to present the importance of analyzing and studying incident energy in low-voltage electrical panels prior to their manufacturing. This allows for the evaluation and selection, whenever possible, of parameters that result in lower incident energy values during the design phase. This involves assessing the incident energy of each equipment for various distinct short-circuit situations and evaluating the method described in IEEE Std 1584-2018. This can prevent electrical arcing and its effects, in addition to avoiding costs in retrofit projects—the process of modernizing or replacing equipment in the panel. It also helps in selecting optimized PPE, ensuring that the workers are not burdened with clothes that have higher-than-necessary protection levels (often uncomfortable) or lower protection levels, which could increase the risk of severe accidents.

II. METHODS

A. Overview of IEEE Std 1584-2018

The IEEE Std 1584-2018 guide is the main normative reference for arc flash studies. It provides an empirically validated mathematical model based on tests for estimating incident energy at specific open circuit voltage levels. These tests used seven calorimeters: three placed perpendicularly and equidistantly to the tip of the electrodes, three below the tip, and one above. This setup represents the chest and face of a person [5]. In the results analysis, only the highest energy measurement among the calorimeters was considered, and it is assumed that the energy absorbed by copper calorimeters is equal to or greater than 90% of the incident energy [9].

The standard presents statistical analyses of the tests and curve fittings of incident energy, considering variables such as voltage, current, arc time, and others. The second edition, released in 2018, introduced a completely new mathematical model for incident energy calculation. However, it made the analysis more complex compared to the first edition of 2002, requiring data that was previously not considered. Tests were conducted with a larger number of electrode configurations, and new equations were developed to calculate arc current, incident energy (IE), and arc flash boundary (AFB), as well as the implementation of the enclosure size factor [3].

For the application of the guide's methodology, it is necessary to determine the input parameters presented below. Furthermore, it is mandatory to perform a short-circuit study, as it is necessary to calculate the current bolted fault (Ibf), and to calculate it, the value of the short-circuit current is required and found through this study. A selectivity study is also important to obtain the protection operating time and, through it, the arc duration [7]. The main input parameters for the arc flash tests used in IEEE 1584 are defined below.

- Open-circuit voltage or nominal test voltage (Voc): Voltage that determines the electrode spacing, which must be considered to prevent the occurrence of an electric arc.

- Short-circuit current or bolted fault current (Ibf): Corresponds to a short-circuit condition with zero impedance at the fault point (or where the assumed impedance is zero). This is the current observed during an electric arc event.

- Arc duration time (Tarc): is the time interval between the initiation of the short-circuit and its total interruption, which is the arc detection time summed with the opening time of the protective device that, after opening, interrupts the fault. Since incident energy is directly proportional to the arc duration time, this is a fundamental parameter for the mathematical model of the IEEE 1584 standard.

- Gap (G): The spacing between electrodes used to prevent electric arcs in real-world applications for a given Voc value.

• Electrode configuration: there are horizontal, vertical configurations and their respective variations, which are used by the IEEE 1584 standard for arc flash tests. Fig. 2 shows the configurations analyzed in the standard, and Table 1 details the meaning of the characteristic acronyms for each configuration.

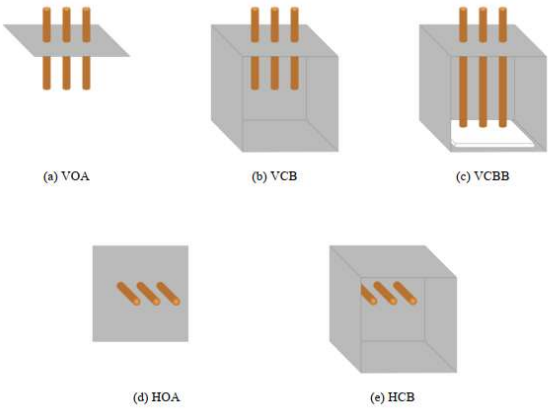


Fig. 2. Electrode Configurations [10]

TABLE 1. DEFINITION OF IEEE 1584-2018 STANDARD ELECTRODE CONFIGURATIONS

Electrode Configuration	Acronym Meaning	Configuration Definition
a. VOA	Vertical conductors/electrodes in Open Air	Vertical conductors/electrodes in open air, in an open environment
b. VCB	Vertical conductors/electrodes inside a Cubic Box	Vertical conductors/electrodes inside a metallic enclosure
c. VCBB	Vertical conductors/electrodes terminated in a insulating Barrier inside a Cubic Box	Vertical conductors/electrodes terminated with an insulating barrier inside a metallic enclosure
d. HOA	Horizontal conductors/electrodes in Open Air	Horizontal conductors/electrodes in open air
e. HCB	Horizontal conductors/electrodes inside a Cubic Box	Horizontal conductors/electrodes inside a metallic enclosure

- Working distance: the distance between the arc source and the worker's face or torso.
- Enclosure: the presence and dimensions affect calculations since energy is more dispersed in open air and more concentrated in enclosed environments.

To apply the IEEE Std 1584-2018 method, 11 steps can be followed [11]:

1. Gather system and installation data;

2. Define system operating modes (Voc, protection settings, etc.);

3. Determine three-phase bolted fault current (Ibf);

4. Define electrode gap and enclosure dimensions based on equipment class and voltage;

5. Define electrode configuration;

6. Define working distance;

7. Calculate arc current and reduced arc current per the method;

8. Estimate arc duration per the method;

9. Calculate IE per the method;

10. Calculate AFB;

11. Choose the higher IE and AFB values for conservative analysis.

Given these steps, the refinement of the method is observed, which, with extensive equations, combined with a greater quantity of calculations whose manual solution is unfeasible, made the use of electronic spreadsheets or other specific computational tools necessary for the calculation. Therefore, for this reason, to encourage and disseminate the importance of studying incident energy beforehand, without complicating it with the use of software with paid or specialized licenses, a spreadsheet was developed in Microsoft Excel with the aim of enabling and facilitating the calculation of incident energy and making the obtaining of results more practical and accessible. It is worth adding that it is not the objective of this work to reproduce all the information and exceptions of the standard, and it is not dedicated to a demonstrative study of the IEEE Std 1584-2018 equations, but rather to evaluate the importance of the study and the changes in variables or assumptions that affect the model's results and to present the spreadsheet created for this purpose, through which the IE values, according to the standard's mathematical model, are calculated.

It is important to mention that in the context of electrical safety and arc flash protection, it is crucial to distinguish between the purposes of IEEE 1584 and NFPA 70E. While IEEE 1584 is a standard that provides methods for calculating incident energy and the arc flash protection boundary, NFPA 70E, "Standard for Electrical Safety in the Workplace," is the standard that establishes requirements for safe work practices and the selection of personal protective equipment (PPE) based on arc flash risk categories. Therefore, the risk categories mentioned in this article directly refer to the definitions and guidelines established by NFPA 70E, which are fundamental for determining appropriate protective clothing, and not to the incident energy calculation methodologies of IEEE 1584.

B. System Overview

Sensitivity analysis is a method used to determine the most influential factors in a system [12]. In other words, it is a technique that assesses how changes in variables or assumptions affect the results of a model or system and aims to estimate the outcomes produced by variations in these parameters.

To apply the developed spreadsheet and perform a sensitivity analysis that can evaluate the effects of changing important variables in incident energy calculation, a low-voltage Motor Control Center (MCC) was considered, defined as a switchgear and control assembly that is usually fed by the substation's input transformer and feeds other larger panels and motors. It can be identified by its more robust structure, with the common existence of two input cubicles, one interconnection cubicle, and multiple outputs. The cubicles are usually equipped with open circuit breakers and a

protective relay [13]. Fig. 3 shows, as an example, the front view of an MCC.

Fig. 3. Load distribution center [14]

Additionally, combined with the circuit breaker, an additional protection function with different operating times was considered, as presented in Table 2. The elements considered were: an arc relay, which detects and acts quickly on arc flash faults; logical selectivity, which ensures the coordinated operation of protective devices, isolating only the faulty section of the system; and an Energy Reducing Maintenance Switch (ERMS), a device designed to temporarily reduce incident energy levels during maintenance operations on electrical panels, aiming to increase operator safety.

TABLE 2. PROTECTION DEVICES AND THEIR OPERATING TIMES

Protection devices	**Operating times**	
	Minimum operating time	***Maximum operating time***
Arc-flash relay [15] + circuit breaker [16]	51	84
Zone-selective interlocking (ZSI) [17] + circuit breaker [16]	54	113
ERMS (Energy Reducing Maintenance Switch) [18] + circuit breaker [16]	75	133

The determination of arc duration must be performed based on the operating time of the system's protections. The arc current interruption time is the sum of the protection sensing time and the physical opening time of the equipment, in this case, a circuit breaker. It is often necessary to consult the manufacturer's manual, or it is permissible to use typical values in the absence of specific literature.

In addition to these requirements, the main low-voltage nominal values used in the industry were considered: 220 V, 380 V, 440 V, and 690 V. The same criterion was applied to the nominal power values: 75 kVA, 300 kVA, 500 kVA, 1 MVA, and 2 MVA. The enclosure dimensions were the largest dimensions of a low-voltage MCC (Motor Control Center) from WEG, based on its datasheet [13], which are: height 2300 mm, width 1400 mm, and depth 1200 mm. These dimensions refer to the complete compartment, considering all columns. An MCC of these dimensions was considered so that, being the largest, it would result in higher IE values and allow for a more critical scenario for analysis. The nominal current and impedance were calculated according to the other characteristics of each case and were used in the calculation of the bolted fault current.

In the context of incident energy analysis according to the IEEE 1584-2018 standard, it is crucial to highlight the limitations of the spreadsheet calculations. Primarily, these calculations do not accommodate scenarios with multiple short-circuit sources. The study was conducted with the assumption of a single source, focusing on the busbar as the main area of analysis. Everything beyond the busbar is considered as an equivalent power source using Thevenin's theorem. Therefore, the analysis is confined to the interior of the panel, excluding considerations such as single-line diagrams or external impedances.

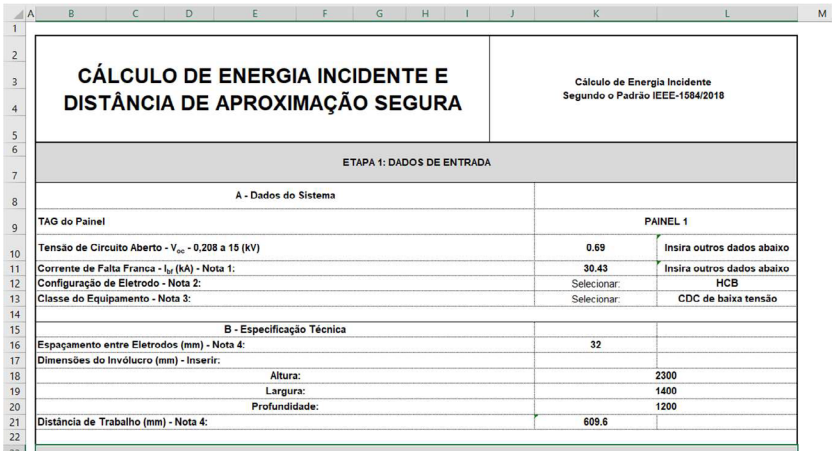
C. Spreadsheet for Calculations

To make the tool more accessible to its target users (industrial workers where IE studies apply), the incident energy calculations were implemented in Microsoft Excel. Required inputs include:

- Panel TAG;
- Open circuit voltage (Voc);
- Bolted fault current (Ibf);
- Electrode configuration (VCB, VCBB, HCB, VOA, HOA);
- Equipment class;
- Enclosure dimensions;
- Arc duration for Iarc and Iarc_min (min/max protection operating times).

With these inputs, the spreadsheet outputs arc current and minimum arc current, incident energy in cal/cm², arc flash boundary in mm, and system risk category.

Fig. 4 provides an overview of the developed spreadsheet, featuring fields related to input data.



CÁLCULO DE ENERGIA INCIDENTE E DISTÂNCIA DE APROXIMAÇÃO SEGURA		Cálculo de Energia Incidente Segundo o Padrão IEEE-1584/2018
ETAPA 1: DADOS DE ENTRADA		
A - Dados do Sistema		
TAG do Painel	PAINEL 1	
Tensão de Circuito Aberto - V_{oc} - 0,208 a 15 (kV)	0.69	Insira outros dados abaixo
Corrente de Falta Franca - I_{bf} (kA) - Nota 1:	30.43	Insira outros dados abaixo
Configuração de Eletrodo - Nota 2:	Selecionar:	HCB
Classe do Equipamento - Nota 3:	Selecionar:	CDC de baixa tensão
B - Especificação Técnica		
Espaçamento entre Eletrodos (mm) - Nota 4:	32	
Dimensões do Invólucro (mm) - Inserir:		
Altura:	2300	
Largura:	1400	
Profundidade:	1200	
Distância de Trabalho (mm) - Nota 4:	609.6	

Fig. 4. Overview of Excel Table

If the input data—particularly voltage and current—fall outside the ranges defined by the standard, the spreadsheet is programmed to notify the user that the values do not meet the required specifications, prompting them to enter valid alternatives.

Additionally, the electrode configuration and equipment class are selected via drop-down menus that display only the valid options for each field. The remaining cells, which contain the formulas and calculated results, are locked for editing, ensuring that the user can modify only the necessary input fields required to generate the results.

Fig. 5 provides an overview of the developed spreadsheet, featuring fields related to input data for arc duration and generated results, which include: arc current, minimum arc current, incident energy in J/cm² and cal/cm², safe approach limit, and risk category according to NFPA 70E. These enable the study of the necessity for protective measures or controls to reduce the energy values found.

ETAPA 2: ESTIMATIVA DAS CORRENTES DE ARCO MÁXIMA E MÍNIMA E DADOS DE ENTRADA		
Corrente de Arco - I_{arc} (kA)	23.621	
Duração do Arco para I_{arc} (ms) - Nota 5:	Inserir:	75
Corrente de Arco Mínima - I_{arc_min} (kA)	20.675	
Duração do Arco para I_{arc_min} (ms) - Nota 5:	Inserir:	133
RESULTADOS		
Energia Incidente - E (J/cm²)	35.351	
Energia Incidente - E (cal/cm²)	8.449	
Limite de Aproximação Segura (mm)	1619	
Categoria de Risco	3	

Fig. 5. Overview of Excel Table section results

The validation of the spreadsheet developed for calculating incident energy and the arc flash safe boundary, in accordance with IEEE 1584-2018, was performed by comparing the results obtained with those from an online arc flash calculation software. For each scenario analyzed in the spreadsheet, the input data were entered into the "Arc Flash Online Calculator" to verify the consistency of the incident energy values and protection boundaries. This approach allowed confirming the accuracy of the calculations implemented in the spreadsheet, ensuring the reliability of the results presented in this article.

III. RESULTS AND ANALYSIS

This section presents the results obtained from the analysis of incident energy and arc flash boundary, carried out using a Microsoft Excel spreadsheet developed in accordance with the methodology described in the IEEE Std 1584-2018 Guide.

Table 3 below shows the highest and lowest values obtained, as well as the open-circuit voltage, nominal power, electrode configuration, arc duration and risk category.

The transformer impedance value was 5.5% in all cases.

TABLE 3. LOWERS AND HIGHER VALUES OF ARC-FLASH HAZARD AND BOUNDARY

Lowers and higher values								
Power (kVA)	**Voc (V)**	**Ibf (kA)**	**Electrode Configuration**	**Arc duration (ms)**	**Iarc (kA)**	**EI (cal/cm²)**	**AFB (mm)**	**Category**
75	690	1,14	VOA	51	0,76	0,37	284,58	1
75	220	3,58	HCB	75	1,43	3,31	1005,14	1
300	690	4,56	VOA	54	10,48	0,32	262,18	1
300	220	14.31	HCB	75	6,05	2,29	838,53	1
500	690	7,61	VOA	51	5,49	0,39	296,14	1
500	220	23,86	HCB	75	9,96	3,48	1029,55	1
1000	690	15,21	VOA	51	11,14	0,82	474,44	1
1000	380	27,63	HCB	75	16,91	5,56	1297,55	2
2000	220	95,43	VOA	51	16,75	1,19	607,26	1
2000	440	47,72	HCB	75	27,73	8,61	1609,12	3

- In general, there was a direct relationship between IE and power, meaning that increased power typically resulted in increased EI. A notable exception was observed in the transition from 75 kVA to 300 kVA, where the incident energy decreased;
- In contrast, EI showed an inverse relationship with nominal voltage for the same power: the higher the voltage, the lower the incident energy, except for 1 and 2 MVA, whose specifics are analyzed below;
- The arc duration also exhibited a direct relationship with EI, with incident energy increasing as arc duration increased. An exception was noted for 300 kVA power, where the arc duration of 54 ms resulted in the lowest incident energy value, as presented in Table 3;
- Regarding electrodes configurations, the VOA (Vertical Open Air) configuration showed the lowest incident energy values, while the HCB (Horizontal Closed Box) resulted in the highest. This is because, in the VOA configuration, most of the radiated energy is directed downward, while the remaining thermal energy propagates equally in all surrounding directions. In closed configurations like HCB, the released energy tends to concentrate at the front of the panel, and the arc will be projected towards the worker, assuming they are in the direction of the busbars, and in the case of HCB, the enclosure effect adds up, resulting in higher incident energy values [10].

Besides general trends, important peculiarities are observed in specific scenarios, as presented and detailed below.

TABLE 4. LOWEST AND HIGHEST INCIDENT ENERGY VALUES FOR 75 AND 300 KVA

Lowest and highest incident energy values for 75 and 300 kVA					
Vnom (V)	**Power (kVA)**	**Electrode Configuration**	**Arc duration (ms)**	**IE (cal/cm²)**	**AFB (mm)**
220	75	VOA	51	0,61	399,88
	300	VOA	51	0,42	316,11
	75	HCB	75	3,31	1005,14
	300	HCB	75	2,29	838,53
380	75	VOA	51	0,56	377,01
	300	VOA	51	0,36	289,32
	75	HCB	75	2,96	951,00
	300	HCB	75	1,96	775,69
440	75	VOA	51	0,53	364,06
	300	VOA	51	0,34	278,76
	75	HCB	75	2,77	921,20
	300	HCB	75	1,83	750,83
690	75	VOA	51	0,37	284,58
	300	VOA	54	0,32	262,18
	75	HCB	75	2,34	848,26
	300	HCB	75	1,57	694,59

- For 300 kVA systems, incident energy values decreased in all cases compared to 75 kVA, as presented in Table 4;
- In the scenario with 690 V and 300 kVA, the highest incident energy value was observed for an arc duration of 51 ms, not 75 ms, as shown in Table 3;
- Table 5 shows that for 500 kVA systems in the HOA configuration and arc duration of 51 ms, incident energy values were very close across all tested voltages.

TABLE 5. INCIDENT ENERGY FOR 500 KVA POWER, HOA BUSBAR AND ARCING TIME 51 MS

Power (kVA)	**Vnom (V)**	**Electrode Configuration**	**Tarc (ms)**	**IE (cal/cm²)**
500	220	HOA	51	1,07
	380	HOA	51	1,08
	440	HOA	51	1,05
	690	HOA	51	1,00

The AFB results, being directly related to incident energy, showed similar trends. However, some specific observations deserve attention:

- In 1 MVA systems, the largest safe approach distance occurred at 380 V.
- For 300 kVA systems, the shortest safe approach distance was recorded at 54 ms.
- The safe approach distance decreased when comparing 300 kVA systems to 75 kVA systems, as presented in Table 4, an observation that requires further analysis of system characteristics at this point, corresponding to the EI conclusion for these values.

For 1 MVA systems, incident energy analysis revealed notable peculiarities:

- It was observed that the risk category remained at 2 for all values in the HCB configuration, considering arc durations of 54 ms and 75 ms;
- At this power, the highest incident energy value was recorded at 380 V, not 220 V, while the lowest occurred at 690 V;
- It is crucial to note that for 1 MVA, the relationship between incident energy and voltage did not remain consistent in a single order. Instead, the order of voltage values for incident energy (from lowest to highest EI value) varied according to busbar configuration:
    - For horizontal busbar configurations (HCB and HOA), the order was: 220 V – 690 V – 440 V – 380 V;
    - For vertical busbar configurations (VCB, VCBB, and VOA), the order was: 690 V – 220 V – 440 V – 380 V.

Regarding the relationship between incident energy and voltage for 2 MVA systems, analyzing the order of voltage values in different busbar configurations reinforces the complexity of the phenomenon. Regardless of arc duration (51 ms, 54 ms, or 75 ms), the order of voltage values for incident energy showed specific patterns for each electrode configuration:

- HCB: The order was 220 V – 380 V – 690 V – 440 V;
- HOA: The order was 220 V – 380 V – 440 V – 690 V;
- VCB: The order was 690 V – 220 V – 380 V – 440 V;
- VCBB: The order was 220 V – 690 V – 380 V – 440 V.

Table 6 presents incident energy values according to busbar and presented voltage order for the three studied arc durations.

TABLE 6. IE FOR 1 AND 2 MVA

Arc Duration (ms)	Electrode Configuration	IE (cal/cm²)	
		1 MVA	2 MVA
51	HCB	3.15 - 3.27 - 3.38 - 3.51	3,60 – 5,24 – 5,34 – 5,44
	HOA	1.61 - 1.85 - 1.86 - 2.04	2.02 - 2.82 - 2.96 - 3.28
	VCB	1.04 - 1.65 - 1.67 - 1.76	1.69 - 1.99 - 2.64 - 2.69
	VCBB	1.98 - 2.19 - 2.28 - 2.43	2.42 - 3.40 - 3.74 - 3.86
	VOA	0.82 - 0.96 - 1.03 - 1.06	1.19 - 1.36 - 1.62 - 1.68
54	HCB	4.24 - 4.39 - 4.55 - 4.73	4.85 - 7.06 - 7.18 - 7.31
	HOA	2.16 - 2.49 - 2.50 - 2.74	2.72 - 3.80 - 3.99 - 4.41
	VCB	1.40 - 2.22 - 2.25 - 2.36	2.28 - 2.68 - 3.55 - 3.62
	VCBB	2.66 - 2.95 - 3.07 - 3.27	3.25 - 4.57 - 5.04 - 5.19
	VOA	1.11 - 1.29 - 1.38 - 1.42	1.60 - 1.83 - 2.18 - 2.26
75	HCB	4.99 - 5.17 - 5.35 - 5.56	5.71 - 8.30 - 8.45 – 8,61
	HOA	2.55 - 2.93 - 2.94 - 3.22	3.20 - 4.47 - 4.69 - 5.19
	VCB	1.65 - 2.62 - 2.65 - 2.78	2.68 - 3.16 - 4.18 - 4.27
	VCBB	3.14 - 3.47 - 3.61 - 3.85	3.83 - 5.38 - 5.93 - 6.11
	VOA	1.30 - 1.52 - 1.63 - 1.68	1.89 - 2.15 - 2.57 - 2.66

These specifics show that the physical arrangement of busbars significantly influences how arc energy is distributed and manifested at different voltage levels, with busbar geometry and voltage being dominant factors in determining the relative order of EI values among voltages, particularly at higher power levels. This suggests that at elevated power levels, other factors become more influential, altering the predictability of direct or inverse relationships with voltage. Therefore, determining incident energy becomes more complex and less linear.

The interactions between voltage, busbar configuration, and arc duration generate behavior that deviates from direct relationship rules, emphasizing the importance of considering the physical layout of the panel in design and risk analysis, as well as rigorous attention to risk mitigation. Figures 5 and 6 present graphs, generated in MATLAB, showing incident energy values and safe arc limits, respectively, for powers of 300, 500, 1000, and 2000 kVA, as a function of nominal voltage and arc duration. It is important to note that in the incident energy graph, results with risk categories (RC) of 2 and 3 are highlighted using filled markers.

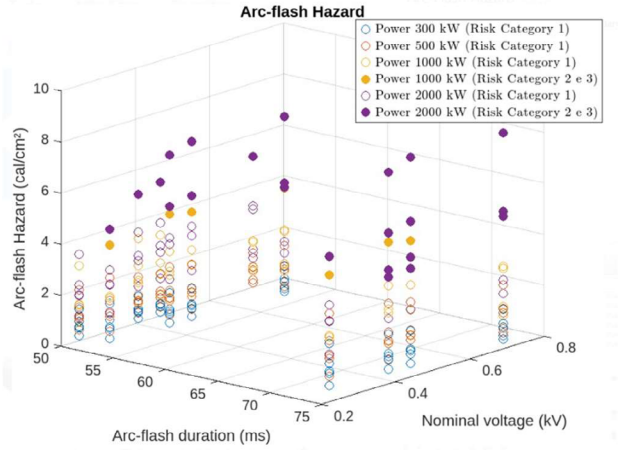


Fig. 6. Arc-flash hazard result values

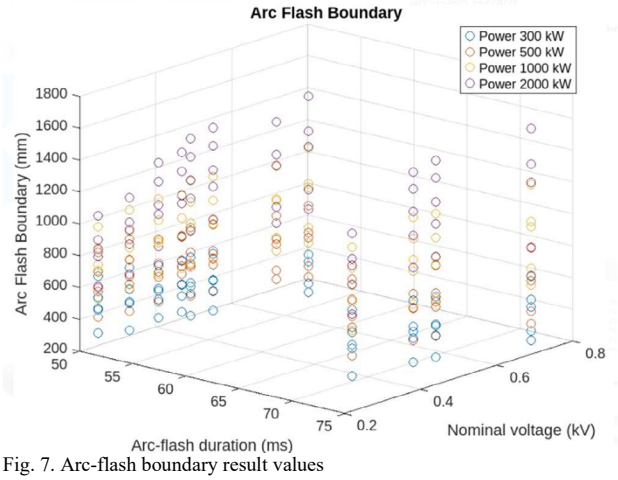


Fig. 7. Arc-flash boundary result values

The results presented in this study highlight a fundamental characteristic of the IEEE Std 1584-2018 Guide: its model for calculating incident energy is empirically derived. This empirical nature implies that the relationships between input variables (nominal voltage, power, arc duration, electrode configuration) and incident energy results and safe approach distance do not always follow a simple direct relationship.

This was clearly demonstrated by the presented results: the order of voltage values for incident energy did not maintain a consistent inverse relationship for all busbar configurations, changing in each case. The observation that for 300 kVA, the shortest distance was at 54 ms, despite the general rule of direct relationship with arc duration, is another example of how the empirical model can generate counterintuitive results at first glance.

This lack of "obviousness" in the results is the main reason highlighting the critical importance of conducting a detailed and preliminary incident energy study in electrical projects, especially in low-voltage panels. Companies that neglect this calculation or perform it inadequately risk using PPE with inappropriate category or excessively high protection level.

Therefore, the analysis of the obtained results reiterates the

need to apply computational tools, such as the developed spreadsheet, to calculate incident energy and safe approach distance, ensuring that control measures and PPE selection are optimized and based on accurate data, not assumptions that may be flawed due to the empirical complexity of the arc phenomenon.

IV. CONCLUSION

This study investigated the analysis of incident energy and safe arc limits in low-voltage panels using the IEEE Std 1584-2018 Guide methodology and a spreadsheet developed in Microsoft Excel. The main objective was to emphasize the importance of conducting these calculations in advance in electrical projects to apply efficient control measures and appropriately select Personal Protective Equipment. The relevance of this study is underscored by the severity of arc flash accidents, which can result in fatalities and irreversible injuries, and the persistent neglect in its proper analysis despite evolving standards and technical knowledge.

The results obtained from applying formulations in the Microsoft Excel spreadsheet, according to technical recommendations of IEEE Std 1584-2018 for various powers, voltages, arc durations, and busbar configurations, corroborate the empirical nature of the model, derived from an extensive volume of real tests. Specific results demonstrate that estimates from the empirical model can exhibit complex and non-linear behaviors, which are only revealed through detailed calculation.

The short-circuit current directly influences the magnitude of incident energy during an electrical arc due to its relationship with the power dissipated in the event. When an electrical arc occurs, the short-circuit current flows through the plasma formed, leading to a rapid release of thermal and luminous energy. Consequently, a high short-circuit current increases the arc's temperature and pressure, which significantly raises the risk of burns and equipment damage.

Therefore, the main conclusion of this work is the indispensability of detailed incident energy analysis in low-voltage panel projects. The omission or inadequate execution of these calculations, due to the complexity of the method, can lead to two equally dangerous situations: the use of PPE with insufficient protection, exposing workers to risks of serious accidents and severe burns, or the use of excessively protective and uncomfortable PPE, which, although safe, may discourage proper use and compromise safety.

The ability to predict incident energy levels with technical rigor, even with results that do not follow an "obvious" linear logic, is crucial to ensuring worker safety and optimizing costs with PPE and protective measures, preventing the need for costly retrofits.

The study reiterates that the use of computational tools, such as the developed spreadsheet, is important to navigate the complexity of the IEEE 1584-2018 standard and obtain data close to reality, enhancing safety in the industrial electrical environment. In these cases, the presented fundamentals are essential for choosing configurations and parameters that will allow better estimation of incident energy.

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Best Industrial Practices Applied as Control Measures to Reduce Incident Energy at Vale's Sol do Cerrado Plant

Filipe Barcelos Resende
Segurança Ocupacional
Vale
Belo Horizonte, Brazil
filipe.resende@vale.com

Henrique Fantoni Primo
Power System Studies
SM&A Electrical Systems and Automation
Belo Horizonte, Brazil
henrique.fantoni@sma-eng.com.br

Anna Arantes Junqueira
Power System Studies
SM&A Electrical Systems and Automation
Belo Horizonte, Brazil
anna.junqueira@sma-eng.com.br

Paulo Henrique Vieira Soares
Eng. de Projetos de Automação
Vale
Belo Horizonte, Brazil
paulo.henrique.v.soares@vale.com

Igor Araujo Camargos
Power System Studies
SM&A Electrical Systems and Automation
Belo Horizonte, Brazil
igor.camargos@sma-eng.com.br

***Abstract*—Given the growing adoption of renewable energy sources, understanding how this new energy matrix works is becoming increasingly important. In the case of solar plants, calculating the incident energy on inverter panels requires dividing it into two segments: alternating current (ac) and direct current (dc). Each of these segments requires specific calculation methods, which will be briefly discussed, with the final incident energy of the panel corresponding to the highest value obtained.**

In order to ensure a high level of safety for its employees, VALE has established an internal procedure that aims to establish an incident energy limit of 8 cal/cm² for any electrical panel (clothing with an ATPV of around 8 cal/cm² is single-layer clothing, which ensures better comfort for workers). However, incident energy limitation is not commonly adopted in solar plants, therefore, the application of good mitigation practices consolidated in the industry becomes essential.

In this context, this article presents four possible engineering control measures to reduce the incident energy in an inverter panel at VALE's Sol do Cerrado photovoltaic plant, presenting the values obtained before and after the adoption of these solutions. The addressed strategies include: intentional miscoordination of conventional overcurrent protections, installation of arc protection relays, modification of the topology of the panel's direct current system and, finally, inclusion of direct current circuit breaker panels in addition to the installation of arc protection relays in the inverter panels.

Through the combined implementation of some of these measures, it is possible to mitigate the final incident energy on the inverter panel, ensuring increased safety for operators and equipment during the occurrence of an electric arc.

Keywords*—*incident energy, control measures, photovoltaic plant, direct current, invert panel

I. INTRODUCTION

Considered one of the largest solar energy parks in Latin America, with an installed capacity of 766 Megawatts-peak, equivalent to the consumption of a city with 800,000 inhabitants, the Sol do Cerrado (SDC) project is part of VALE's strategy to reduce CO_2 emissions to zero by 2050. It has been in operation since July 2023 and has the capacity to generate approximately 16% of all the energy consumed by VALE in Brazil. In total, there are 17 photovoltaic plants, which are connected to Brazil's interconnected electrical system via the Jaíba Substation, through two 340 MVA transformers (230 - 34.5 - 34.5 kV).

The purpose of this paper is to present the best industrial practices applied as control measures to reduce incident energy in VALE's Sol do Cerrado project, considering recommendations presented in the new ABNT NBR 17227 standard [1].

Initially, a summary of the Safety Standards used in VALE's industrial plants and the methods used to calculate the incident energy on alternating current and direct current systems will be described.

Next, the case study involving the AC and DC systems of the plant's inverter panels will be delineated, showing their characteristics, the comparison between the results obtained and the final incident energy.

To mitigate the magnitude of the final incident energy, which was calculated for the inverter panels of the photovoltaic plant, four alternatives of engineering control measures will be analyzed: intentional miscoordination of conventional overcurrent protections, installation of arc protection relays, modification of the topology of the direct current system of the panel and, finally, inclusion of direct current circuit breaker panels along with the installation of arc protection relays in the inverter panels.

Through the combined implementation of some of these measures, it will be possible to mitigate the incident energy on the inverter panel to values below the limit of **8 cal/cm²**, defined in PNR-000051 [2] for VALE's industrial systems, ensuring, during the occurrence of an electric arc, increased safety for operators and equipment.

II. Safety Standards

VALE is a global company that prioritizes the safety of people and the environment in its activities, with the following as its main value and commitment: "Life comes first" [3]. To ensure compliance with this requirement through the use of standard fire-resistant clothing, the company has internal guidelines such as PNR-000051 [2], the objective of which is to establish the minimum technical requirements necessary to guarantee a high level of safety for employees at its facilities, especially regarding incident energy and electric arc.

According to NFPA 70E [4], protective clothing for work on energized circuits must guarantee the protection of the user against high temperatures caused by the formation of electric arcs during a short-circuit. These garments must withstand the energy that falls on their external face to ensure that in the inner layer, the energy does not exceed 1.2 cal/cm², the limit supported by human skin for second-degree burns.

The ASTM F1959 technical standard [5] defined an indicator called ATPV (Arc Thermal Performance Value) to measure fabric performance and characterize arc flash protective clothing. The ATPV rating is the incident energy on a material or a multilayer system of materials that results in a 50 % probability that sufficient heat transfer through the tested specimen is predicted to cause the onset of a second-degree skin burn injury based on the Stoll curve. The ATPV value is determined by the process-corrected logistic regression curve, obtained through tests carried out by the manufacturer, considering the Stoll Curve (Thermal Energy X Time, produced from data on human tissue tolerance to heat, used to predict the onset of a second-degree skin lesion caused by a burn). The ATPV of VALE's standard fire-resistant clothing is 10.1 cal/cm², as reported by the manufacturer on Fig. 1. This value was defined by VALE and is a comfortable garment for continuous use that allows professionals to easily handle equipment.

Another fabric performance indicator was defined by the European Community in the technical standard IEC 61482-1-1 [6]. This indicator, called ELIM (Incident Energy Limit), is determined based on the ATPV test method, but uses the arithmetic mean of the three highest incident energy values immediately preceding the first evidence of a second-degree burn by heat transmission or rupture of the garment.

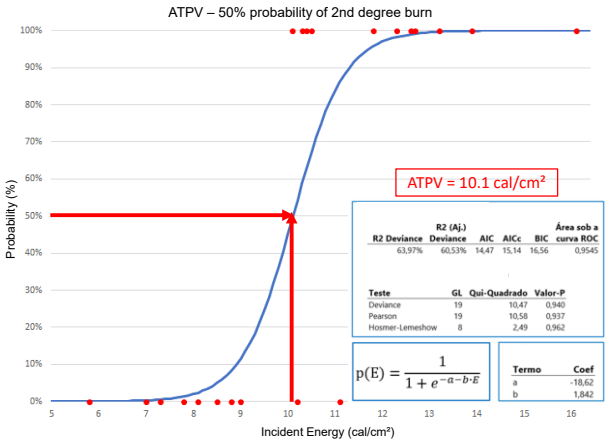

Fig. 1. ATPV curve of Vale standard clothing

Considering the results of the tests carried out according to ASTM F1959 technical standard [5], provided by the manufacturer, the calculated ELIM value of VALE's standard fire-resistant clothing is 8.8 cal/cm², as shown in Fig. 2.

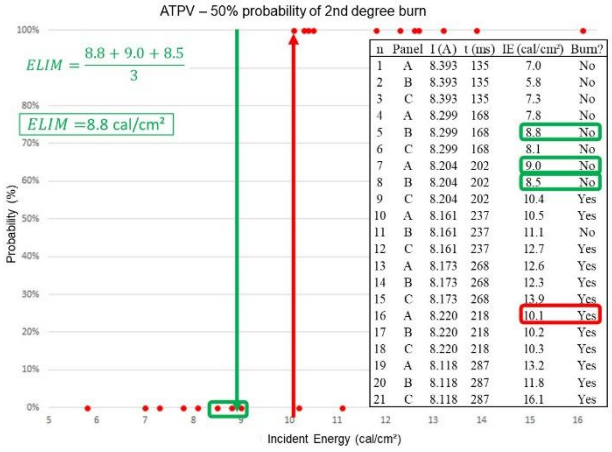

Fig. 2. ELIM calculation for Vale's standard fire-resistant clothing

Based on the values of the ATPV and ELIM indicators of the standard fire-resistant clothing and in order to guarantee the maximum safety of professionals, letter i) of item 6.1.1 of PNR-000051 [2] defines the following **Safety Standard** for industrial plants: "***The maximum permitted Incident Energy level*** *in the equipment, for all* ***VALE*** *operations, is* ***8 cal/cm²****, including the line and load side*".

III. Calculation Methodologies

The following items will briefly present the methodologies used to calculate the incident energy in AC and DC systems, respectively.

A. Alternating Current

The calculation of the incident energy for the 690 V system of the inverter panels was performed according to the method established by the IEEE 1584-2018 standard [7], whose equations are derived from statistical analyses based on a series of experimental tests. Since the IEEE 1584 methodology is already consolidated and well known by the scientific community, further details will not be covered.

B. Direct Current

Currently, there is no standardized methodology for calculating the incident energy of DC systems, especially for solar generation. Therefore, the calculations presented in this paper made use of a set of models already demonstrated and used by the scientific community.

The equivalent circuit model was based on the work of A. D. Stokes and W. T. Oppenlander [8], obtained through an exhaustive study of vertical and horizontal electric arcs between electrodes in open air. To apply this model to enclosures, the correction factors proposed by R. Wilkins, cited in the article by Ammerman [9], were used.

a) Calculation of Electric Arc Current and Resistance:

The paper written by A. D. Stokes and W. T. Oppenlander [8] resulted in the following equations:

$$I_t = 10 + 0.2 * Z_g \quad (1)$$

$$V_{arc} = (20 + 0.534 * Z_g) * I_{arc}^{0.12} \quad (2)$$

$$R_{arc} = \frac{(20 + 0.534 * Z_g)}{I_{arc}^{0.88}} \quad (3)$$

Where:

- Varc is the electric arc voltage in volts
- Iarc is the electric arc current in amps
- Zg is the gap between the conductors
- Rarc is the resistance of the electric arc in ohms
- It is the transition current

To solve these equations, an iterative solution must be used to determine the electric arc voltage and resistance, finding the optimal operating point of the system.

To determine the final value of the electric arc current, W. Sekulic [10] proposed that, for systems with solar generation, the iterative solution be used in conjunction with the current versus voltage (IV) characteristic curves of the photovoltaic panels, as shown in Fig. 3.

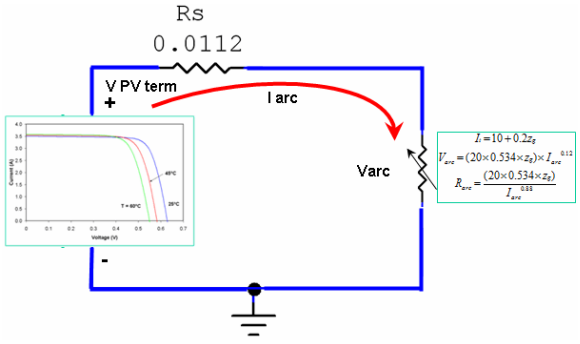

Fig. 3. Illustration of the solution criteria for Varc, Iarc and Rarc [10]

The iterations start by using the maximum short-circuit current of the modules and, for each current interval of the IV curve, the arc resistance is updated until the final solution is found [10].

b) Calculation of Electric Arc Power and Energy:

Considering the values of the current and resistance of the electric arc, the power value was calculated using the expression below:

$$P_{arc} = I_{arc}^{2} * R_{arc} \quad (4)$$

Where:

- Parc is the power of the electric arc in watts
- Iarc is the electric arc current in amps
- Rarc is the resistance of the electric arc in Ohms

Arc energy is a function of power and time and can be determined by:

$$E_{arc} = P_{arc} * t_{arc} \quad (5)$$

Where:

- Earc is energy in watts per second or Joules
- tarc is the duration of the electric arc in seconds

In enclosures, the energy behavior is different from the outdoor configuration, being directed outwards from the open end of the panel. Therefore, it was necessary to apply correction factors, through the methodology of R. Wilkins, cited in the article by Ammerman [9]:

$$E_i = k * \frac{E_{arc}}{(a^2 + d^2)} \quad (6)$$

Where:

- "d" is the working distance in mm
- "a" and "k" are correction constants defined by R. Wilkins [TABLE I.]

TABLE I. VALUES OF THE CONSTANTS "A" AND "K" DEFINED BY R. WILKINS

Optimal Values of "a" and "k"		
Enclosure type	***a (mm)***	***k***
Low voltage panel	100	0.127
Low voltage switchgear	400	0.312
Medium voltage switchgear	950	0.416

IV. CURRENT INCIDENT ENERGY

Below are the calculated values for the incident energy on the AC and DC systems of the solar plant's inverter panels.

A. AC System

In the AC system, the incident energy was calculated considering the methodology described in III.A, whose input data are presented below:

- Nominal voltage: 690 V
- Three-phase short-circuit current: 62.2 kA
- Electrode configuration: VCBB
- Enclosure width: 475 mm
- Enclosure height: 1100 mm

- Enclosure depth: 648 mm
- Distance between electrodes: 70 mm

The calculations considered the analysis points shown in Fig. 4 (before and after the 690 V circuit breaker).

If an electric arc occurs on the AC side of the 690 V photovoltaic inverters, there will be a contribution from the upstream system (34.5 kV) and from the solar panels (690 V). For an electric arc on the utility side (point 1 in Fig. 4), the current flow from the 34.5 kV system will be extinguished in 0.190 s (0.055 s circuit breaker opening + 0.135 s of 7SR51 overcurrent tripping time). After the 34.5 kV circuit breaker is turned off, the current flow from the solar panels (690 V) will have a maximum duration of 100 ms due to the tripping of the solar inverter's anti-islanding protection.

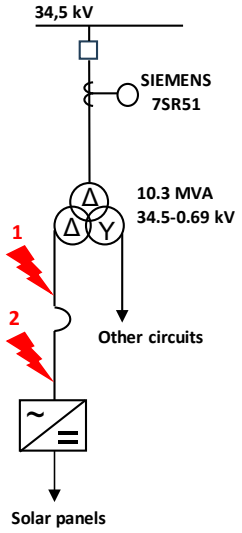

Fig. 4. Analysis points of the electric arc in the AC system.

In the event of an electric arc occurring on the solar panels side (point 2 in Fig. 4), the current flow from the 34.5 kV system will be extinguished in 0.04 s by the inverter panel main circuit breaker. In this case, the current flow from the solar panels (690 V) will not be interrupted since the voltage reference for inverter synchronization is obtained at a point which is upstream of the main inverter circuit breaker, therefore the anti-islanding protection will not be activated.

B. DC System

On the DC side, the incident energy was calculated considering the methodology described in 3.2, whose input data are presented below:

- Operating voltage: 1219 Vdc
- Arc voltage: 323.48 Vdc
- Fault current: 2451 A
- Arc current: 2451 A
- Constant “a”: 950 mm
- Constant “k”: 0.416
- Distance between electrodes: 200 mm

The calculations considered the analysis points presented in Fig. 5.

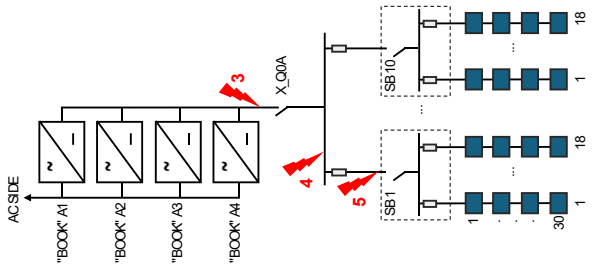

Fig. 5. Electric arc analysis points in the DC system of inverters.

If an electrical arc occurs on the DC side of the inverter panels, there will only be a contribution from the string boxes (the inverter does not convert AC to DC).

For an electric arc on the utility side (points 3 and 4 in Fig. 5), since no protective device will be sensitized (X_Q0A is a switch only), it was considered that the solar panels will contribute for 2 seconds (maximum typical time).

Also, for an electric arc on the side of a string box (point 5 in Fig. 5), it was considered that the current contribution from the faulted circuit will last for at least 2 seconds, since no protective device will be sensitized. In addition, the current contribution from the other string boxes will only be extinguished by the fuse in a time greater than 2 seconds.

C. Final Incident Energy

The incident energy on each of the systems (AC and DC) is shown in Table 2.

TABLE II. SUMMARY OF INCIDENT ENERGY LEVELS

System	Points of arc analysis	Incident Energy (cal/cm²)
AC	1	**21**
	2	**18**
DC	3, 4 and 5	**12**

Therefore, as the final incident energy of the plant's inverter panels (**21 cal/cm²**) is higher than the acceptable limit (8 cal/cm²), mitigation measures are necessary.

V. ALTERNATIVES FOR MITIGATION

The following items will present four proposed alternatives for mitigating incident energy on inverter panels.

A. Alternative 1 – AC System – Intentional Miscoordination

A possible solution to reduce the incident energy on the AC side is to reduce the current pickup of the instantaneous overcurrent function of the SIEMENS 7SR51 protective relay, feeding the 34.5/0.69 kV transformer, by miscoordinating it with the inverter panel incoming circuit breaker and reducing the tripping time from 0.135 s to 0 s. In addition, it is necessary to disable the instantaneous function of the low voltage circuit breaker.

Thus, regardless of the point at which an electric arc occurs (1 or 2 in Fig. 4), the current flow from the 34.5 kV system will be extinguished in 0.088 s (55 ms of circuit breaker opening + instantaneous tripping by the SIEMENS 7SR51 protective relay located in the primary of the 34.5/0.69 kV transformers + 20 ms of protective relay processing + 25 ms of function operation + 8 ms of contact operation). Additionally, due to the actuation of the solar inverter's anti-

islanding protection, the current flow from the solar panels (690 V) will have a maximum duration of 100 ms after the 34.5 kV circuit breaker is turned off.

This alternative reduces the incident energy to **10 cal/cm²** at analysis points 1 and 2 in Fig. 4.

B. Alternative 2 – AC System – Installation of Electric Arc Protection Relays

Another possible solution for the AC side (points 1 and 2 in Fig. 4) is the installation of arc protection relays on the inverter panels. A transfer trip is necessary to completely extinguish the electric arc, switching off the upstream circuit breaker (34.5 kV) and the photovoltaic inverters.

An arc protection relay with a typical tripping time of 7 ms was considered. For the opening times, the following values were adopted:

- Opening of medium voltage circuit breakers: 55 ms;
- Opening of low voltage circuit breakers: 40 ms;
- Switching of the inverter IGBTs in case of receiving an external trip: 40 ms (20 ms of signal processing at the digital input + 20 ms of safety time for equipment shutdown).

By adopting this solution, the incident energy is reduced to the values shown in TABLE III.

TABLE III. INCIDENT ENERGY LEVELS WITH ADOPTION OF ALTERNATIVE 2

System	Points of arc analysis	Incident Energy (cal/cm²)
AC	1	**6.52**
	2	**5.01**
DC	3 and 4	**12**
	5	**12**

C. Alternative 3 – DC System – Modification of the Topology of the Direct Current System

One of the alternatives for mitigating the incident energy on the DC side is to section inverter panel's internal busbar, eliminating the parallelism between the "books". Fig. 6 shows the current topology of this system and Fig. 7 shows the new topology with the changes in red.

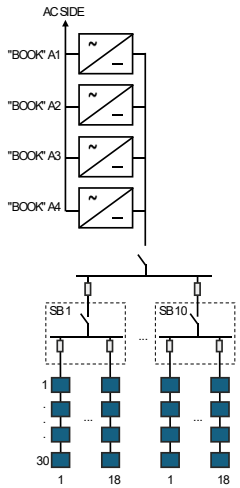

Fig. 6. Current topology of the DC side of solar inverters.

With this modification, it is necessary to purchase 2 new disconnect switches per inverter (set of 8 books).

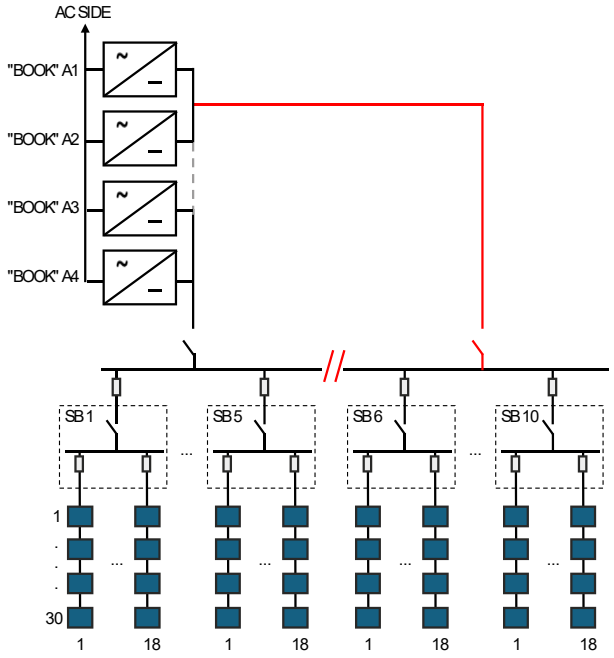

Fig. 7. Topology of the DC side of solar inverters with sectioning of the "books".

The possible electric arcs analyzed were the same as in item 4.2, but now the maximum current contribution in the worst case will come from only 5 string boxes. As a result, the short-circuit values will be lower, also reducing the incident energy on the DC side of the inverter panels. However, the tripping times will not change since the devices will either not be sensitized or the actuation will take longer than 2 seconds.

As a result, the incident energy on the DC side of the inverter panels is reduced to **5.70 cal/cm²**.

D. Alternative 4 – DC System – Inclusion of DC Circuit Breaker Panels

An alternative to reduce the incident energy levels on the DC side is to include a circuit breaker panel outside the e-house, containing 1 circuit breaker for every 5 string boxes, as shown in Fig. 8, totaling 2 circuit breakers for each set of 4 "books".

In addition to the new panel, it is necessary to purchase an arc protection relay for each set of 4 inverter "books", to be installed in the inverter panel, whose optical fibers must encompass the entire DC bus of both the inverter panel and the new circuit breaker panel, in addition to sending a trip signal to the new DC circuit breakers and to the inverters.

These new circuit breakers must be of thermomagnetic or adjustable type and have an opening coil ("shunt trip") to receive the trip signal from the arc protection relays.

The possible electric arcs analyzed were the same as in item 4.2, and at any of the points the arc protection relay will trip in a typical time of 7 ms and the opening time of the circuit breakers will be 50 ms.

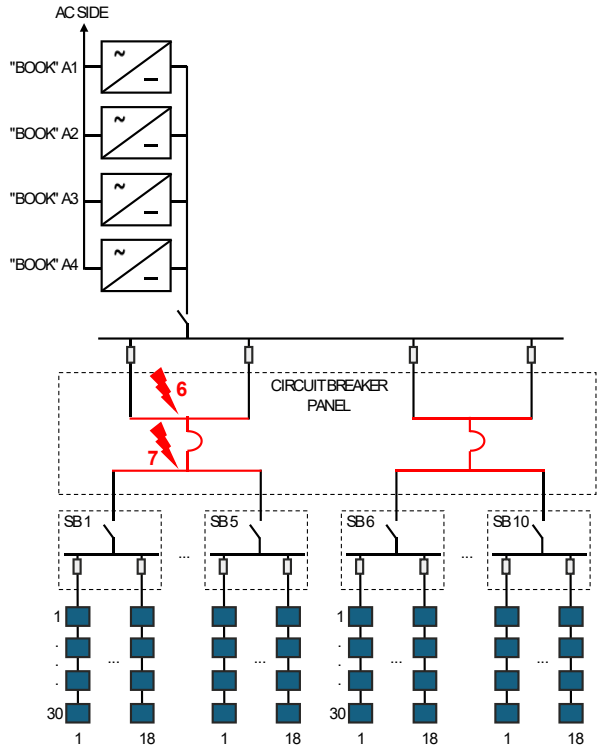

Fig. 8. DC circuit topology with inclusion of the circuit breaker panel.

In the event of an electric arc on the utility side of the circuit breaker panel (No. 1 in Fig. 8) the arc protection relay will also operate in 7 ms, with subsequent opening of the circuit breakers in 50 ms in addition to the inverters stopping the switching of the IGBTs in 40 ms after receiving the external trip. In the event of an electric arc on the solar panels side (No. 2 in Fig. 8), the arc protection relay will also operate in 7 ms and the inverter will stop switching after 40 ms, however the current contribution from the faulted string box and from the other string boxes connected to the same circuit breaker will not be extinguished since no device will be sensitized, adopting 2 seconds for the calculation.

By adopting this solution, the incident energy is reduced to the values shown in TABLE IV.

TABLE IV. INCIDENT ENERGY LEVELS WITH ADOPTION OF ALTERNATIVE 4

System	Points of arc analysis	Incident Energy (cal/cm²)
AC	1 (Fig. 4)	**21**
	2 (Fig. 4)	**18**
DC	3, 4 and 5 (Inverter Panel – Fig. 5)	**0.35**
	6 (Circuit Breaker Panel – Fig. 8)	**0.09**
	7 (Circuit Breaker Panel – Fig. 8)	**1.47**

E. Proposed Final Solution

Since there can be 690 Vac and 1500 Vdc in the same inverter panel compartment, the incident energy of these panels is always the highest between the AC system and the DC system.

Therefore, for the final incident energy to be less than 8 cal/cm², the proposed solution is the joint adoption of alternatives 2 and 4, which includes:

- Installing DC circuit breaker panels outside the e-house;
- Installing arc protection relays in inverter panels, with fiber optic loops running through:
  - All power compartments of inverter panels (AC and DC);
  - The circuit breaker panels outside the e-house.

The arc protection relay must send transfer trips to the 34.5 kV circuit breaker, to the DC circuit breakers and to the inverters, as detailed in items 5.2 and 5.4.

Fig. 9 shows a simplified single-line diagram indicating the fiber optic loops and the transfer trips required.

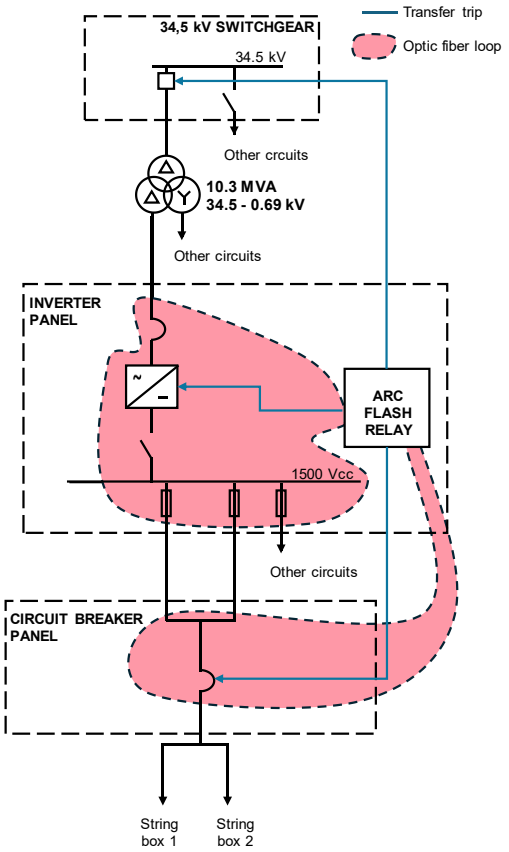

Fig. 9. Simplified single-line diagram – indication of fiber optic loops and transfer trips.

Applying the proposed solution, the final incident energy calculated for the inverter panel will be **6.52 cal/cm²**, as shown in TABLE V.

TABLE V. FINAL INCIDENT ENERGY

System	Points of arc analysis	Alternative	Incident Energy (cal/cm²)
AC	1 (Fig. 4)	2	**6.52**
	2 (Fig. 4)	2	**5.01**
DC	3, 4 and 5 (Inverter Panel – Fig. 5)	4	**0.35**
	6 (Circuit Breaker Panel – Fig. 8)	4	**0.09**
	7 (Circuit Breaker Panel – Fig. 8)	4	**1.47**

VI. Conclusion

The article initially presented a brief summary of the analyses that were carried out to define VALE's Safety Standards, considering the value of 8 cal/cm² as the maximum Incident Energy level allowed in the panels of its industrial plants, according to PNR-000051 [2]. It briefly presented the methodologies used to calculate the incident energy in AC systems, using the method established by the IEEE standard 1584-2018 [7], and DC systems, using the equivalent circuit model developed by A. D. Stokes and W. T. Oppenlander [8] and considering the correction factors proposed by R. Wilkins, cited in the article by Ammerman [9], for application in enclosures.

A case study was presented on the AC and DC systems of the inverter panels of VALE's Sol do Cerrado solar plant. The calculations in the AC system were performed considering the occurrence of a short circuit at two points, one before and one after the 690 V circuit breaker. In the case of the DC system, 3 points were analyzed, the first and second on the utility side and the third on the side of a string box. In all of these 5 points, the incident energy levels exceeded the limit of 8 cal/cm², reaching 21 cal/cm² at point 1 of the AC system.

In view of this result, four possible engineering control measures were proposed to reduce incident energy. The final solution adopted in this case study was the implementation of yet another engineering control measure, although not a common one. This measure involves the acquisition of a DC circuit breaker panel with an arc protection relay to be installed in the inverter panel. Thus, with the arc protection relay tripping the DC circuit breakers, the inverter and the 34.5 kV circuit breaker, the calculated incident energy level was 6.52 cal/cm², lower than the maximum value of 8 cal/cm².

It can be concluded that the article was successful in proving that, with the combined implementation of control measures, it is possible to mitigate the final incident energy in photovoltaic system inverter panels, ensuring the safety of operators and minimizing physical damage to the equipment in the event of an electric arc.

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Practical solutions to reduce high incident energy in the arc flash study

Claudio Sergio Mardegan
Engepower
Barueri, SP, Brazil
claudio.mardegan@engepower.com

Marcio Bottaro
University os Sao Paulo
São Paulo, SP, Brazil
marcio@iee.usp.br

Filipe Barcelos Resende
Vale S. A.
Belo Horizonte, MG, Brazil
filipe.resende@vale.com

Wendler Luis Nogueira Matos
Engepower
Barueri, SP, Brazil
wluis@engepower.com

***Abstract*—The Arc Flash study is essential for enhancing electrical safety by determining the appropriate personal protective equipment (PPE) required when accessing electrical panels. The standard that provides guidelines for the Arc Flash study is NFPA 70E. When calculating incident energy, this standard highlight various methods, with the choice depending on several factors, such as voltage level and whether the arc occurs within a panel or in open air. For voltage levels between 208V and 15kV, the IEEE 1584 calculation method is generally applied. Above 15 kV, if the arc occurs within a panel, extending the IEEE 1584 method can be considered. However, if the arc occurs in open air, Ralph Lee's method, EPRI, or NESC are used. When high incident energy values are identified, particularly in low-voltage industrial systems, certain mitigation techniques should be recommended in the Arc Flash study. As a best practice, if the incident energy exceeds 8 cal/cm², mitigation measures must be proposed. The following options should be assessed based on technical and economic criteria: adjusting the protective device settings, implementing a second set of settings, installing an arc protection relay, or utilizing an Arcing Quenching Device (AQD). Ultimately, if mitigation is not feasible, the panel should only be operated when de-energized. Therefore, it is crucial to apply the appropriate incident energy calculation method while also considering possible energy reduction strategies. To support engineers in selecting the most suitable approach for a given system, an Arc Flash study flowchart will be presented, comparing different solutions to minimize the risk of people injury and equipment damage.**

Keywords*—Arc flash, arcing fault current, incident energy, arc flash protection relay, arc flash hazards.

I. INTRODUCTION

Electrical arc flash is a dangerous phenomenon resulting from an uncontrolled electric arc between energized conductors or between conductors and ground. This event releases an intense burst of thermal energy, pressure shock waves, toxic gases, blast fragments and intense light that can cause severe injuries of operating personnel, permanent damage to equipment, costly damage of the switchgear and extended operational downtime [1]. The arc plasma can reach temperatures of up to 20,000ºC, leading to extreme heat and an abrupt rise in pressure inside the compartment / panel. Arc flash hazards represent one of the most critical threats to the safety of personnel working in or near energized electrical equipment, particularly in industrial and utility-scale power systems. It is necessary to carry out risk management, determining if additional protective measures are required, including use of PPE - Personal Protective Equipment [2].

The common causes of an arc flash are: aging of the equipment / insulation (higher risk for installations in service for tens of years), accumulation of moisture or dust, corrosion, bad cable terminations, loose busbar joints and also human errors, such as dropped tools or poorly performed maintenance [1]. Up to 80% of electrical incidents are caused by human error (based on review of OSHA incidents) [3].

Arc flash events pose one of the most severe hazards in electrical power systems. Studies indicate that thousands of workers are injured annually due to arc flash incidents, many of which involve high incident energy levels exceeding PPE capabilities. Arc flash incidents occur five to ten times each day, according to NFPA 70E [1].

The recognition of arc flash risks and the development of systematic methods to quantify and mitigate them have evolved significantly over the past decades. Early efforts focused primarily on overcurrent protection and basic PPE, but the increasing complexity of power systems required more sophisticated approaches. The introduction of the IEEE Std 1584 in 2002 provides the first widely accepted empirical model for calculating arc flash incident energy. Its 2018 revision introduced a more refined calculation method, incorporating new parameters such as enclosure size, electrode configuration, and gap between conductors, improving the accuracy of risk assessments [4]. Organizations such as the IEEE, the Occupational Safety and Health Administration, and the National Fire Protection Association are committed to improving worker safety, especially in protecting against arc flash hazards [5]. A timeline of the history of arc flash safety development can be made, since the publication of the NEC (National Electrical Code) in 1897, the Stoll curve in 1969, the creation of OSHA (occupational safety and health administration) in 1970, the elaboration of NFPA70E in 1979, the paper by Ralph H. Lee in 1982 [6], the first mention of arc flash within NFPA70E in 1995, the paper by R. L. Doughty, T. E. Neal and H. L. Floyd II in 2000 [7], IEEE1584 calculation method in 2002, and other important

dates until the revision of the IEEE1584 calculation method in 2018 [8].

Arc flash studies are now a core requirement for electrical safety compliance and risk management, particularly under NFPA 70E standards [9]. These studies aim to quantify the incident energy at different points in an electrical system, identifying areas where energy exceeds the thermal capability of available PPE or presents an unacceptable risk to workers. A critical factor influencing the results of these studies is the time-current coordination of protection devices. Systems designed for traditional coordination may allow longer clearing times, inadvertently increasing the energy released during an arc event. Therefore, coordination-while essential for service continuity-must be carefully balanced with arc flash mitigation strategies.

High incident energy levels, often exceeding 8 cal/cm^2, are not uncommon in low-voltage switchgear, motor control centers, and transformer secondaries. In such cases, PPE alone is not an adequate defense. While PPE forms the last line of protection, relying solely on it may expose workers to unacceptable risk, especially in high-energy zones. NFPA 70E explicitly encourages the use of engineering controls over administrative or PPE-based solutions. This drives the need for proactive methods that aim to reduce the energy at the source. If the calculated incident energy is greater than 40 cal/cm^2, it is not recommended to carry out the activity with the circuit energized, and it is necessary to turn off the system.

One of the two methods may be used for the selection of arc flash PPE:

1. The incident energy analysis method per 130.5 (G).
2. The arc flash PPE category method in per 130.7 (C)(15).

It is important to note that either method can be used, but not both, to assess the incident energy in a specific equipment. If the incident energy is calculated, the result cannot be used to select a PPE category from Table 130.7(C)(15)(c) [2].

Choosing the right PPE for the activity at a given energized electrical equipment is not an exact choice, but finding the most appropriate incident energy level and consequently the adequate PPE for each case is essential to increasing worker safety. Specifying a PPE with a larger or smaller ATPV – Arc Thermal Performance Value that is necessary, has its disadvantages. Using a higher level of PPE than is appropriate is undesirable, but safe. However, PPE can cause discomfort and increase the time required to perform the activity in this case. On the other hand, when an incident involving an electric arc occurs and it is discovered that the worker was using PPE that was not suitable for the incident energy level is not acceptable [2].

The IEEE 1584:2018 provides an empirical model to calculate incident energy, which forms the basis for risk assessment required by NFPA 70E. However, it is common to identify locations in the power system with dangerously high incident energy levels.

Several practical engineering solutions are available to reduce incident energy and improve personnel safety [10]. These include optimized relay settings to reduce fault clearing time, arc flash relays that detect light and current simultaneously to trip upstream breakers more quickly, and arc quenching devices that extinguish the arc within a few milliseconds by diverting the fault current into a low-impedance path, this consists in a controlled bolted connection of all 3 phases to earth potential [1]. The last method is an “active” strategy to avoid the negative impacts to the switchgear, to get a better system and process availability. Other strategies include implementing maintenance modes or zone-selective interlocking (ZSI) during work operations, using differential protection schemes, and system reconfiguration to shift fault contributions. Each of these techniques has its merits, cost implications, and applicability depending on system topology an operational constraint.

The Brazilian standard that deals with safety in working with electricity is NR-10 [11]. It establishes that workers must wear appropriate clothing to ensure safety. In this sense, the first version of the Brazilian standard that deals with electric arc and incident energy, ABNT NBR 17227:2025, was recently published and demonstrates the relevance of the topic in recent years [12].

This paper explores the engineering and protection solutions aimed at reducing energy levels to acceptable limits, enabling compliance and operational safety. Through analysis and case-based discussion, the paper aims to demonstrate how targeted engineering interventions can significantly improve safety outcomes and ensure compliance with industry standards. Emphasis is placed on balancing protection coordination with rapid fault clearing time and integrating modern arc mitigation technologies into existing systems. Techniques such as arc flash relays, arc quenching devices, and optimized coordination adjustments are discussed. We will discuss the typical causes of high incident energy, mitigation techniques with simulation examples, analysis the effectiveness of each solution, followed by conclusions and practical recommendations.

II. Incident Energy Calculation Methods

The IEEE 1584:2018 calculation method is widely used for systems with voltages between 208 V and 15 kV, for electrical arcs inside panels or open air. For medium voltage systems above 15 kV, extending the method can be considered for arcs in panels. However, if the electric arc is in open air, the Ralph Lee, EPRI or NESC method should be used. In general, Ralph Lee is more conservative, giving high energy results. The most appropriate method for each system must be evaluated, directly impacting the value of the calculated energy and the decision of incident energy reduction techniques. In industrial systems, the IEEE 1584:2018 calculation method is widely used. After 16 years of the first version, IEEE1584:2002, more than 1800 tests have been added to the 2018 version (the first version had about 300 tests). In addition, the 2002 version had two electrode configurations, while the 2018 version has five. It also has six enclosure sizes, compared to three in 2002. The equations are more complex to increase the accuracy of the method [13].

III. Techniques to Reduce High Incident Energy

The modeling of the electrical system in short-circuit, coordination and arc flash calculation programs must be done carefully and whenever possible with the real data of the equipment. Some considerations are as follows, in the case of generators, it is very important to have all the reactance data and time constants of the machine, as the decrement curve causes a reduction of the short-circuit current over time, contributes to the reduction of the incident energy. Cable

lengths is essential, longer cables increase impedance and reduces short-circuit current, possibly leading to longer fault clearing times and contributing to a higher incident energy. Motor modeling is important because they contribute to the fault current in the subtransient period. The correct representation of the circuit breaker curves is necessary, taking into account the error range in the fault clearing time, since in general commercial software use the longest fault clearance time, considering the curve's error margin [14].

The incident energy increases if the arc clearing time increases, and it also increases if the arc current value increases, for the same elimination time. In practical situations, coordination studies are often performed without considering the arc flash studies, that is, focusing on the elimination time of the bolted fault current. However, since the arc fault is lower, it is possible that the clearing time is not the same as that of the bolted fault and is in a region of inverse time curve, resulting in a high incident energy value. Therefore, to reduce the incident energy it is necessary to reduce either the value of the arc fault or the value of the arc clearing time [15]. Some techniques aimed at reducing incident energy will be discussed below. It is also important to emphasize the importance of using arc-resistant panels to increase protection for electrical equipment. Although this practice does not reduce the value of incident energy, it helps to prevent the burning of protection devices, busbars and panels.

A. Time-current coordination

The inverse time curves used in ANSI 51 time-delayed overcurrent protection work as follows: the lower the current value, the longer the fault clearance time. Since the arc fault current is lower than the bolted fault current, the actuation time can vary from a few cycles to more than one second, depending on the number of protective devices in the system and the coordination intervals between them. One way to reduce the arc fault clearing time is to use a definite time element in relays, or a short time delay element in circuit breakers, to ensure that the arc fault is cleared in the same time as a bolted fault, reducing the value of the calculated incident energy [16]. It is also an option to decide whether to accept losing coordination between protection devices, to prioritize reducing the arc clearing time. It is very important that the coordination study of a system is carried out together with the arc flash study, so that it is not necessary, after approval of the coordination study, to request changes to settings if high incident energies are found.

B. Logic coordination between relays

Logical coordination consists of interlocking the actuation of the protection relays. The pickup of the relay closest to the fault blocks the actuation of the upstream relay. The only relay that is not blocked is the one closest to the location of the short-circuit, sending a trip to the protection circuit breaker that must clear the fault. In the event of an opening failure, the trip must be sent to the upstream circuit breaker. Using this coordination, the fault clearing time can be reduced to about 100 ms [17].

C. Zone-Selective Interlocking (ZSI)

Logical coordination is known as zone selective interlocking at low voltage. Zone selective interlocking was developed as an equivalent of bus differential protection (87B) for low-voltage switchgear. It is an interesting option because it does not require the creation of procedures for workers to perform the activity. If the circuit breaker trip units have the ZSI function, the arc elimination time is guaranteed to be reduced [14]. The ZSI protection methodology is the creation of protection zones, and depending on which zone the short circuit occurred in, the upstream circuit breaker will be the only one to sensitized to the current, without having to wait for coordination time with the downstream circuit breaker, and can eliminate the fault in less time [5].

D. Maintenance mode

Maintenance mode is a way to reduce incident energy by changing the protective device's adjustment group. The objective is to reduce the time taken to clear an arc fault, in relation to the original time that guarantees the system's selective coordination. In other words, while the worker is performing the activity, the priority will be to eliminate the arc as quickly as possible, and not to ensure coordination. As soon as the activity is finished, the adjustment group returns to the original, whose priority is coordination. However, it is necessary to create procedures to teach workers how to make this change in the adjustment group, for example by changing the state of a switch on the panel door. However, there is a possibility that the worker will forget to change the setting and the arc fault clearing time will not be reduced, or that he will forget to return the switch to the original position, and the system will lose coordination in the event of a short circuit. [14].

E. Arc protection relay

Due to the high speed of light sensing, sensors have been applied to detect the light emitted during the electric arc and send trip signals to the protective devices. Optical fiber and point sensors are used to detect the light intensity [18]. Light and current monitoring relays can be used to quickly detect the electric arc, in times of the order of 1 - 2.5 ms, and send a trip signal to the circuit breaker upstream, resulting in a total arc clearing time of between 55 and 75 ms.

F. Arc Quenching Device (AQD)

There are arc quenching devices that create a bolted fault to mitigate the energy of the electric arc. These devices can extinguish the arc in times of the order of 1 to 5 ms. In this case, the system equipment, such as transformers, switchgears, generators and motors will be subject to three-phase short-circuit current [19].

G. Reduction of the fault current level

The previous techniques are based on reducing the fault clearance time, but it is also possible to reduce the incident energy by reducing the fault current value. Current limiting fuses, current limiting reactors and high-impedance transformers may be used to limit the available fault current [5]. The disadvantage of the reactor is that it must be well dimensioned so as not to cause a voltage drop in steady state that is harmful to the system [1]. These solutions must be used carefully, as reducing the arc current value may cause the protection to take longer to clear the fault.

IV. METHODOLOGY

The methodology adopted consists of modeling the electrical system and calculating short-circuit and arc-fault currents, then making protection and coordination adjustments between protective devices. Subsequently, some test scenarios will be simulated to evaluate techniques for reducing incident energy when values become high. The first

step in carrying out a short-circuit, selective coordination and arc flash study is to model the electrical system, representing components such as generators, transformers, cables, loads, buses and protective devices (circuit breakers, fuses and relays). The short-circuit current of the bolted fault and arc fault are calculated for the system buses. The electrical system was modeled using commercial software for short-circuit, coordination and arc flash studies. The short-circuit values followed ANSI standards. This is a case study of a system in which the incident energy value on a panel was high, requiring reduction techniques to comply with PPE and increase worker safety. Item 'A' provides details on the system modeling and item 'B' presents data related to the arc flash study.

A. Electrical system data

A 13.8 kV system was modeled, with representation of the utility relay, the primary transformer 13.8 kV / 0.48 kV relay in coordination with the utility, the transformer secondary circuit breaker, a motor equivalent in the secondary bus, and a feeder that goes to a motor control center. Table I contains the utility data, Table II the cable on the transformer primary, Table III the feeder cable to the MCC, Table IV the data on the equivalent motor on the transformer secondary bus, and Table V the transformer data. The one-line diagram of the modeled system is shown in Fig. 1.

TABLE I. UTILITY DATA.

Parameter	Value
Rated voltage [V]	13800
Rated MVA	100
Three phase short circuit [A]	5735.40
X/R positive sequence	2.7070
Single phase short circuit [A]	3800.00
X/R zero sequence	1.80

TABLE II. TRANSFORMER PRIMARY CABLE DATA.

Parameter	Value
Conductor type	Copper
Insulation type	XLPE
Insulation class	8.7 / 15 kV
Cable size [mm^2]	70
Conductors per phase	1.00
Length [m]	15.00
Positive resistance [Ohms/km]	0.3430
Positive reactance [Ohms/km]	0.1450
Zero resistance [Ohms/km]	1.0976
Zero reactance [Ohms/km]	0.6960

TABLE III. MOTOR CONTROL CENTER CABLE DATA.

Parameter	Value
Conductor type	Copper
Insulation type	PVC
Insulation class	0.6 / 1 kV
Cable size [mm^2]	240
Conductors per phase	4.00
Length [m]	80.00
Positive resistance [Ohms/km]	0.0978
Positive reactance [Ohms/km]	0.1660
Zero resistance [Ohms/km]	0.3912
Zero reactance [Ohms/km]	0.6640

TABLE IV. MOTOR EQUIVALENT DATA.

Parameter	Value
Rated voltage [V]	480.00
Rated size [HP]	1500.00
Power factor	0.82 lag
Efficiency	0.91
Poles	4
Synchronous RPM	1800.00
Inrush factor	6.00
Xd'' [pu]	0.1667
X/R	10.50

TABLE V. POWER TRANSFORMER DATA.

Parameter	Value
Insulation	Oil
Primary voltage [V]	13800
Secondary voltage [V]	480
Primary connection	DELTA
Secondary connection	WYE-GROUND
Phase shift angle	30º
Nominal power [kVA]	2000
Type	Standard core
Z [%]	6.5
X/R	7.2905
Inrush factor [pu]	8.00

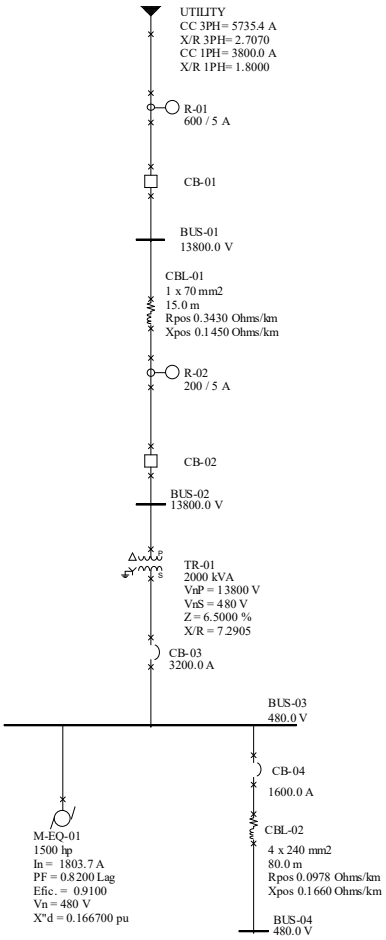

Fig. 1. One-line diagram of the industrial electrical system, with 13.8 kV utility.

B. Arc flash configuration

It was used IEEE 1584:2018 standard, with ANSI AC short circuit method. For each bus, it was necessary to define the equipment type: SWG (Switchgear), PNL (Panel), CBL (Cable), AIR or MCC (Motor Control Center). If it was AIR,

the options are VOA (Vertical conductors / electrodes in open air) or HOA (Horizontal conductors / electrodes in open air). If another type was chosen, the options are: VCB (vertical conductors / electrodes in a metal box / enclosure), VCBB (vertical conductors / electrodes terminated in an insulating barrier in a metal box / enclosure) or HCB (horizontal conductors / electrodes in a metal box / enclosure) [4]. The panel dimensions were maintained from IEEE 1584:2018 standard (box height, width and depth). The busbar gap and working distance as well. The highest incident energy values are obtained considering the line-side protective device of each panel / bus. The configured data for all bars are shown in Table VI, which informs the bar type, electrode type, panel dimensions (not available in the case of Open Air), gap and working distance.

TABLE VI. SYSTEM BUS CONFIGURATION ACCORDING TO IEEE 1584:2018 FOR ARC FLASH STUDY.

Bus name	Equipment type	Electrode configuration	Box width (mm)	Box height (mm)	Box depth (mm)	Gap (mm)	Working distance (mm)
BUS-01	Air	VOA	-	-	-	152	457
BUS-02	Swithgear	HCB	762	1143	762	152	914
BUS-03	Swithgear	HCB	508	508	508	32	610
BUS-04	Motor Control Center	VCB	305	356	254	25	457

V. RESULTS AND DISCUSSION

A. *Results of original non-optimize coordination*

The first step was to study the coordination of the system, following protection criteria such as: for a short circuit in the transformer primary, the primary relay must take instantaneous trip, but for the maximum short circuit in the secondary side (asymmetrical current), the primary relay must be coordinated with the secondary circuit breaker, which must clear the fault with the short time delay element. Likewise, for a short circuit that occurs in the secondary output feeder, the feeder protection circuit breaker must clear the short circuit first, and be coordinated with the transformer secondary circuit breaker. Fig.2 shows the system coordination and protection curves, with the transformer damage curve and the inrush current point at 0.1 s, the transformer primary cable damage curve, the utility relay R-01, the customer relay R-02, the secondary circuit breaker CB-03 and the feeder circuit breaker going to the motor control center CB-04. The caption description of Fig. 2 is: A - Nominal current of the transformer at 13.8 kV, B - Symmetrical short-circuit current of the 0.48 kV secondary, referred to the primary, C - Asymmetrical short-circuit current of the 0.48 kV secondary, referred to the primary, D - Symmetrical short-circuit current of the primary and E - Asymmetrical short-circuit current of the primary. For this condition, it was considered that the transformer primary relay has only the inverse time curve and instantaneous adjustment, and we will call this non-optimized adjustment, condition ‘A’.

Table VII contains a summary of the results of the arc flash study. It is possible to view the name of the protection device that eliminated the arc fault in the line side condition, the value of the bolted fault on the bus and that passes through the protective device, the value of the arc fault on the bus and that passes through the protective device, the fault clearing time, the circuit breaker opening time, the arc flash boundary and the value of the incident energy according to IEEE 1584:2018.

The incident energy value on Bus-01 was 5.08 cal/cm^2, on Bus-02 it was 1.44 cal/cm^2 and on Bus-04 it was 6.18 cal/cm^2. These are acceptable incident energy values. However, the incident energy on Bus-03 was 59.9 cal/cm^2, with an arc clearing time of 0.9759 s plus the circuit breaker opening time. This value is not acceptable, as it exceeds the value of 40 cal/cm^2. The arc flash boundary was 4183 mm. In this situation, the worker could only perform the activity with the transformer secondary panel de-energized. Therefore, some technique must be adopted to reduce the incident energy on this panel. Aiming to reduce the incident energy, Table VIII contains the initial case of 59.9 cal/cm^2, called condition 'A', and four techniques to reduce the incident energy value, which will be described below.

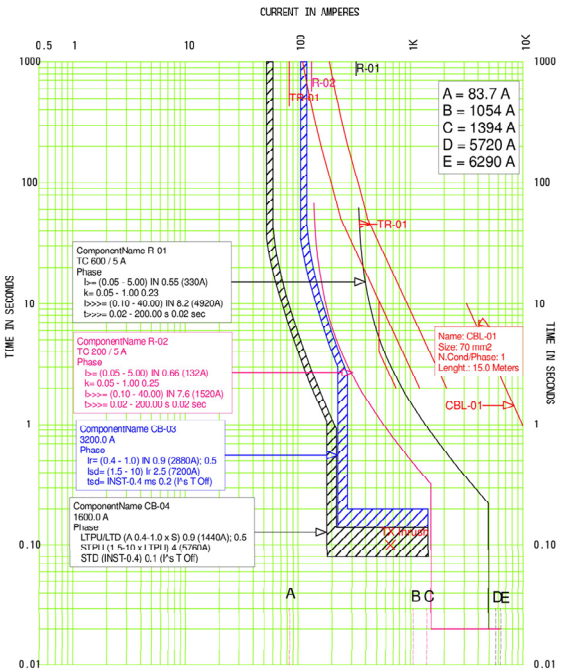

Fig. 2. Time-current coordination of the protection devices, with transformer primary relay adjustment with inverse time curve only.

B. *Results of optimized coordination*

One of the most commonly used techniques is to insert a definite time setting into the protection relay, which clears the arc fault at the same time as it clears the bolted fault. This is

an optimized setting that maintains coordination with the downstream protection device and ensures a reduction in the arc clearing time. In this case, a definite time setting with a timing of 0.35 s was inserted into the relay, as shown in Fig. 3. The caption description and the curves of the other elements are the same as in Fig. 2. This technique will be referred to as condition 'B'. Table VIII shows that, by reducing the arc clearing time from 0.9759 s to 0.35 s, the incident energy reduced from 59.90 cal/cm^2 to 29.5 cal/cm^2, which, although still a high value, is now available on the market more easily. Consequently, the arc flash boundary also reduced, from 4183 mm to 2950 mm.

C. *Loss of coordination*

Condition 'C' will be to further reduce the arc clearing time by deciding to lose coordination between the primary and secondary of the transformer, aiming to increase worker safety. The time of the definite time adjustment of the transformer primary relay was reduced from 0.35 s to 0.15 s, with loss of coordination. It can be seen in Table VIII that the energy decreased to 16.6 cal/cm^2 and the arc flash boundary reduced to 2221 mm.

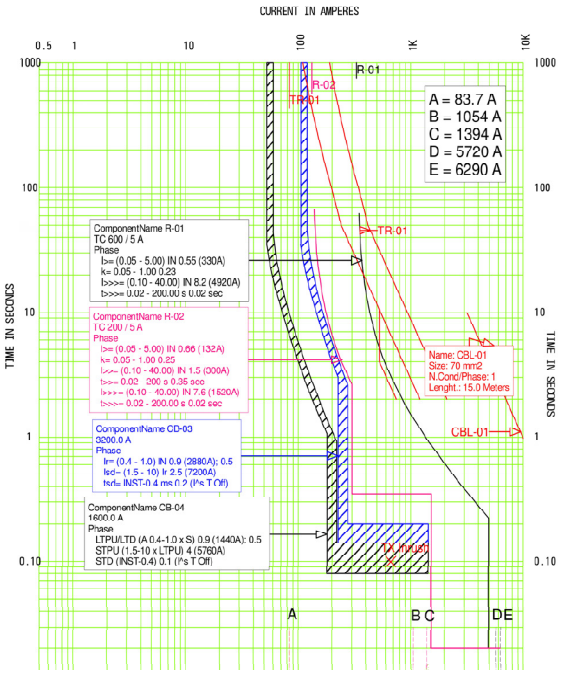

Fig. 3. Time-current coordination of the protective devices, with transformer primary relay adjustment with optimized definite-time adjustment.

D. *Arc flash relay*

Condition 'D' was using an arc protection relay, with a detection time of 2.5 ms for electric arcs in the transformer secondary panel, which should send a trip to turn off the transformer primary relay, in the line side condition. In this case, the time reduced from 0.15 s to 0.0025 s, still with the breaker opening time. The energy value reduced to 7.05 cal/cm^2 and the arc flash boundary to 1458 mm.

E. *Arc Quenching Device (AQD)*

Condition "D" used an arc protection relay tripping an arcing quenching device, with an actuation time of 5 ms. The total fault clearing time is 2.5 ms for the arc relay + 5 ms for the AQD, totaling 7.5 ms. In this case, the time was reduced from 0.0855 s (arc relay + circuit breaker opening time) to 0.0075 s, without the circuit breaker opening time, since the AQD short-circuits the three phases to ground. The energy value was reduced to 2.32 cal/cm² and the arc flash boundary to 844 mm. This was the lowest value obtained in the simulations performed, and was chosen to generate the arc flash label for the transformer secondary panel. Fig. 4 shows the label, according to NFPA70E. It highlights the need to use appropriate PPE, the incident energy value obtained, the name of the bus, the name of the protective device that is acting (arc relay together with the AQD), the working distance, arc flash boundary, description of the necessary PPE and other information. This model can be used in arc flash studies, and at the bottom there are appropriate places to insert the company contact number, the company name and the date the label was generated.

TABLE VII. SUMMARY OF ARC FLASH RESULTS FOR SYSTEM BUSES.

Bus name	Protective device name	Bus kV	Bus bolted fault (kA)	Bus arcing fault (kA)	Protective device bolted fault (kA)	Protective device arcing fault (kA)	Trip/Delay time (s)	Breaker opening time (s)	Arc flash boundary (mm)	Incident energy (cal/cm^2)
BUS-01	R-01	13.8	5.94	4.97	5.74	4.80	0.2292	0.083	1172	5.08
BUS-02	R-01	13.8	5.92	5.34	5.72	5.16	0.02	0.083	1020	1.44
BUS-03	R-02	0.48	41.07	22.92	30.32	16.92	0.9759	0.083	4183	59.90
BUS-04	CB-04	0.48	26.58	19.88	26.58	19.88	0.14	0.00	1275	6.18

TABLE VIII. RESULT OF THE ARC FLASH STUDY FOR BUS-03, TRANSFORMER SECONDARY, WITH DIFFERENT TECHNIQUES FOR REDUCING THE ARC CLEARING TIME.

Bus name	Protective device name	Condition	Bus kV	Bus bolted fault (kA)	Bus arcing fault (kA)	Protective device bolted fault (kA)	Protective device arcing fault (kA)	Trip/Delay time (s)	Breaker opening time (s)	Arc flash boundary (mm)	Incident energy (cal/cm²)
BUS-03	R-02	A	0.48	41.07	22.92	30.32	16.92	0.9759	0.083	4183	59.90
BUS-03	R-02	B	0.48	41.07	26.58	30.32	19.63	0.35	0.083	2950	29.50
BUS-03	R-02	C	0.48	41.07	26.58	30.32	19.63	0.15	0.083	2221	16.60
BUS-03	R-02	D	0.48	41.07	26.58	30.32	19.63	0.0025	0.083	1458	7.05
BUS-03	R-02	E	0.48	41.07	26.58	30.32	19.63	0.0025	0.005	844	2.32

Fig. 4. Arc flash label, containing information on incident energy value, arc flash boundary and others. The one with the lowest incident energy value was obtained using arc relay and Arc Quenching Device.

F. Suggested flowchart for arc flash study

Fig. 5 shows a flowchart for the arc flash study, and according to the calculated incident energy, incident energy reduction techniques are proposed. After collecting data from the electrical system and modeling it in appropriate software, the arc flash study will be performed, and the incident energies will be calculated for the first time. It is recommended that if the energies are less than 8 cal/cm², energy reduction techniques are not necessary and the study can be completed with the generation of arc flash labels. If the energy is greater than 8 cal/cm² at any bus, energy reduction techniques are required. An optimized time adjustment can be made to reduce the arc elimination time, this can be done with a definite time element for relays or a short time delay element for circuit breakers. A second calculation of the incident energy is performed, again checking whether the energy is greater than 8 cal/cm². If it is greater, logical selectivity for relays or zone selective interlocking for circuit breakers can be used, and the incident energy is calculated for the third time. If the energy remains high, an arc protection relay can be used, and if it is still necessary to reduce the incident energy, an arc quenching device can be installed.

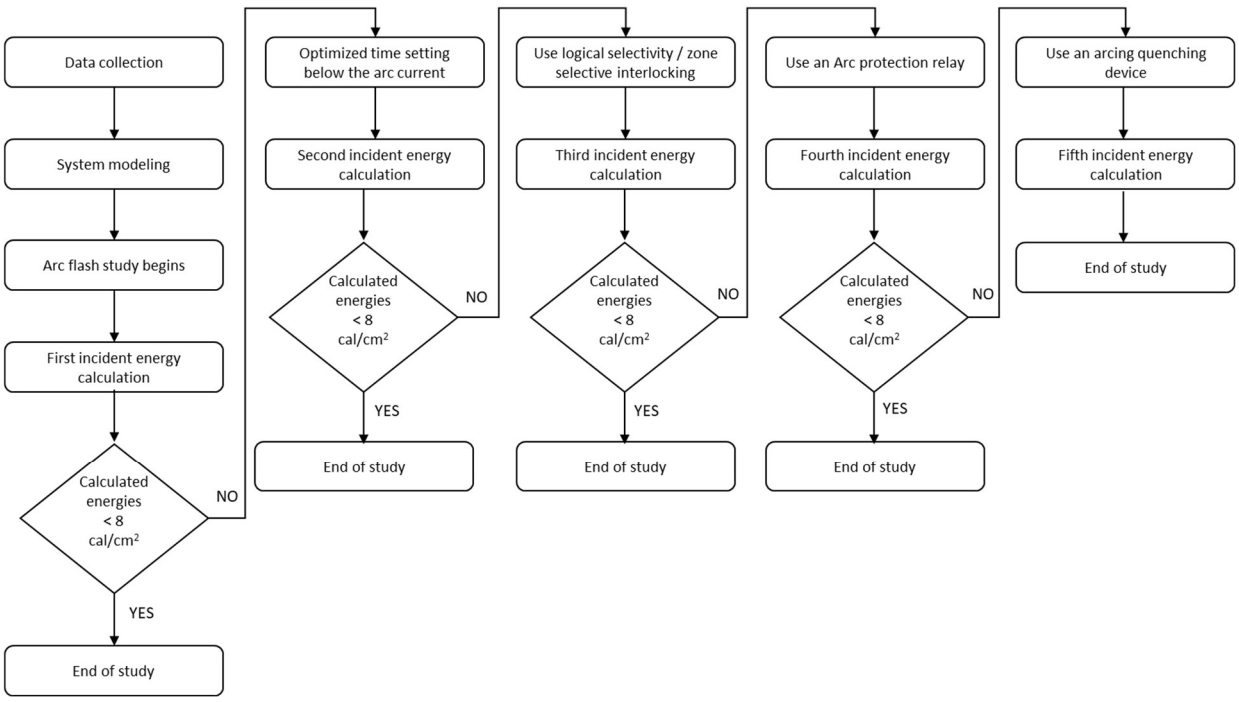

Fig. 5. Suggested flowchart for arc flash study.

VI. CONCLUSIONS

1. Carrying out short-circuit, coordination and arc flash studies are mandatory under Brazilian NR 10 standard and international standards.
2. The standards prescribe the minimum safety conditions. We must always evaluate the conditions to increase the safety of workers.
3. Clothing does not guarantee 100% probability of protection.
4. Often, even with the maximum clothing class (40 cal/cm^2), it is not possible to provide adequate protection to workers. In these cases, efforts should be made to reduce the protection time using the techniques proposed in this paper. The techniques are, optimized time adjustment with definite time element for relays or short time delay elements for circuit breakers, use of logical selectivity for relays or zone selective interlocking for circuit breakers, installation of arc protection relay and installation of arcing quenching device.
5. Nowadays, it is no longer acceptable to carry out a coordination study without carrying out an arc flash study in parallel, since the times used in the coordination study affect the incident energy results.
6. Arc flash studies help not only to protect people, but also to ensure the operational continuity of the plant and MTTR (mean time to repair) in the event of damage due to faults.
7. It is recommended to purchase clothing from companies whose clothing is guaranteed by certified tests.
8. Whenever possible, one should try to implement the techniques with optimized adjustments before moving on to solutions that involve new installations and equipment replacements.
9. Possible arc faults due to insulation failures must be minimized by performing periodic predictive
10. maintenance, using, among others, thermographic and ultrasound inspection techniques.
11. It is recommended that arc flash studies be carried out always so that the incident energy remains below 8 cal/cm^2 and that all electrical workers wear at least clothing that can withstand incident energy up to 8 cal/cm^2.
12. It is recommended that, even if you have arc-resistant panels, photosensitive arc monitoring relays be installed, as this will preserve the integrity of the panel and make it ready to operate after an electric arc.
13. A flowchart for carrying out arc flash studies was suggested, with a step-by-step guide to assessing incident energy, which can be used by engineers and technicians responsible for the studies.

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Measurement of Arc Flash Incident Energy in Low-Voltage Three-Phase Panels Using an Optical Calorimeter

Fernanda Cristina Salvador Soares
Instituto de Energia e Ambiente
Escola Politécnica
Universidade de São Paulo
São Paulo, Brasil
fcsalvad@iee.usp.br

Márcio Bottaro
Instituto de Energia e Ambiente
Universidade de São Paulo
São Paulo, Brasil
marcio@iee.usp.br

Josemir Coelho Santos
Escola Politécnica
Universidade de São Paulo
São Paulo, Brasil
josemir@pea.usp.br

Luis Eduardo Caires
Instituto de Energia e Ambiente
Universidade de São Paulo
São Paulo, Brasil
luis@iee.usp.br

Paulo Futoshi Obase
Instituto de Energia e Ambiente
Universidade de São Paulo
São Paulo, Brasil
obase@.usp.br

Rogério Masaro
Instituto de Energia e Ambiente
Universidade de São Paulo
São Paulo, Brasil
rogerio@iee.usp.br

***Abstract* — Calculating incident energy is essential for assessing the risk to which professionals involved in the operation and maintenance of electrical installations are exposed, allowing the definition of appropriate control measures and aiming at protecting workers, preserving the environment and ensuring the operational continuity of the system. The IEEE 1584 Standard is a calculation guide globally adopted by the industry for arc-flash hazard calculations and uses an empirical model updated in 2018. It was developed based on approximately 1860 tests, covering open-air and enclosed configurations, performed with different parameters, such as: operating voltage, fault currents, fault clearing time, working distances and conductor's gap. During the IEEE 1584 development process, incident energy measurements were performed using calorimeters such as those specified in ASTM F1959, consisting of copper discs instrumented with an inserted thermocouple wire sensor. However, thermocouple-based measurements are susceptible to electromagnetic noise, requiring mathematical signal filtering techniques that may affect accuracy. ASTM F1959 allows the use of alternative calorimeters provided they are calibrated and have a similar response to the calorimeter with a thermocouple sensor. This study proposes the use of an optical calorimeter for measuring the incident energy of electric arcs produced in a three-phase panel in IEEE 1584 VCBB configuration. The calorimeter is equipped with an optical sensor and a thermocouple for simultaneous assessment of measuring systems. The results show that calorimeters with optical sensors demonstrates key advantages as immunity to electromagnetic noise and faster response times. It was evidenced that incident energy measured is higher when compared to that measured with the thermocouple sensor. These findings suggest that the choice of sensor technology can significantly impact the calculated incident energy and, consequently, influence the specification of protective measures in electrical systems, especially given that IEEE 1584 equations are based on data derived from thermocouple measurements.**

Keywords* — *arc flash, incident energy, optical calorimeter, IEEE 1584, thermocouple measurements

I. INTRODUCTION

Arc flash is an electric arc event with great dissipation of thermal energy as radiant, convective and conductive heat [1]. According to Mardegan *et. al.* [2], an electric arc is a high-energy discharge that occurs when the dielectric strength between an energized conductor and a grounded point is compromised. The amount of energy released during this event is extremely high and depends on several factors, including the system's nominal voltage, the magnitude of the fault current, and the fault clearing time. During an arc flash accident, the incident energy (IE) received by a person's skin surface is a key factor in determining the severity of thermal injuries. Statistics indicate that only 25% of arc flash accidents occur without the presence of the operator, 10% with the operator present and the panel door closed and 65% of accidents occur during maintenance [2]. Thus, estimating the IE is essential for assessing the risk to which professionals involved in the operation and maintenance of electrical installations are exposed, allowing the definition of appropriate control measures and aiming at protecting workers, preserving the environment and ensuring the operational continuity of the system. The IEEE 1584 standard [1], widely adopted across industries, provides an empirical model for calculating incident energy. The 2018 revision of the standard is based on approximately 1,860 tests conducted

in both open-air and enclosed (box) configurations, considering a range of parameters such as system voltage, fault current, fault clearing time, working distance, and conductor gap.

A study published in 2021 [3], which compared the predicted values using the IEEE 1584-2018 methodology and tests in circuit-breaker cabinets, live-front contact switches and live-front transformers, pointed out that the IEEE 1584 model may underestimate IE, particularly in horizontal electrode configurations, and that multiplicative factors or other analysis approaches would be required to match data from real equipment.

The IE measurements that gave rise to the IEEE 1584 calculation models were performed using calorimeters such as specified in ASTM F1959 [4], consisting of copper discs with a thermocouple embedded on the rear side. However, temperature measurement with a thermocouple sensor is affected by electromagnetic noise. Fig. 1 shows the temperature signal measured with a thermocouple-based calorimeter during a 10-cycle arc flash event. Induced electromagnetic noise is observed, which requires the use of signal filters to eliminate this interference before determining the maximum temperature.

Prior to its latest edition, ASTM F1959 allowed the use of alternative calorimeter designs, provided they are properly calibrated and demonstrate a response behavior similar to the standard thermocouple-based devices. Bacin *et al.* [5] demonstrated that it is possible to measure incident energy using data extracted from the recording of a thermal imaging camera aligned with a calorimeter. A previously published study [6] demonstrated that the use of a calorimeter with a fiber optic temperature sensor presents significant improvements in the measurement of incident energy, particularly in terms of eliminating electromagnetic noise, without requiring the need for mathematical filters. These sensors also feature faster response times compared to thermocouples, which makes them more accurate in high-rate temperature rise scenarios, often resulting in higher measured values.

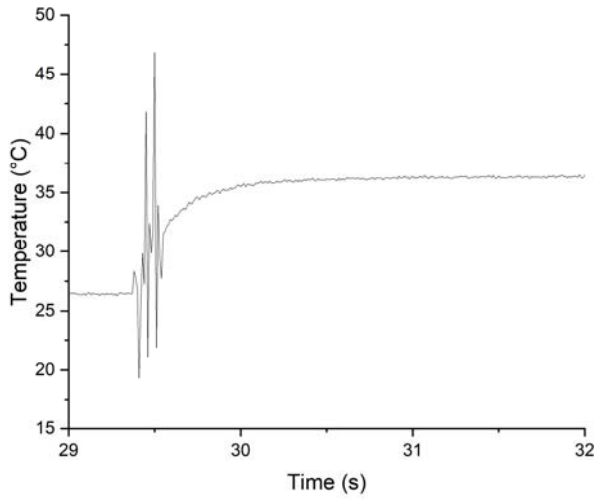

Fig. 1. Fig. 1. Temperature signal measured with thermocouple sensor in a 10-cycle arc flash event

II. Materials and Methods

The present work aims to perform incident energy measurements in a three-phase electrical panel, using two calorimeters mounted according to ASTM 1959 and a third calorimeter with a thermocouple and an optical fiber temperature sensor embedded. The measured values are then compared against those calculated using the IEEE 1584 2018 methodology to evaluate the consistency and reliability of each measurement approach.

The tests were conducted at the PPE Arc Flash Laboratory of the Institute of Energy and Environment of the University of São Paulo (LAEVe- IEE/USP). A three-phase electrical panel was assembled in the VCBB configuration (Vertical Conductors Terminated in an Insulating Barrier within a Metal Box Enclosure), operating at 320 V, 60 Hz and measuring 600 mm (width) × 1000 mm (height) × 250 mm (depth), with a conductor gap of 17 mm, as illustrated in Fig. 2.

To measure the IE, three calorimeters, designated C1, C2 and C3, were positioned at a distance of 340 mm from the panel (representing the working distance). The height of calorimeter C2 was aligned with the panel electrodes, and the other calorimeters, C3 and C1, were 110 mm and 185 mm above C2, respectively, as shown in Fig. 3.

The calorimeters were constructed in accordance with ASTM F1959, consisting of an 18 g copper disc with a diameter of 40 mm and a thickness of 1.6 mm, each fitted with a 0.256 mm K-type thermocouple wire inserted in the rear face. Each copper disc was mounted on a Marinite cylinder body to ensure thermal insulation.

Additionally, a fiber optic temperature sensor (F.O.) was added to calorimeter C3 following the method previously demonstrated [6]. Thus, calorimeter C3 was mounted with a thermocouple sensor and a fiber optic temperature sensor, both at the same depth in relation to the heat-receiving surface (0.3 mm). The three calorimeters were painted with black paint with emissivity greater than 0.9.

Fig. 2. Three-phase electrical panel in VCBB configuration with a gap between conductors of 17 mm

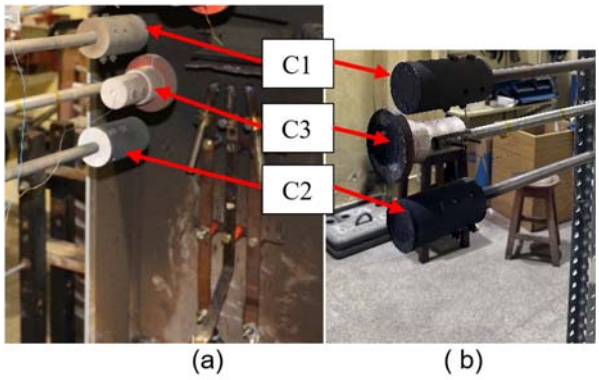

Fig. 3. Positioning of the calorimeters in front of the electrical panel: (a) rear view of the calorimeters; (b) front view of the calorimeters

The F.O. sensor, manufactured by Proximion, was connected to a Micron Optics interrogator, model SM230, operating at a sample rate of 500 samples per second (S/s), while the thermocouples were connected to a thermocouple input module manufactured by National Instruments, model NI-9213, with a sample rate of 100 S/s, adjusted via FPGA programming template.

The arc flash was ignited using a copper conductor, also known as fuse wire, which was tied to the three electrodes of the panel to provide a low-impedance path for the short circuit. A total of eight arc flashes of 10 to 40 mains cycles (166 ms to 666 ms) were performed. The electrical parameters were monitored so that the I_{arc} (rms arcing current) could be determined. The temperature rise was recorded during the application of the electric arc and for the following 30 seconds. The IE in each of the three calorimeters was calculated according to ASTM F1959. After that, the IE was estimated using the IEEE 1584 method via the spreadsheet "Estima Energia Ed01 Rev02.xlsx" [7], based on the measured parameters of the electrical arcs (IEEE 1584 corrected) and considering a theoretical bolted fault current of 6.5 kA (IEEE 1584 theoretical), both represented in a same graph for comparison.

III. RESULTS

Table I shows the number of mains cycles for each of the applied arc flash, the bolted fault current for three-phase faults (I_{bf} , in kA) and the average measured rms arcing current (I_{arc}, in kA). Fig. 4 shows the oscillogram for arc n° 1, within 10 mains cycles.

Fig. 5 shows the temperature signal measured in calorimeter C3 with thermocouple (TC) and fiber optics (F.O.) sensors, during and after the application of Arc No. 8, a 40-cycle arc flash event. It is clearly observable the noise in the thermocouple sensor signal during the arc flash application. Such noise is not observed in the signal obtained with the fiber optic sensor. In addition, temperature differences were found between the measurements made with the thermocouple and fiber optic sensors, probably due to the fact that the response time of the fiber optic sensor is shorter than the response time of the thermocouple sensor, as demonstrated in a previous study [6].

The incident energy of each arc flash, estimated by the IEEE 1584 method, based on the input data of system voltage, bolted fault current, conductors' gap, arc clearing time, dimensions of the panel and working distance, is presented in Table II. This table also presents the IE values measured by each of the three calorimeters: C1 and C2 with thermocouple sensors, and C3 with thermocouple and fiber optic sensors.

Comparing the IE values measured with the calorimeter C3 it is possible to observe a variation of up to 5.7% between the thermocouple and fiber optic sensor. For arc flashes over 20 mains cycles, the IE measurements obtained with the fiber optic sensor were consistently greater than the thermocouple sensor, and up to 5.9% closer to the incident energy values predicted by IEEE 1584.

The data in Table II were plotted on a graph, as shown in Fig. 6, representing the comparison of the values measured with the three calorimeters and the values estimated by IEEE 1584, assuming a VCBB panel configuration with the parameters used in the experimental setup. Calorimeter C1, presented the smallest difference within the values estimated by IEEE 1584, from 1% to 23%. In arcs # 4, # 5 and # 8, however, the IE measured in calorimeter C3 were closer to the IEEE 1584 predictions. This suggests that heat wave propagation can vary under nominally identical electrical and geometric conditions. Fig. 7 shows four frames of the heat wave propagation video obtained during measurements of an arc with 10 mains cycles, at times 180 ms (A), 200 ms (B), 260 ms (C) and 320 ms (D) after the application of the arc flash.

TABLE I. NUMBER OF MAINS CYCLES, AVERAGE MEASURED RMS ARC VOLTAGE (V) AND THE AVERAGE MEASURED RMS ARCING CURRENT FOR EACH OF THE ARC FLASH APPLIED

Arc N°	Mains cycles	Arc Voltage (V)	I_{arc} (kA)
1	10	145.4	4.39
2	10	147.9	4.13
3	20	138.0	4.38
4	25	138.4	4.33
5	27	143.1	4.24
6	30	129.4	4.83
7	35	132.1	4.58
8	40	137.0	4.47

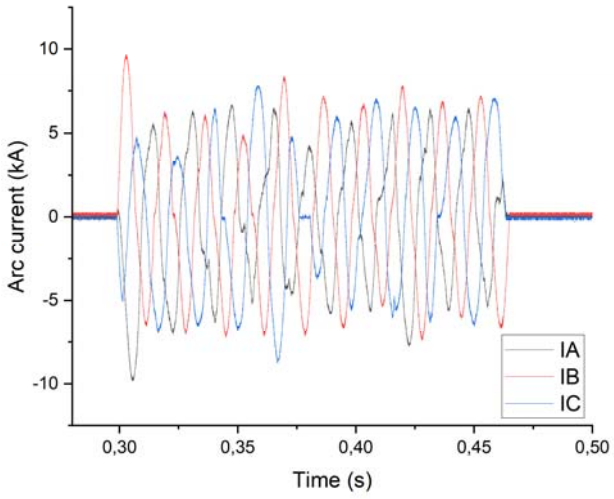

Fig. 4. Oscillogram of the current of electric arc No. 1 with 10 mains cycles

The dispersion between the IE values measured with the three different calorimeters is probably related to the fact that the measurement at a single point does not represent the IEEE 1584 measurement model, which was made considering the maximum energy among seven calorimeters in a well determined geometry not followed in the present study.

In the IEEE 1584 model, the tests were performed on arcs of up to 30 cycles, the results were normalized for arcs of 6 and 12 cycles, since it was considered that there is a linear relationship between time and incident energy. However, the measurements published by Short and Eblen [3], showed that the heat rate may increase with duration for some scenarios. The results revealed an increasing trend in this normalized energy with longer arc durations, attributed mainly to the growth of high-temperature zones accompanying arc propagation. This effect can also be evidenced in the measurements made in the present work, were the incident energy flux for each of the calorimeters was calculated by dividing the incident energy value by the arc time as depicted in Fig. 8. The mean value and standard deviation are summarized in Table III.

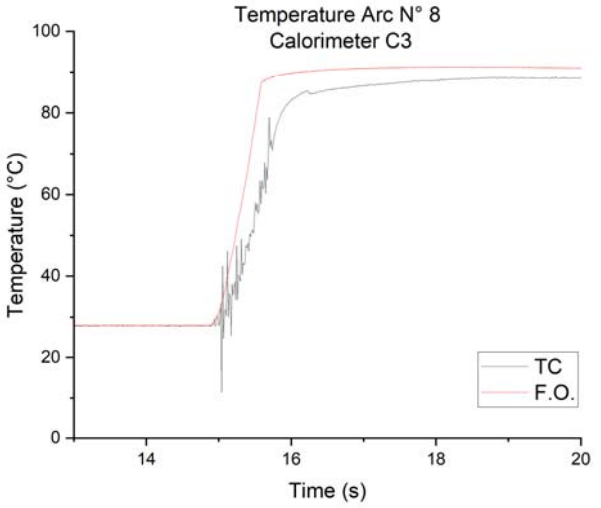

Fig. 5. Temperature measured in calorimeter C3 during and after application of Arc No. 8 , with 40 mains cycles

TABLE II. INCIDENT ENERGY (IE) MEASURED WITH THE CALORIMETERS WITH THERMOCOUPLE SENSOR C1 AND C2, WITH THE CALORIMETER WITH THERMOCOUPLE AND FIBER OPTIC SENSORS C3 AND THE IE CALCULATED BY THE IEEE 1584 METHOD

Arc N°	Measured IE (cal/cm²)				Predicted IE by IEEE 1584 (cal/cm²)
	C1	*C2*	*C3 TC*	*C3 F.O.*	
1	1.7	1.0	1.2	1.2	2.1
2	1.9	1.2	1.3	1.3	1.9
3	4.1	3.7	3.4	3.5	4.1
4	5.6	5.8	5.0	5.3	5.1
5	6.6	6.7	5.8	5.9	5.4
6	6.0	4.8	5.2	5.3	6.9
7	7.8	6.3	6.5	6.7	7.6
8	9.8	8.2	8.1	8.4	8.5

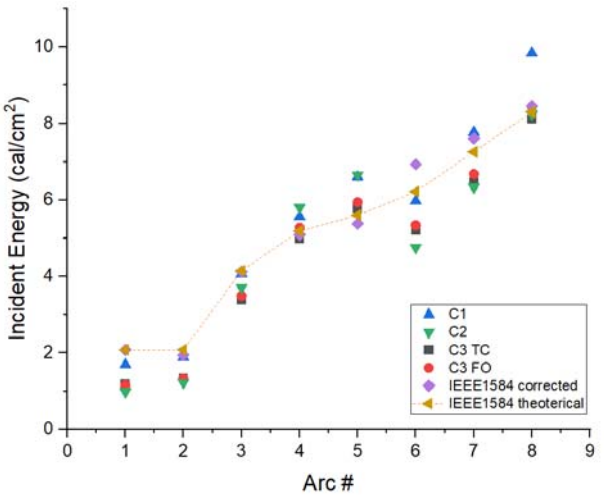

Fig. 6. A comparison of IEEE 1584-2018 predictions to the measured incident energy for VCBB panel. Dash line is used to guide eyes on IEEE 1584 theoretical data.

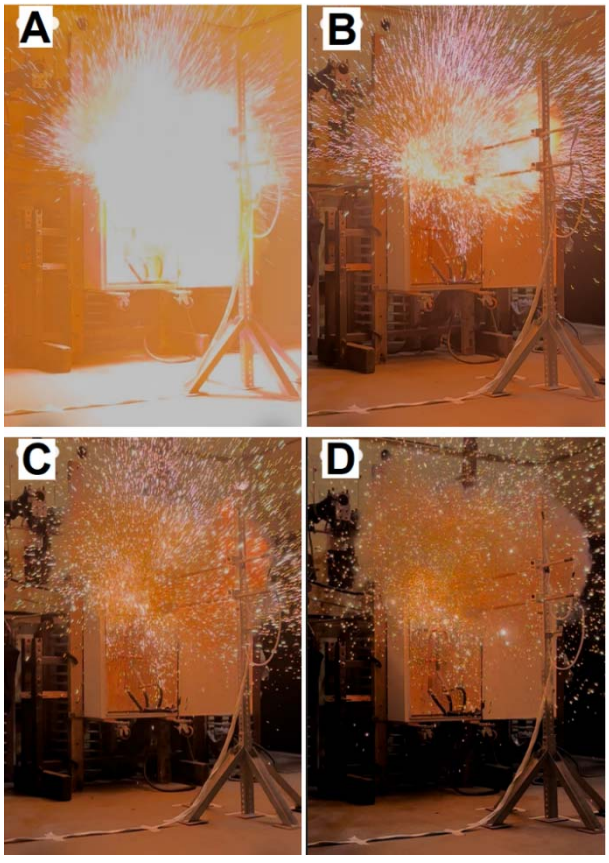

Fig. 7. Frames from the video of an electric arc with 10 mains cycles at times 180 ms (A), 200 ms (B), 260 ms (C) and 320 ms (D)

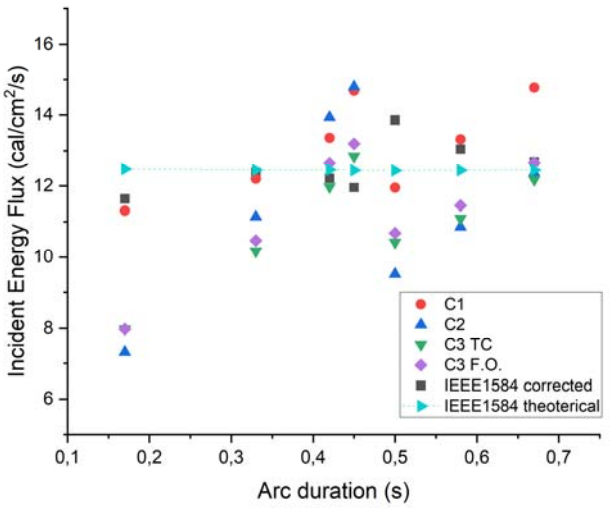

Fig. 8. The ratio of incident energy flux as a function of arc time, were IEEE 1584 corrected is based on the measured parameters of the electrical arcs and IEEE 1584 theoretical is related to the theoretical bolted fault current of 6.5 kA. Dash line is used to guide eyes.

TABLE III. AVERAGE INCIDENT ENERGY (IE) FLUX IN EACH OF THE CALORIMETERS

Predicted / Measured	IE Flux (cal/cm²/s)	
	Mean	*Standard Deviation*
IEEE 1584	12.5	0.7
C1	12.7	1.6
C2	10.7	3.1
C3 TC	10.5	2.0
C3 FO	10.8	2.3

From the data in Table III, it is possible to verify that the average incident energy flux of calorimeter C1 is the closest to IEEE 1584, and the value measured in calorimeter C3 with thermocouple sensor was the lowest. Calorimeter C2, which was positioned below the others, was the one that presented the greatest variability in the measurements. The high standard deviation observed when comparing measured values with IEEE 1584 predictions, highlights the inherently stochastic nature of heat propagation of the arc flash. The average energy fluxes obtained in calorimeter C3 (TC and FO) and C2 is very similar, but C3 standard deviation is lower.

IV. CONCLUSIONS

The measurements in calorimeter C1 were the closest to the incident energy values estimated by IEEE 1584, showing that it is important that the measurements are made using a larger set of calorimeters, since the measurement at a single point does not represent the IEEE 1584 measurement model and the total incident energy distribution for a given setup.

When performing calculations according to IEEE 1584, there are assumptions that must be well defined so that the incident energy in a real situation corresponds to the calculated values. Although the model considers a linear relationship between arc time and incident energy, the measurements conducted in this work demonstrated an increasing energy within the duration of the electric arc.

The results obtained confirmed that it is possible to measure the incident energy in an electrical panel using a calorimeter with a fiber optic temperature sensor. The optical calorimeter demonstrated immunity to electromagnetic interference and exhibited a faster temperature response compared to traditional thermocouple-based calorimeters. The incident energy measurements made with the optical calorimeter were up to 5.7% higher than the measurements made with the calorimeter specified by ASTM F1959. Thus, the use of optical calorimeters in a large approach as stated by IEEE 1584, would refine the empirical energy estimation model, enhancing worker protection risk analysis.

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Experimental Evaluation of a Power Thyristor-Based Industrial Arc-Flash Quenching Device

Fernando Venâncio Amaral
Graduate Program in Electrical Engineering
Federal University of Minas Gerais
Belo Horizonte, Brazil
fovamaral@ufmg.br

Victor Hugo Soares Lopes
Graduate Program in Electrical Engineering
Federal University of Minas Gerais
Belo Horizonte, Brazil
victorlopes@ufmg.br

Claudio Alvares Conceição
Department of Electrical Maintenance
Petróleo Brasileiro S.A.
Betim, Brazil
claudioac@petrobras.com.br

Filipe Barcelos Resende
Technical Management Department
Vale S.A.
Nova Lima, Brazil
filipe.resende@vale.com

Sidelmo Magalhães Silva
Department of Electrical Engineering
Federal University of Minas Gerais
Belo Horizonte, Brazil
sidelmo@ufmg.br

Braz de Jesus Cardoso Filho
Department of Electrical Engineering
Federal University of Minas Gerais
Belo Horizonte, Brazil
braz.cardoso@ieee.org

***Abstract*—Increasing industry demand for safety in the workplace has led to the proposition of solutions for the mitigation of arcing fault effects on equipment and personnel. This has been intensified after arc flash risk was recognized around the world as a danger no less important than electric shock. The most recent technology for arc quenching relies on a power electronics-based switch, composed of two antiparallel thyristors connected in series with a current-limiting impedance. The device is immediately operated when an arcing fault is detected in the busbar of a switchgear or motor control center, quenching the arcing path in a time interval of the order of microseconds. As a result, the incident energy is practically eliminated. The main advantage of this technology is the possibility of multiple usages without the substitution of any component after an operation, as well as the ability of real-time monitoring of the electronic devices for a reliable operation. On the other hand, the main concern is the application of power semiconductors under off-label conditions, which brought the demand for a deep study on the data sheet ratings and development/validation of a design strategy. This work presents the prototype of such a device, which has been drawn and built for power systems up to 440 V, 25 kA (three-phase, symmetrical bolted fault level), as well as experimental results of tests performed in the laboratory. The premises adopted for the design of the equipment are briefly discussed, and the test setup is described along with oscillograms and image captures of the developing/extinguishing faults. The tests have been progressively executed from reduced to full voltage and current levels, without and with the actuation of the equipment, and finally under rated conditions according to the IEC TR 61641:2014.**

Keywords—electrical safety, explosion protection, short-circuit currents, industrial electronics

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I. Introduction

While the ideal solution is to deenergize an electrical system during maintenance, this may not be possible in mission critical facilities such as commercial buildings, hospitals and data centers [1], [2]. Such scenario has created the need for electrical workers to operate and perform maintenance at exposed live parts of electrical equipment like switchgears (SWGRs) and motor control centers (MCCs) [3], which is a condition prone to incidents due to human error [4-8], component degradation [9], [10], accumulation of moisture and dust, contamination and corrosion [4], [11], transient voltage surges [5], presence of animals [12], [13], etc. This situation can lead to internal arcing faults, which are mainly characterized by high temperature (up to 20,000 °C) plasma release and pressure shock waves (rise between 0.3 and 0.7 kgf/cm^2 in less than 10-15 ms) [14]. For the sake of comparison, a phase-to-phase fault on a 480 V system with 20 kA of fault current lasting for 200 ms provides 2 MJ of energy, which corresponds roughly to two sticks of dynamite [15]. According to the Occupational Safety and Health Administration (OSHA), industrial arc-flash (AF) events are the cause of approximately 80% of electrically-related accidents and fatalities among qualified electrical workers [16], [17]. Employee is exposed to hazards like blast fragments, hot toxic gases, intense light and high noise level during the execution of energized work around the faulty compartment of the concerned panel, resulting in potential injury or death [10], [18], [19]. Downtime, production outage, equipment replacement and reputational damage can also occur [10], [20], [21]. In flammable areas like oil & gas industry, these consequences can be even more catastrophic [15] ,[22], [23].

A. Arc-flash Mitigation

After a system has been designed and constructed, reduction of the fault clearing time is the most feasible strategy for the decrement of the incident energy (IE) [3], [6], [24]. Additionally, variations in available fault current over the day/night and incorrect assumptions regarding conductor impedances, regenerating sources and motor contribution, as well as variance in source voltage due to system loading, lead to errors in the calculation of the IE [19], [25], which in turn can lead to the wrong choice of personal protective equipment. Moreover, it is preferable to eliminate an arcing fault in its early phase, in which electrical energy is not yet converted to mechanical / thermal forms [26] and a phase-to-ground fault have not escalated into a three-phase one, which takes up to two power-frequency cycles [27], [28], [29], with a considerable increase in the fault current level. Still, it is possible that the arc initiates including the three phases of the busbar [30].

The curable burn threshold for the human body has been defined as 1.2 cal/cm^2 (5 J/cm^2), which is currently used to define the AF boundary [31]-[33]. NFPA 70E defines as "flash protection boundary" the approach limit at a distance from live parts that are insulated or exposed within which a person could receive a second-degree burn. The IE at this boundary is calculated to be 1.2 cal/cm^2 [34], [35]. To obtain IE levels lower than 8 cal/cm^2 over a broad range of possible fault currents, the protection must clear the fault at 50 ms or less. To be at or below the energy level of 4 cal/cm^2, the system must clear in 25 ms or less. Typical LV circuit breaker (CB) operating times are 25 ms (molded case) and 50 ms (power CB) [3], [36]. However, when the time required for fault detection and trip signaling is taken into account, total opening time of 50 ms or more is verified [37]. On the other hand, to achieve less than 1.2 cal/cm^2, clearing should occur within 10 ms [24].

B. Quenching Devices

Since series CBs do not eliminate the arcing fault adequately, an alternative is to deploy a parallel, normally open, active arc elimination[1] system to extinguish an internal arc by redirecting the uncontrolled energy release into a defined and controlled connection of all 3 phases to earth potential. The voltage at the point of the fault is collapsed to a low value so that arc is no longer sustainable. Arc elimination devices are designed to quench a burning internal arc in less than 1/3rd of a cycle (≈ 5 ms at 60 Hz), despite several cycles of high fault current flow through the system until clearing by an upstream device [10], [38]. Notice how a time interval of 5 ms is compatible with the operating time of the detection system (≈ 1 ms) as well as with the limit of 6 ms to achieve the peak pressure wave inside the switchgear and the limit of 10 ms to achieve less than 1.2 cal/cm^2.

Along with tripping the arc quencher, the arc detection system sends a trip command to the upstream CB, which eliminates the short-circuit current within a few cycles. Thus, the elimination of the fault is carried out in two phases: in the first phase, the arc is quenched by the arc-flash quenching device, and then, the short-circuit current is eliminated by the CB. This technology is listed in IEC standards as an option to provide highest possible level of protection to persons in case of an internal arc in a SWGR, besides procedural simplicity, power system reliability and improved system availability. Troubleshooting, repair, testing, and return to service are simplified and relatively quick. In addition, quenching devices can be added after normal equipment installation, as well as the ability to be easily tested without the need for cumbersome high-current and / or high-voltage test equipment [24].

Various manufacturers have different technologies related to the shorting of the circuit, ranging from mechanical devices based on pyrotechnical pressure elements and micro gas cartridges [39] to electromechanical equipments based on arcing chambers and Thomson coil elements [40], [41]. Both kinds have some technological limitations like mandatory replacement after one or a few operations and the impossibility of being tested in normal operation - they have to be trusted.

C. The Power Thyristor-based Arc-flash Quenching Device

Fig. 1 presents a schematic diagram of the solution that is explored in this work. Phase-to-ground connection is made through an impedance (Z_{Sk}, k = {A,B,C}) in series with two thyristors connected in anti-parallel (S_k). The main reason for choosing the thyristor is its fast turn-on speed - which is crucial, high current and voltage capabilities, high thermal endurance, compact size and lower price compared to other solid state candidates of similar rating.

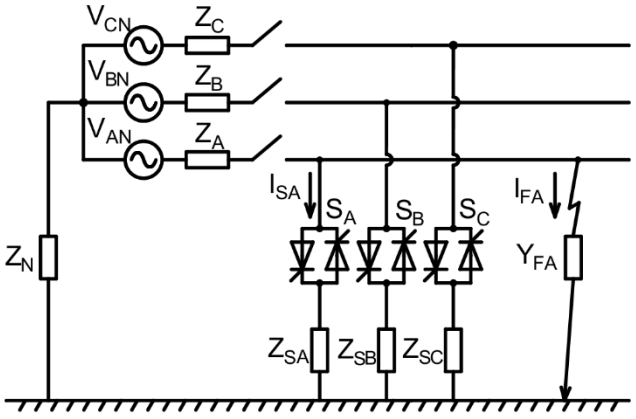

Fig. 1. Schematic of the thyristor-based quenching device.

Still in Fig. 1, Z_N is the transformer neutral-to-ground impedance (if any) and Y_{FA} is the arcing admittance supposing a single-phase A-to-ground fault. Once the switch S_A is closed, fault current I_{FA} commutes from the arcing path (Y_{FA}) to the quenching device path (Z_{SA}). The shunt impedance Z_{Sk} limits the short-circuit current to a lower value compared to bolted-fault current. Another benefit is that thyristors can be monitored / diagnosed during normal operation (online). The three phases of the arc-flash quenching device always operate disregarding the type of arcing fault.

D. Contributions and Organization of the Paper

The main contribution of this paper is to present the practical assembly and experimental test of a prototype of the thyristor-based quenching device, which has been conceived for 440 V, 25 kA (three-phase, symmetrical bolted fault level).

[1]Also called crowbar unit, arc quencher, high-speed earthing device or arc-flash suppressor. Standard EN 50110-1 defines "arc quenching" as "A fast-acting low-impedance arc-flash mitigation system which has a total clearing time from arc-flash initiation to complete extinguishing of the arc-flash event in less than 6 ms." NFPA 70E Annex O.2.3(4) gives a similar definition, but does not state a maximum time. However, it requires that "the energy-reducing active arc-flash mitigation system works without compromising existing selective coordination in the electrical distribution system."

Time-domain computational modeling and simulation performed in MATLAB® and ATPDraw™ to support the design, including the electrothermal behavior of the power thyristors and arc-flash models developed from experimental results registered in the IEEE-NFPA Collaborative Research Project, have been presented in a previous paper – see [42].

II. Design of the Prototype

This section presents the development of the prototype of a switchgear that has been built to be subjected to real arcing fault tests. It is a 440 V equipment composed by three columns – see Fig. 2: incoming (left - where the power system is connected), the electronic AF quenching device (center) and feeder (right - where the arcing fault is produced by a thin bare copper wire). Fig. 3 presents a drawing showing a closer view of the withdrawable compartment that contains the quenching device.

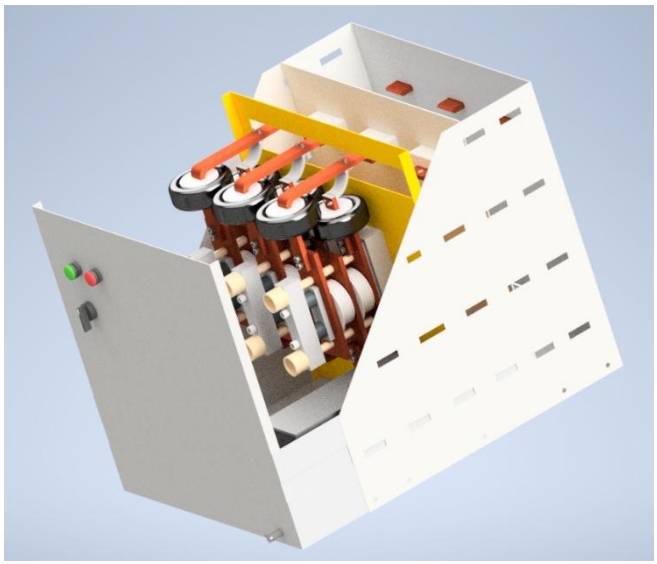

Fig. 3. 3D view of the thyristor-based quenching device compartment.

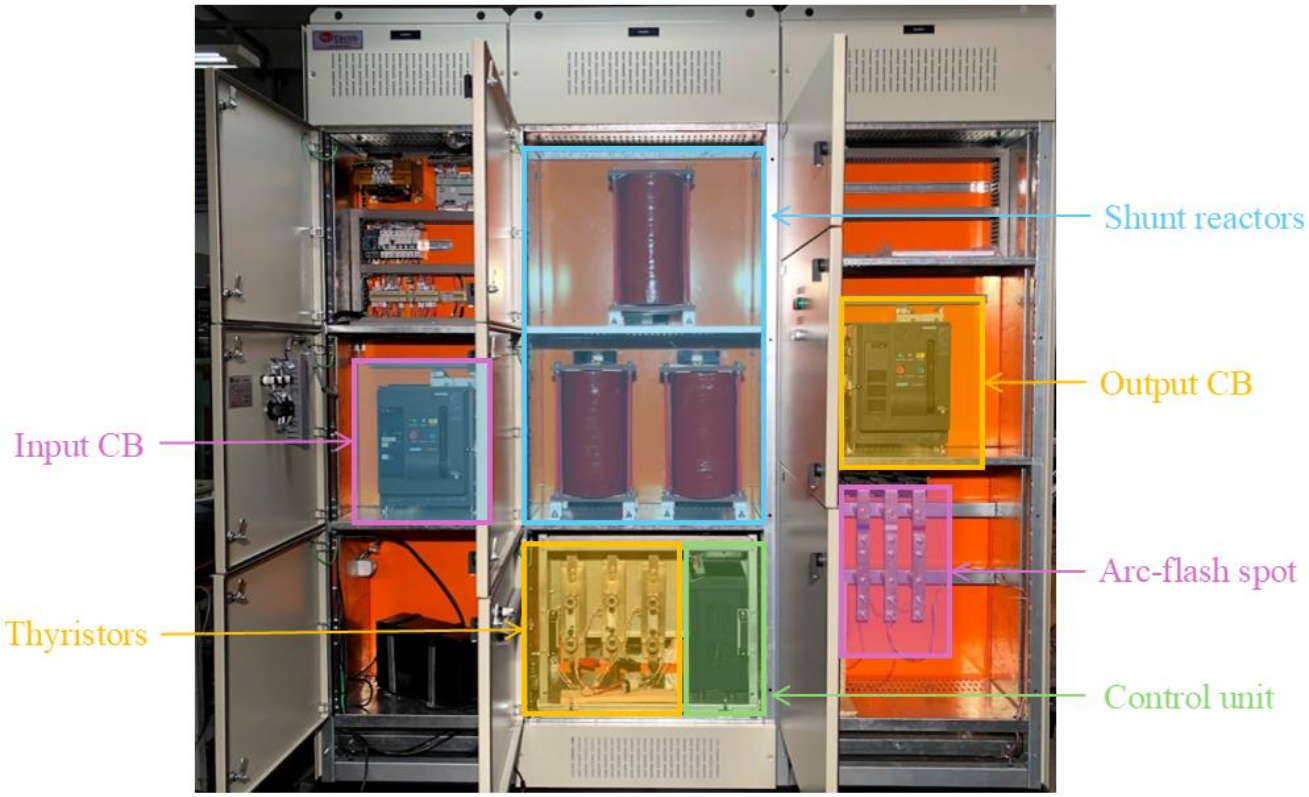

Fig. 2. A picture of the switchgear prototype.

The design and specification of the elements of the quenching device for such prototype are detailed below.

A. Shunt Impedances

These elements are single-phase, air-core, 40 µH reactors.for the first tests, which have been performed under reduced-current values. Over the course of the tests, these components have found to be bulk and larger than needed, being changed to 3.2 µH coils made of insulated cables. Besides operating as a current-limiting impedance, the reactors operate as a snubber that limitates the rate of rise of the current across the thyristors during the device turn-on.

B. *Thyristors*

Part number N3533ZC200 from Westcode has been adopted for the prototype. This part number is capable of withstanding a peak non-repetitive surge current of 50 kA. RC snubbers have been added in parallel with the switches to limit the rate of rise of the voltage during device turn-off.

III. Test Procedure

The tests have been executed at TESLA Power Engineering laboratory, in Universidade Federal de Minas Gerais (UFMG). In order to ensure safety for people and for the prototype, these tests have been progressively executed from soft - reduced current levels - to full operational conditions.

Fig. 4 presents a schematic diagram of the setup built to execute these experiments. To achieve reduced current levels, current-limiting reactors of 20 µH have been inserted in series with the 440 V power system, along with a 130 m long power cable of 10 mm^2, which increases the upstream impedance by $R_{cbl,ac} \approx 238$ mΩ and $X_{cbl} \approx 16.9$ mΩ. In addition, a 40 m long power cable with the same gauge (which results in $R_{cbl,ac} \approx 73.2$ mΩ and $X_{cbl} \approx 5.2$ mΩ) has been inserted between the switchgear output and a remote point where there is a short auxiliary copper bus short-circuited by a thin bare copper wire that triggers the arcing fault.

Three of the performed experiments are presented in this paper. In each one, the execution has been done twice, initially with the AF quenching device disabled (suffix a) and later with the equipment in normal operation (suffix b).

IV. Experimental Results

A. *Trial P1*

The first test (test P1: quenching device disabled - P1a, and quenching device active - P1b), has been executed with the configuration shown in Fig. 4. Fig. 5 / Fig. 6 and Fig. 7 / Fig. 8 show the waveforms registered during the execution of the tests P1a and P1b respectively. The trip signal from the arc flash relay (AFR) is also shown in Fig. 8. Notice how the busbar voltages are immediately quenched when the trip signal is toggled. In this case, however, the time interval (≈ 25 ms) from the beginning of the fault and the toggling of the trip signal was significantly longer than expected, especially due to the low fault currents and the consequent long period of time required to burn out the triggering wire. The flat-topped line-to-line busbar voltage has reached values of roughly 350 V during the fault, which has been promptly reduced to less than 100 V with the operation of the quenching device. Fig. 9 and Fig. 10 illustrate a comparison between the AF filmed during the tests at their worse (more intense) frames. These frames did not occur at the same instant from the beginning of their respective experiments.

Fig. 5. Busbar voltage (line-to-line) – trial P1a.

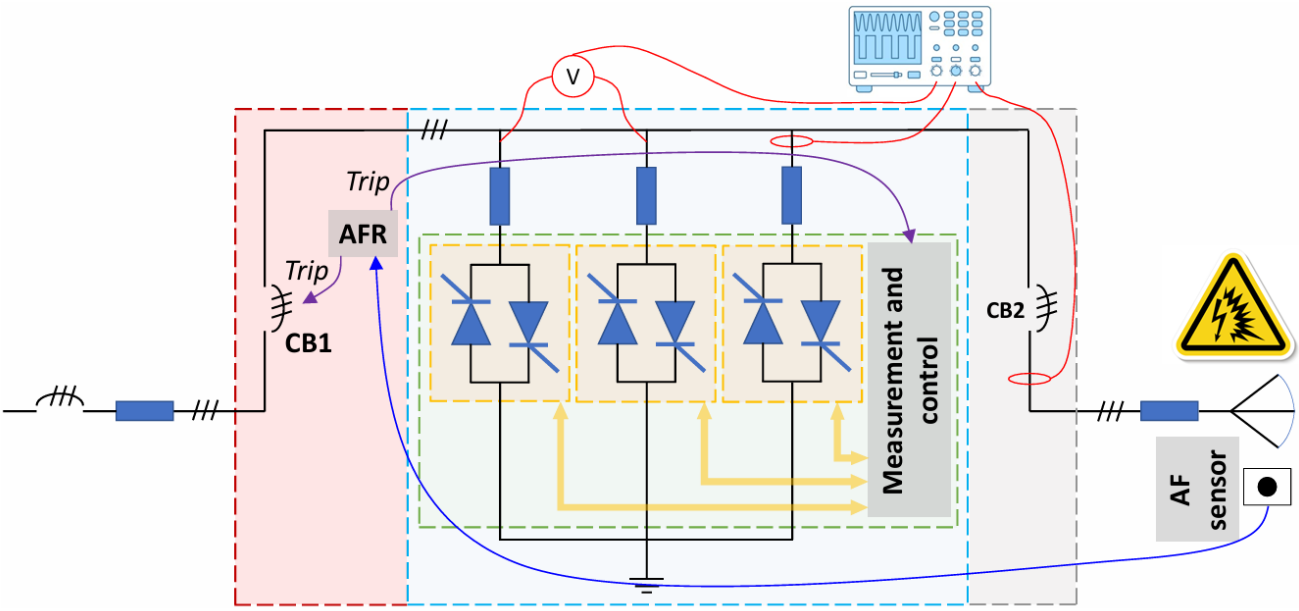

Fig. 4. Schematic of the laboratory experiments: incoming compartment (left, magenta), AF quenching device (center, blue) and output section (right).

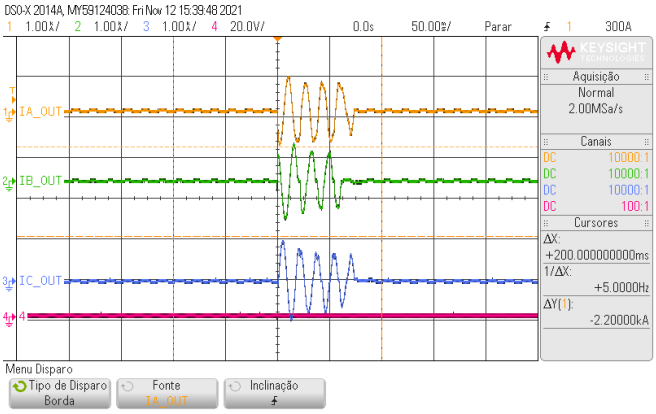

Fig. 6. Current through the arc – trial P1a.

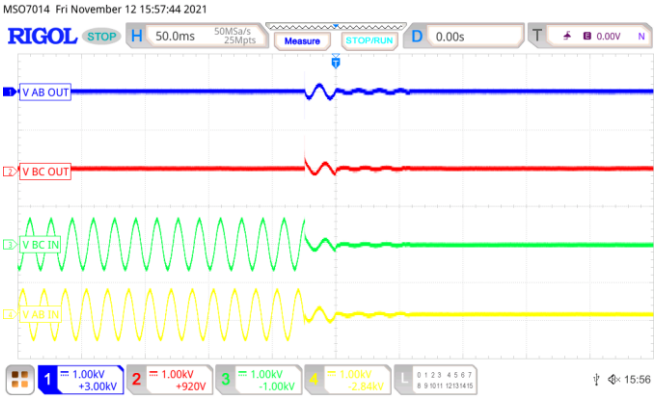

Fig. 7. Busbar voltage (line-to-line) – trial P1b.

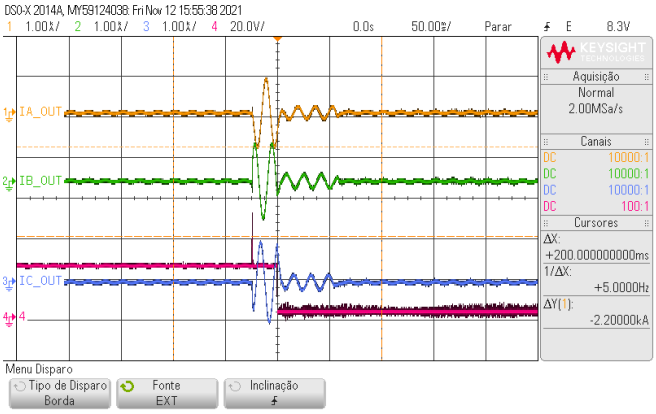

Fig. 8. Current through the arc and trip signal – trial P1b.

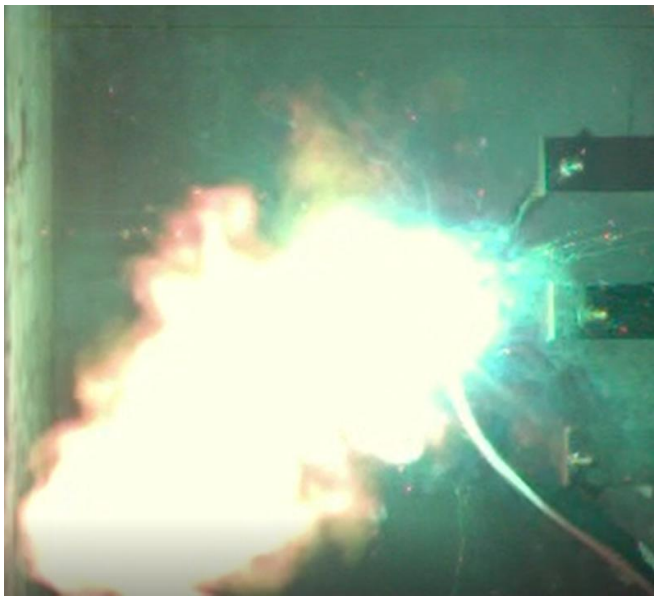

Fig. 9. Frame recorded during test P1a at its more intense moment.

Fig. 10. Frame recorded during test P1b at its more intense moment.

B. Trial P4

Before the execution of trial P4, the current-limiting reactors and power cables have been removed. Fig. 11 / Fig. 12 present the results acquired with the AF quenching device inoperative (P4a). The fault survived for approximately 60 ms, with the peak line-to-line busbar voltage less than 600 V and peak AF current of 4.3 kA. By repeating the test with the AF quenching device operative, the fault elimination was initiated practically at the same time the trip signal was issued by the AFR, which occurred 1 ms after the fault started. The time taken to complete the transfer of the arcing fault current to the quenching device was nearly 4 ms. The current through the device continued flowing for 19 ms, reaching a peak value equal to 7 kA. Fig. 13, Fig. 14 and Fig. 15 show the waveforms captured during the test P4b.

Fig. 11. Busbar voltage (line-to-line) – trial P4a.

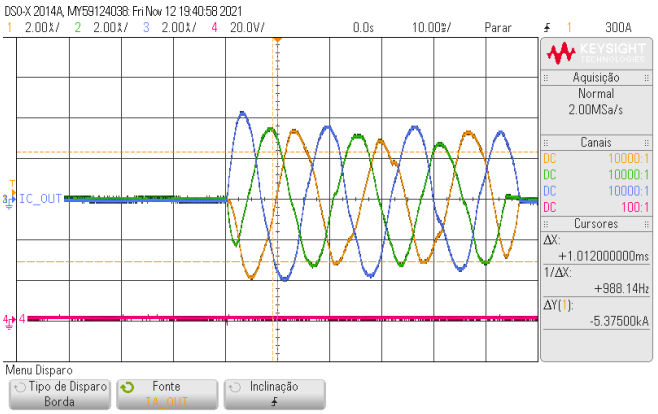

Fig. 12. Current through the arc – trial P4a.

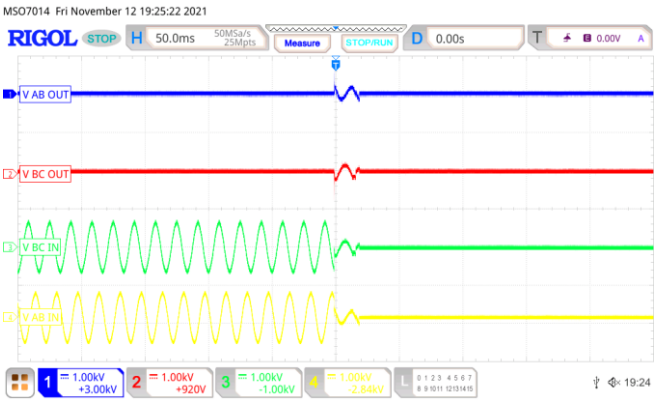

Fig. 13. Busbar voltage (line-to-line) – trial P4b.

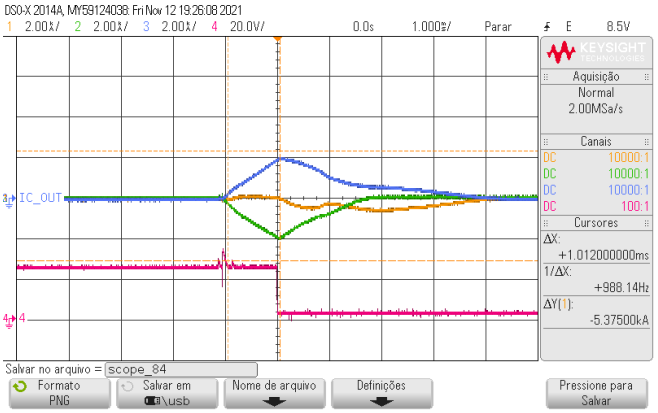

Fig. 14. Current through the arc and trip signal – trial P4b.

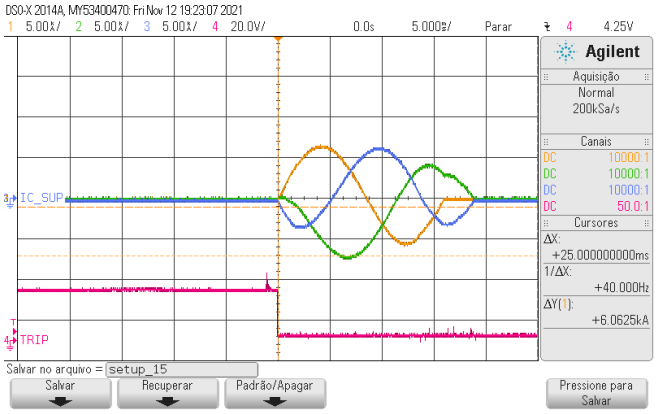

Fig. 15. Current through the quenching device – trial P4b.

Fig. 16 illustrates a frame of a video recorded during the execution of test P4a, while Fig. 17 shows the auxiliary busbar and the thin bare copper wire right after the execution of test P4b. Notice how a considerable part of the wire was found to be undamaged.

Fig. 16. A frame of a video recorded during trial P4a.

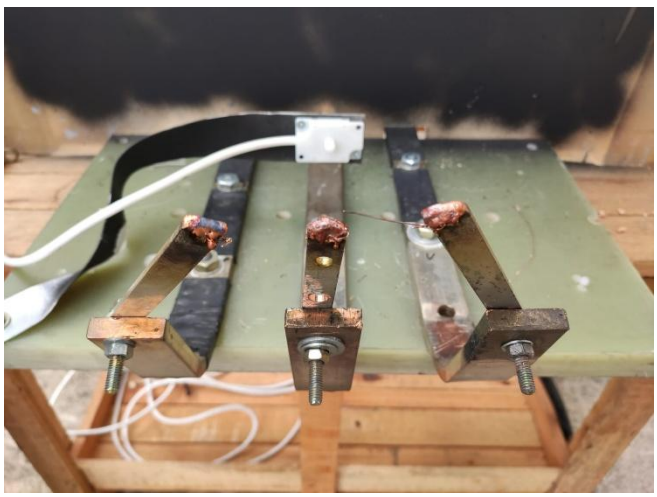

Fig. 17. Auxiliary busbar and thin copper wire after trial P4b.

C. *Trial P5*

Before the accomplishment of the last test, P5, the shunt impedances of 40 µH were finally replaced by the 3.2 µH coils. Fig. 18 to Fig. 20 represent the waveforms captured during the test, which has been performed only with the AF quenching device active. The time to detect the arc by the AFR

did not change in comparison to test P4b, but the time spent to transfer the current from the arcing path to the quenching device decayed to less than 600 µs. The peak current through the quenching device increased to 11 kA.

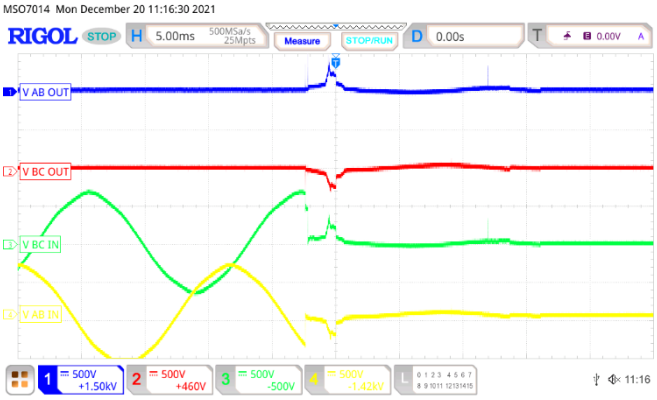

Fig. 18. Busbar voltage (line-to-line) – trial P5.

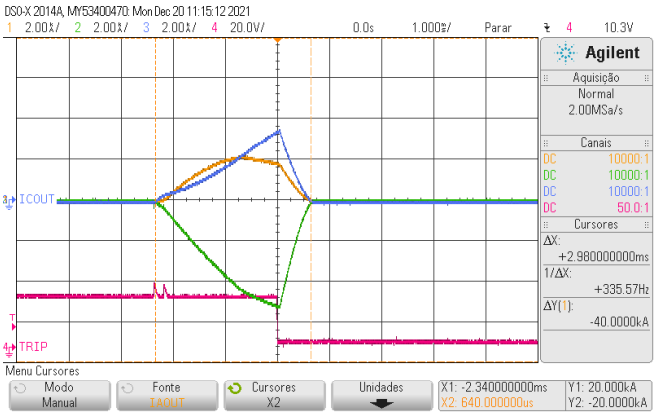

Fig. 19. Current through the arc and trip signal – trial P5.

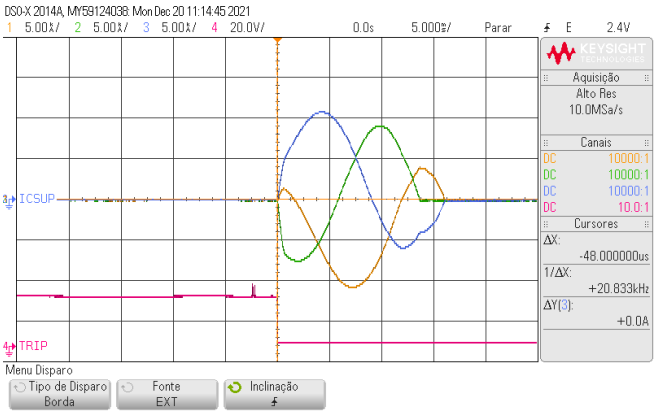

Fig. 20. Current through the quenching device – trial P5.

The electrical energy irradiated during the test has been calculated from the .csv files recorded in the experiment. To do so, the power-invariant Clarke transformation was applied to the line-to-line voltages and line currents. Then the three-phase active power has been calculated, as well as the electrical energy by taking the area under the power and transforming the result from joules to cal. Fig. 21 shows the obtained result.

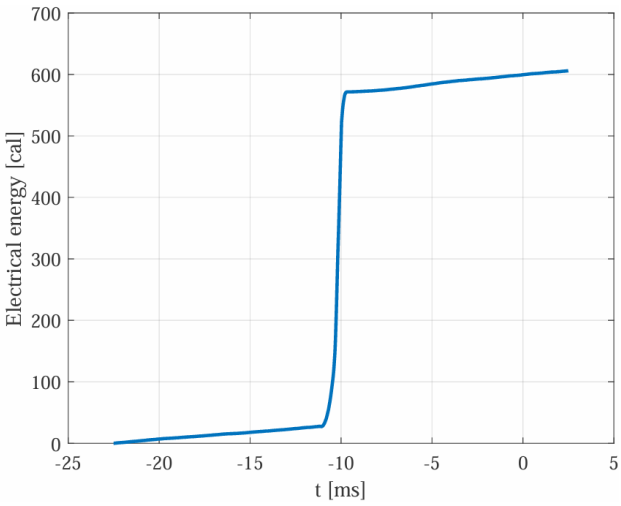

Fig. 21. Electrical energy dissipated – trial P5.

The calculated value quantifies electrical energy, not incident energy. The calculation of the IE demands that an electro-thermal energy conversion process is modeled according to the physical parameters of the switchgear, which in turn results in an energy density in cal/cm^2. Considering conservatively that all the energy propagates directly (or is 100% reflected from the other surfaces of the cubicle) to the open front door of a typical compartment of a switchgear and the operator is working at this surface, the energy density can be calculated as:

$$E_{a,sfc} = \frac{600}{80^2} = 0{,}09\,\frac{cal}{cm^2} \qquad (1)$$

where the frontal size of the compartment is 31.5” x 31.5”. This value is greatly below the threshold of 1.2 cal/cm^2.

D. Tests Executed at Cepel

The prototype discussed in this paper has been tested at the High Current laboratory (AP1) of Centro de Pesquisas de Energia Elétrica (Cepel / Eletrobras), where the switchgear has been subjected to the same tests that would be executed to certify an arc-resistant switchgear. It was fully tested according to IEC TR 61641:2014 [43] and testified to be compliant with the technical report. The main conditions of the test are: upstream power system with open-circuit voltage equal to 105% of the rated voltage, power factor of 0.25 (asymmetry factor of 2.1), three-phase symmetrical RMS short-circuit of 25 kA (peak current of approximately 52.5 kA) and duration of 300 ms [43].

V. Conclusion and Future Work

It has been shown in this paper, from extensive experimental results, that the electronic AF quenching device is effective for shunt arcing fault elimination in industrial / commercial LV power systems. The results obtained during the arcing fault experiments have made clear that once the AF quenching device is properly applied to the power system, the calculation of IE levels becomes dispensable. Instead, the computation of the electrical energy dissipated during the fault is more appropriate, being extremely advantageous since it does not involve geometric parameter-based empirical equations.

The development of a prototype for 690 V / 60 kA is currently being done, including enhancements on the assembly of the AF quenching device so that it becomes closer

of a product. The authors plan to extend the applicability to medium-voltage systems as well.

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Infrared Thermography for Incident Energy Measurement in Arc Flashes under VOA Configuration Supported by Statistical Analysis

Pedro Bacin
Institute of Energy and Mobility
Federal University of Santa Maria
Santa Maria, Brazil
pedro.bacin@acad.ufsm.br

Vitor Bender
Institute of Energy and Mobility
Federal University of Santa Maria
Santa Maria, Brazil
vitor.bender@ufsm.br

Márcio Bottaro
Energy and Ambient Institute
University of São Paulo
São Paulo, Brazil
marcio@iee.usp.br

Marina Camponogara
Institute of Energy and Mobility
Federal University of Santa Maria
Santa Maria, Brazil
marina.camponogara@acad.ufsm.br

Tiago Marchesan
Institute of Energy and Mobility
Federal University of Santa Maria
Santa Maria, Brazil
tiago@ufsm.br

Rafael Beltrame
Institute of Energy and Mobility
Federal University of Santa Maria
Santa Maria, Brazil
beltrame@gepoc.ufsm.br

Gilnei José Santos
CPFL Energia
Campinas, Brazil
gilnei.santos@cpfl.com.br

Carlos Simões
CPFL Energia
Campinas, Brazil
cas@cpfl.com.br

Bowen Zheng
State Grid Corporation
Beijing, China
zhengbowen@cpfl.com.br

Bo Tan
State Grid Corporation
Beijing, China
tanbo@cpfl.com.br

***Abstract*— Accurate estimation of incident energy (IE) in arc flash events is essential for improving electrical safety. This study explores the application of infrared thermography as a thermal sensing technique for calorimetric measurements, offering a non-contact alternative to conventional methods. Tests were performed in a high-current laboratory using a vertical open-air (VOA) three-phase electrode configuration, as defined in IEEE Std 1584-2018. A total of 20 paired measurements were collected under similar arc current and duration conditions, with IE values ranging from 0.91 to 1.02 cal/cm². These values were compared to estimates obtained from the IEEE Std 1584-2018 model. Statistical analysis included a paired t-test and the two one-sided tests (TOST), which assess statistical equivalence within predefined acceptance margins. The observed differences remained within acceptable limits, suggesting consistent behavior between thermographic measurements and standard-based estimations. Additional exploratory analysis was conducted to examine distribution characteristics and support interpretation. While not intended to replace conventional instrumentation, the thermographic approach demonstrated feasibility as a complementary method for IE estimation. Broader studies under diverse conditions are recommended to further evaluate its applicability.**

Keywords—arc flash, incident energy, IEEE Std 1584-2018, infrared thermography, high-current laboratory

I. INTRODUCTION

Arc flashes pose severe hazards in electrical systems due to their ability to produce extremely high temperatures, intense radiation, and molten metal ejections within a very short time. These effects can result in serious burns, injuries, and fatalities among workers [1]. Since the 1980s, scientific research has intensified to better understand the phenomenon and to estimate the incident energy (IE) released during arc flashes [2], initially driven by the theoretical model proposed by Lee [3]. These efforts have led to significant advancements, including the development of both theoretical and empirical models for IE calculation, such as the IEEE Std 1584-2018 [4], the establishment of safety standards like NFPA 70E® [5], and calorimetric measurement methodologies based on ASTM F1959/F1959M and IEC 61482-1-1 [6], [7].

However, despite notable advancements in arc flash research and safety practices, the actual reporting rate of arc flash-related incidents remains limited [8]. For instance, in Brazil, incidents caused by arc flashes are frequently underreported or misclassified, as available accident statistics often combine arc flash injuries with electrical shock data due

to legal, financial, and investigative challenges. As a result the true number of fatalities and injuries from arc flashes is likely higher than officially reported [9], [10]. Furthermore, studies from burn centers indicate that arc flash injuries represent a significant portion of electrical burn cases, further highlighting the potential underestimation of this hazard [11]. Therefore, accurate measurement and reporting of IE are important to strengthening worker protection.

Measurement of IE in arc flash testing has traditionally relied on calorimeters equipped with type K thermocouples, as recommended by standards such as ASTM F1959/F1959M and IEC 61482-1-1: 2019 [6], [7]. This methodology is widely acknowledged as the most robust and reliable for experimental evaluation of IE in arc flash scenarios. Nevertheless, certain limitations persist, including susceptibility to electromagnetic interference (EMI) and mechanical challenges related to sensor installation [12], [13].

In response, fiber optic sensing technologies have emerged as promising alternatives, combining high immunity to EMI and rapid thermal response, though some technical and cost-related challenges remain under investigation [14], [15]. Infrared thermography (IRT) has also been explored as a complementary method, initially through exploratory studies [16] and more recently through structured research efforts [10], [17], [18], proposing non-contact thermal monitoring of calorimeters for IE estimation. Despite challenges such as sensor saturation during the arc event, thermographic techniques offer advantages including EMI immunity and simplified installation, supporting continued research and development in this area.

This study investigates the estimation of IE during arc flash events by applying IRT to calorimetric measurements. Laboratory tests were conducted under a vertical open-air (VOA) three-phase electrode configuration—defined by vertically aligned electrodes positioned in open air without any enclosure—according to IEEE Std 1584-2018, and calorimetric arrangements based on IEC 61482-1-1 recommendations for IE measurement, with adaptations to enable non-contact temperature acquisition.

The thermographic IE measurements were compared against reference values calculated according to IEEE Std 1584-2018 through a comprehensive statistical evaluation. Paired t-tests were applied to assess significant differences, while the two one-sided tests (TOST) procedure was employed to investigate statistical equivalence. Complementary analyses, including nonparametric evaluations, were also performed to enhance the robustness of the validation process. The main objective of this study is to demonstrate the feasibility of IRT as a complementary method for IE estimation, initially validated under the VOA configuration but designed with potential for broader application to other arc flash scenarios. Its contribution lies in providing experimental validation and incorporating the use of TOST to strengthen confidence in the reliability of thermographic approaches.

To achieve this objective, the present paper is structured into five sections. Section II presents the theoretical basis concerning arc flash phenomena, IE estimation models, measurement principles, and statistical analysis techniques. Section III describes the experimental arrangement and outlines the methodology adopted for thermographic IE measurement. Section IV reports the results obtained, followed by a statistical evaluation using parametric and nonparametric analysis. Finally, Section V summarizes the main findings and discusses perspectives for future research.

II. Background and Theoretical Basis

This section presents the fundamental concepts supporting this study. It addresses the models used for IE estimation, discusses experimental approaches for IE measurement, and introduces the statistical techniques employed for data analysis and validation.

A. Incident Energy Estimation

The estimation of IE in arc flash events can be performed through different methodologies, depending on the system characteristics. In the present work, the methodology established by IEEE Std 1584-2018 was adopted due to its empirical robustness and solid experimental foundation. IEEE Std 1584-2018 provides two distinct models based on the system voltage: one for systems operating between 208 V and 600 V, and another for systems ranging from 601 V to 15,000 V, both models applicable exclusively to three-phase short-circuit conditions. The model corresponding to systems between 601 V and 15,000 V was selected, as it aligns with the experimental conditions addressed in this study. This methodology considers several key parameters for accurate IE estimation, including the open-circuit voltage (V_{oc}) available short-circuit current (I_{bf}), arc duration (t_{arc}), electrode gap (G), electrode configuration (vertical or horizontal, either enclosed or open), and working distance (d) [4].

Regarding the experimental setup, IEEE Std 1584-2018 specifies that, for each incident energy test, an array of seven copper based calorimeters must be positioned in front of the electrodes at a distance from their centerline. Three calorimeters are arranged horizontally at the same elevation as the electrode tips, another three are positioned 152.4 mm below this elevation, and one calorimeter is placed 152.4 mm above the center electrode tip. The middle calorimeters in each horizontal row are aligned with the center electrode [4]. In the experiments conducted for this study, this same arrangement was replicated, using a vertical open-air (VOA) configuration and a working distance of 800 mm, according to the recommendations of IEEE Std 1584-2018.

An example of the IE estimation, performed according to the IEEE Std 1584-2018 methodology, is presented in Fig. 1. This example was calculated using the spreadsheet tool made available through the IEEE DataPort™ platform [19], with additional validation carried out through internally developed calculation spreadsheets. The scenario illustrated in Fig. 1 was specifically selected as it corresponds to the experimental

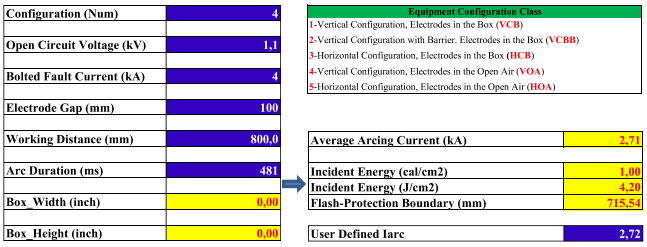

Fig. 1. Example of IE estimation based on IEEE Std 1584-2018 [19].

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conditions adopted throughout this study. In this approach, parameters such as arc current (I_{arc}) and t_{arc} were directly measured during the tests and combined with the other planned input parameters, were used to calculate both the IE and the arc flash protection-boundary (AFB).

B. Incident Energy Measurement

The calorimeters used for IE measurement were built following standardized dimensions and material guidelines to ensure reliable thermal measurements during arc flash events. Each calorimeter consists of a copper disc with a thickness of 1.6 mm ± 0.1 mm, a diameter of 40.0 mm ± 0.1 mm, and a mass of 18 g ± 1 g [7]. To enhance thermal radiation absorption, the exposed surface of the copper disks was coated with a high-temperature black matte spray paint, achieving an emissivity greater than 0.9 across the relevant wavelength range. This surface treatment was particularly important because the disks were monitored using IRT.

A modification was introduced to the original IEC design: the rear hole in the insulating support was increased from 3 mm to 10 mm to facilitate unobstructed infrared camera visualization. Based on sensor absorptivity analyses, copper calorimeters absorb at least 90% of the IE, allowing the absorbed and IE values to be considered equivalent [20]. The main dimensions of the copper disks and the insulating support are illustrated in Fig. 2.

Marinite A® was selected as the insulating support material for the calorimeters, primarily due to its greater availability in South American countries such as Brazil. Although Marinite P®, I&M®, or Monolux® 500 are the materials recommended by IEC 61482-1-1, the use of Marinite A did not result in significant deviations in temperature measurements. Previous studies have demonstrated that the thermal insulating properties of Marinite A are sufficiently similar for the purposes of IE estimation, with minimal influence on the measurement accuracy [13]. Therefore, the adaptation was deemed acceptable for the experimental procedures conducted in this study.

The IE estimation using copper-based calorimeters relies on the measurement of the temperature rise (ΔT) caused exclusively by the arc flash, from arc ignition to extinction. The estimation of IE primarily depends on the initial and final temperatures measured in the copper disk. This approach follows the principles of classical calorimetry and the first law of thermodynamics, relating the absorbed heat to the material's mass (m), specific heat capacity (C_p), and temperature change. Thus, the IE absorbed by the calorimeter was calculated by integrating the temperature-dependent C_p over the temperature interval, as shown in Eq. (1):

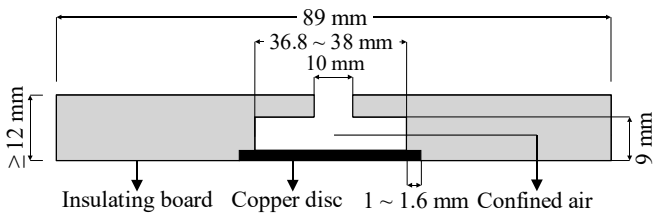


Fig. 2. Calorimeter construction details [7].

$$IE = \frac{m}{a \cdot 4.184 \cdot 10} \cdot \int_{T_0}^{T} C_p dT \quad (1)$$

where m is the copper mass (g), a is the exposed surface area (cm²), and T_0 and T are the initial and final copper disc temperatures (K), respectively. Since C_p varies with temperature, it was determined according to the Shomate equation using coefficients available from the National Institute of Standards and Technology (NIST) for copper in the solid state between 289 K and 1358 K [21], [22]. By solving the integral analytically using the Shomate polynomial expansion, the IE can be expressed in cal/cm² as shown in Eq. (2):

$$IE = \frac{10 \cdot m}{a \cdot 63.546 \cdot 41.840} \cdot \left[A \cdot (T - T_0) + B \cdot \left(\frac{T^2 - T_0^2}{2} \right) + C \cdot \left(\frac{T^3 - T_0^3}{3} \right) + D \cdot \left(\frac{T^4 - T_0^3}{4} \right) + E \cdot \left(\frac{1}{T_0} - \frac{1}{T} \right) \right] \quad (2)$$

where A, B, C, D, and E are the Shomate coefficients for copper[1] and 63.546 corresponds to the molar mass of copper.

In accordance with the recommendations of IEEE Std 1584-2018, the final IE estimation adopted for each test was the value corresponding to the calorimeter that exhibited the highest temperature rise among the seven sensors [4]. This conservative approach ensures that the maximum exposure scenario is captured in the risk assessment.

C. Statistical Approach

A statistical analysis was conducted to evaluate the reliability and equivalence of IE measurements obtained via IRT in comparison to reference values estimated according to IEEE Std 1584-2018. These reference values, derived from deterministic empirical equations, do not exhibit intrinsic variability. However, to account for small fluctuations observed during testing—primarily caused by variations in protection system interruption times and I_{arc} oscillations—a natural variability range was considered around the reference values. This adjustment ensured that the analysis reflected realistic experimental conditions without compromising the rigor of the evaluation. The statistical framework adopted included [23—27]:

- Descriptive statistics were applied to characterize the distribution of IE values obtained by thermography and those estimated from IEEE Std 1584-2018.
- A paired Student's t-test was conducted to assess whether statistically significant differences existed between the measured and estimated IE values, assuming normality of the paired differences.
- The TOST procedure was applied to assess the statistical equivalence between the thermographic measurements and IEEE Std 1584-2018 values. This method determines whether the difference between two paired samples lies within predefined equivalence margins, allowing a formal conclusion of equivalence rather than simply failing to reject a difference.
- Visual non-parametric analyses were employed to examine the data distribution, identify potential outliers, and evaluate agreement between the datasets without relying on specific distributional assumptions.

[1]Shomate coefficients for copper (solid, 298–1358 K): A = 17.72891, B = 28.09870 × 10^{-3}, C = −31.25289 × 10^{-6}, D = 13.97243 × 10^{-9}, and E = 0.068611 × 10^{6} [21], [22].

These combined analyses provided a robust and comprehensive assessment of both statistically significant differences and practical equivalence under the operational variability observed during laboratory tests.

III. Methodology

The arc flash tests considered in this study were conducted at the High Current Laboratory (HCLab) of the Institute of Energy and Mobility (IEM) at the Federal University of Santa Maria (UFSM), Brazil, which is equipped to perform high-current arc flash testing. The following subsections describe the experimental setup, including the main laboratory infrastructure, the test configuration, and the methodology for the IE measurement via IRT.

A. Experimental Setup

The laboratory infrastructure used for the tests is schematically illustrated in Fig. 3. The setup comprises a 5 MVA three-phase transformer, three single-phase adjustable reactors—each equipped with twelve taps for reactance regulation—and protection systems based on circuit breakers (CBs) and protective relays [28]. By adjusting the overall circuit impedance, this configuration allows for the generation of arc currents between 1 kA and 20 kA, ensuring reproducibility of I_{arc} levels across the different test conditions.

Arc ignition was initiated by positioning an ignition wire with a cross-sectional area of 0.5 mm² between the electrodes. Upon energization, the wire melted, initiating the arc flash, which was sustained until interruption by the low-voltage relay. The arc duration, determined by the relay operation time, significantly influenced the amount of energy released during each event. Precise control of arc extinction was essential, as even slight variations in arc duration directly affected the measured incident energy values. Current measurements were obtained using current transformers (CTs) installed at both sides of the system. To enhance accuracy, the acquired signals were processed with a cosine filter, as recommended in Annex G.5 of IEEE Std 1584-2018 [4], enabling determination of I_{arc} and t_{arc} for each test.

Thermal measurements during the arc flash tests were conducted using a FLIR® A6753sc MWIR thermal camera, as illustrated in Fig. 4. The camera was positioned to monitor the temperature rise of copper calorimeters arranged according to the VOA configuration adopted in this study. Optical parameters — such as emissivity, ambient temperature, and object distance — were configured through the FLIR® ResearchIR Max software to ensure accurate thermal recordings. Proper alignment of the camera and calorimeters ensured a clear line of sight and accurate thermal data acquisition, serving as the basis for estimating the IE absorbed by the sensors.

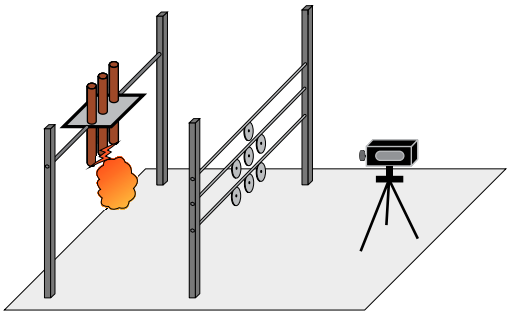


Fig. 4. Thermographic setup for IE measurement in VOA configuration.

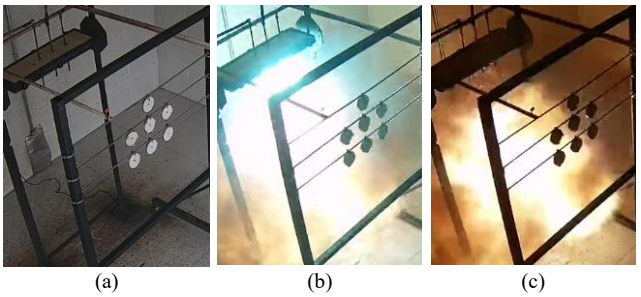
B. Incident Energy Measurement Using Infrared Thermography

To illustrate the methodology for IE measurement using IRT, a representative test condition within the scenarios analyzed in this study was selected. The configuration of this test is summarized in Table I and corresponds to the conditions used for IE estimation based on the IEEE Std 1584-2018 model shown in Fig. 1. Laboratory records captured before, during, and after the arc flash are presented in Fig 5.

The thermal recording of the test, conducted under the conditions specified in Table I and following the setup shown in Fig. 4, captured the behavior of the seven copper-based calorimeters. The camera was positioned at 3.4 m, which corresponded to the maximum distance that allowed all seven calorimeters to be framed using a 50 mm lens. The recording, performed at 100 Hz, extracted temperature readings within a 1.5-second interval from arc initiation, excluding frames within this interval that were affected by saturation during arc propagation due to fumes and extremely high plasma temperatures. Figs. 6(a) and 6(b) show the thermal images immediately before and after ignition. These data allowed the determination of the initial and final temperatures for each calorimeter, providing the basis for estimating the IE via IRT.

TABLE I. Thermographic IE Example Test Configuration

Configuration	V_{oc} (kV)		I_{arc} (kA)	t_{arc} (ms)	G (mm)	d (mm)
VOA	1,1		2,72	481	100	800



(a) (b) (c)

Fig. 5. Arc flash sequence for methodology example test. (a) Before ignition. (b) During arc propagation. (c) At extinction.

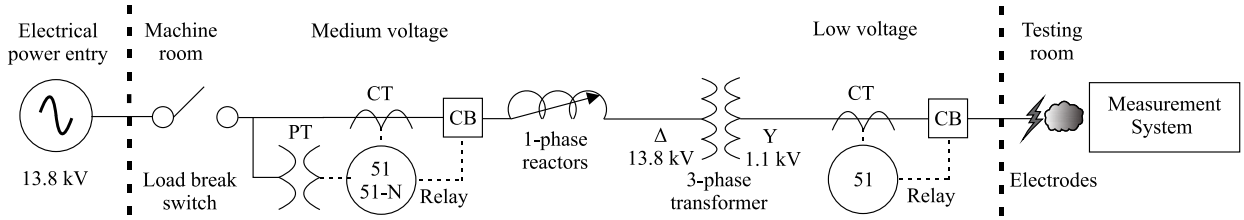
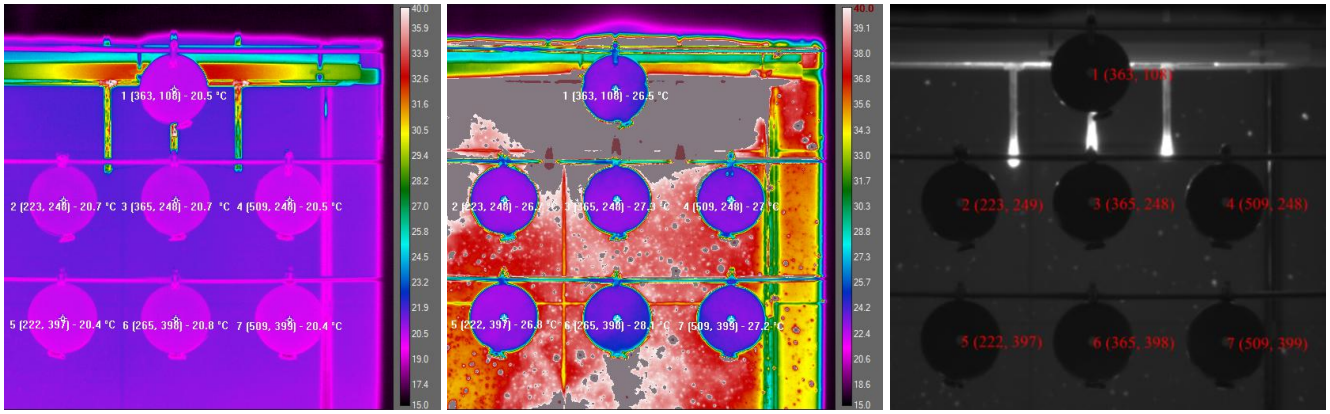


Fig. 3. Single-line diagram of High-Current Laboratory [28].



(a) (b) (c)

Fig. 6. Thermal recording of IE in calorimeters during an arc flash test under VOA configuration. (a) Thermal image before arc arc flash. (b) Thermal image after arc flash. (c) Identification of calorimeter coordinates for data extraction in external software.

The recorded thermal data were then exported from the FLIR ResearchIR Max software into *.mat* files for post-processing. In this procedure, thermal data were analyzed in MATLAB®, enabling the extraction of temperature values from specific coordinates associated with each calorimeter [17], [18]. Fig. 6(c) illustrates the identification of these coordinates, facilitating data extraction for IE evaluation.

Further data processing was performed through a dedicated algorithm developed in MATLAB. Initially, the algorithm reads the thermal data exported as *.mat* files from the FLIR ResearchIR Max software, containing the sequential temperature frames recorded during the test. The script organizes these frames in chronological order and associates them with the manually identified calorimeters' coordinates [17]. For each calorimeter, the algorithm calculates the average temperature within a defined region surrounding the selected coordinate, thereby minimizing local variability and measurement noise. To enhance signal stability, a four-point moving average filter is subsequently applied to the temporal temperature profile.

From the resulting temperature profiles, the minimum and maximum temperatures within the acquisition window were identified, providing the necessary information for IE estimation. Using these values and the C_p parameters established by IEC 61482-1-1:2019, the algorithm computes the IE absorbed by each calorimeter. An example of the temperature rise observed for each calorimeter under the representative test condition is illustrated in Fig. 7.

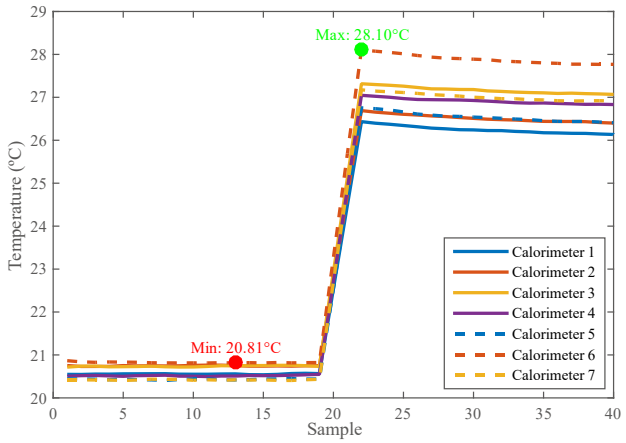


Fig. 7. Temperature rise in the calorimeters during the arc flash test.

As shown in Fig. 7, the calorimeter that exhibited the highest temperature elevation—and consequently the highest IE for this test condition—was calorimeter 6, previously identified in Fig. 6. For the scenario summarized in Table I, this calorimeter had an initial temperature of 20.81 °C (293.96 K) and reached 28.10 °C (301.25 K) after the arc flash test, resulting in a ΔT of 7.29 °C. The mass of this calorimeter was 18.375 g, and its exposed area was 12.566 cm². The C_p of copper over the temperature range was determined based on the Shomate equations, leading to an integrated enthalpy variation of approximately $1.784 \cdot 10^2$ J/mol, as expressed in Eq. (2). Considering these parameters and applying Eqs. (1, 2), the IE for calorimeter 6 was determined, as shown in Eq. (3).

$$IE = \frac{10 \cdot 18.375}{12.566 \cdot 63.546 \cdot 41.840} \cdot 1.784 \cdot 10^2 \cong 0.98 \text{ cal/cm}^2 \quad (3)$$

Based on the calculation presented in Eq. (3), the IE absorbed by Calorimeter 6 under the selected test condition was 0.98 cal/cm². For comparison, the IE estimated using the IEEE Std 1584-2018 model, as shown in Fig. 1, was 1.00 cal/cm². Thus, the IE measured by infrared thermography was approximately 2% lower than the value predicted by the IEEE model. When considering the average IE obtained across all seven calorimeters, the result was 0.89 cal/cm², corresponding to approximately 90% of the maximum measured IE. These findings reinforce the consistency between the experimental measurements and the standard-based estimations, providing a basis for further analysis in the following sections.

IV. Results

This section presents the statistical analysis performed to assess data normality, equivalence testing, non-parametric characteristics, and other relevant aspects. The objective is to provide a comprehensive examination of the measured and estimated IE values, emphasizing the degree of agreement between the thermographic measurements and the IEEE Std 1584-2018 estimations under the tested conditions.

Table II presents the results for the predefined VOA configuration, within the observed ranges of I_{arc} and t_{arc}. Due to practical limitations in reproducing identical values across all tests, I_{arc} varied from 2.54 kA to 2.72 kA, and t_{arc} ranged from 472 ms to 500 ms. The table summarizes I_{arc}, t_{arc}, ΔT, and IE values, measured by IRT and estimated by IEEE Std 1584-

TABLE II. INCIDENT ENERGY MEASURED BY INFRARED THERMOGRAPHY FOR THE VOA CONFIGURATION (V_{OC} = 1.1 KV, G = 100 MM, D = 800 MM) WITH ARC CURRENT AND DURATION RANGES OF 2.54–2.72 KA AND 472–500 MS.

Test*	I_{arc} (kA)	t_{arc} (ms)	ΔT (°C)	Measured IE (cal/cm²)	IEEE Std 1584-2018 IE (cal/cm²)	Dif. (%)	Test*	I_{arc} (kA)	t_{arc} (ms)	ΔT (°C)	Measured IE (cal/cm²)	IEEE Std 1584-2018 IE (cal/cm²)	Dif. (%)
1[a]	2,7	494	7,28	0,98	1,02	-3,92	11[d]	2,58	480	6,71	0,93	0,95	-2,11
2[a]	2,69	488	7,36	0,99	1,01	-1,98	12[e]	2,598	490	7,12	0,97	0,97	0,00
3[a]	2,63	485	7,44	1,00	0,98	2,04	13[e]	2,58	485	7,46	1,02	1,02	0,00
4[a]	2,54	481	7,10	0,95	0,93	2,15	14[d]	2,53	472	6,82	0,94	0,91	3,30
5[a]	2,57	493	7,10	0,95	0,97	-2,06	15[d]	2,52	500	7,09	0,97	0,96	1,04
6[b]	2,54	483	6,74	0,92	0,94	1,06	16[d]	2,596	490	6,82	0,94	0,97	-3,09
7[c]	2,69	496	7,19	0,98	1,02	-3,92	17[c]	2,602	472	6,90	0,94	0,94	0,00
8[a]	2,69	482	7,05	0,95	0,99	-4,04	18[c]	2,52	472	6,66	0,91	0,91	0,00
9[a]	2,72	481	7,33	0,98	1,00	-2,00	19[c]	2,54	473	6,67	0,91	0,92	-1,09
10[a]	2,69	489	7,63	1,02	1,01	0,99	20[c]	2,61	476	6,79	0,93	0,95	-2,11

General mean					
I_{arc}(kA)	t_{arc} (ms)	ΔT (°C)	Measured IE (cal/cm²)	IEEE Std 1584-2018 IE (cal/cm²)	Difference (%)
2,609	484,1	7,063	0,959	0,9685	-0,70

*Calorimeter with the highest temperature rise: [a]6, m = 18,375 g. [b] 2, m = 18.858g. [c]3, m= 18.609 g. [d]4, m = 18.852 g. [e]7, m=18.781 g.

2018, along with their percentage differences. These results served as the basis for statistical analysis aimed at assessing the agreement between experimental measurements and standard-based predictions.

A. Parametrical Analisys

Before initiating parametric analyses, it is necessary to verify the normality of the datasets. The Shapiro-Wilk test was applied to the IE values obtained by IRT and those estimated according to IEEE Std 1584-2018. To complement the statistical evaluation, a Q-Q plot was generated to visually assess the alignment of the sample quantiles with the theoretical quantiles of a normal distribution. The resulting plot is presented in Fig. 8.

As shown in Fig. 8, the data points for both methods generally align with the reference trendlines, indicating adherence to the normal distribution. The IE values measured by infrared thermography exhibit tighter clustered around the ideal line, with a higher coefficient of determination (R^2 = 0.9609) and Shapiro-Wilk statistic (W = 0.953, p = 0.409). In contrast, the IE values predicted by IEEE Std 1584-2018 show slightly greater dispersion from the reference line, with R^2 = 0.9513 and W = 0.936 (p = 0.198). Since the p-values for both datasets exceed the significance threshold (α=0.05), the hypothesis of normality cannot be rejected with 95% confidence. Therefore, the assumptions of normality required for applying parametric paired-sample tests are considered satisfied.

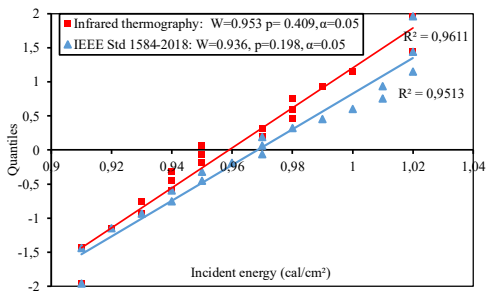


Fig. 8. Q-Q plot for IE measured by IRT and estimated by IEEE 1584-2018.

Although both datasets, as shown in Fig. 8, met the assumptions for parametric analysis, a small systematic bias between the two methods was observed. While this does not compromise the conclusions, future work may address this aspect to further improve agreement. Following the normality assessment, a paired-sample t-test was performed to verify whether the mean difference between the IE values measured by IRT and those predicted by IEEE Std 1584-2018 could be considered statistically significant. The null hypothesis (H_0) assumed that no difference existed between the mean IE values obtained by the two methods (H0=0). Thus, Table III summarizes the main statistical results obtained from the paired t-test.

The observed t-value (2.033) was slightly lower than the critical value (2.093) for a significance level of α = 0.05, while the p-value (0.0562) slightly exceeded the adopted significance level, leading to the non-rejection of H_0. The 95% CI for the mean difference ranged from −0.0003 to 0.0193 cal/cm², suggesting that, under the evaluated conditions, the true difference between the measured and estimated values is minimal and consistent with a scenario of limited discrepancy.

The standard error observed (0.0047 cal/cm²), corresponding to approximately 49% of the mean difference. This value reflects the intrinsic variability expected under experimental conditions involving arc flash tests. Although this percentage indicates a moderate level of dispersion relative to the mean, it remains consistent with the nature of high-energy transient phenomena and does not compromise the overall

TABLE III. PAIRED T-TEST RESULTS FOR IE VALUES EVALUATION.

Parameter	Value	Parameter	Value
Mean difference (cal/cm²)	0,095	Cohen's effect (d)	0,455
Standard deviation of differences (cal/cm²)	0.0209	Observed t	2.033
Standard error (cal/cm²)-(%)	0.0047 (49,18 %)	Critical t (α = 0.05, two-tailed	2.093
Confidence interval (95%)	[−0.0003, 0.0193]	p-value	0.0562
Correlation (r)	0,828	Decision (H_0)	Not rejected

reliability of the observed trend. While increasing the number of samples could reduce this variability, the destructive nature of the tests and the influence of multiple interacting parameters impose practical limitations on such an approach.

Additionally, the analysis revealed a good correlation coefficient (r = 0.828) between the paired data, indicating a high degree of consistency between the two results. The moderate Cohen's effect size (d = 0.455) suggests a practical difference, although modest and insufficient to reach statistical significance under the present conditions. The relatively narrow confidence interval (CI), combined with the effect size and observed correlation, supports the interpretation that the differences are minor and within experimental uncertainty, justifying progression to equivalence testing.

Although the paired t-test indicated no statistically significant difference between the measured and estimated IE values, this analysis alone is not sufficient to support the assumption that the methods are equivalent within predefined acceptance margins. To address this limitation, an equivalence analysis was performed using the TOST procedure. Acceptance margins of ±5% and ±2.5% relative to the mean IE value predicted by IEEE Std 1584-2018, were adopted to define practical limits for comparison.

In this scenario, H_0 assumed that the methods were not equivalent, while the alternative hypothesis (H_1) considered them equivalent within the specified margins. The TOST results confirmed equivalence for both acceptance ranges, with p-values falling in the 10^{-3} to 10^{-11} range and statistical power exceeding 90% in most cases. These results provide strong evidence to reject H_0 and support the equivalence of the IRT measurements to the IEEE Std 1584-2018 estimations under the tested conditions.

Fig. 9(a) complement these results by visually illustrating the distribution of the paired sample differences and their relation to the predefined acceptance margins. The paired points are closely distributed around the central axis, with small vertical displacements, reflecting agreement between the two methods. On the right side of Fig. 9(a), all individual differences fall within the ±5% margin, and the majority are also within the stricter ±2.5% margin. The 95% CI for the mean difference (−0.0003 to 0.0193 cal/cm²) lies entirely within both margins, emphasizing that the observed discrepancies are minor and consistent with the expected variation for this test scenario.

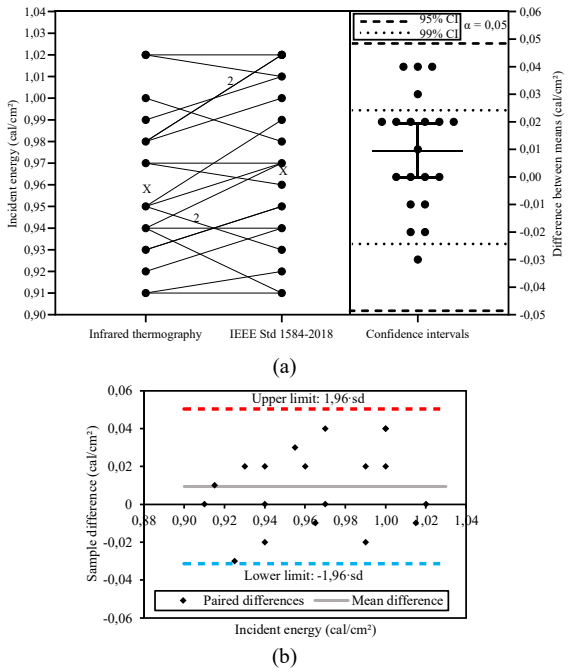


Fig. 9. Comparison of paired IE values: equivalence analysis. (a) TOST with confidence interval analysis. (b) Bland-Altman plot.

To further evaluate method agreement, a Bland-Altman plot was constructed, as shown in Fig. 9(b). The points were symmetrically dispersed around the central line, with no evidence of directional or proportional bias between the IRT and IEEE Std 1584-2018 estimations. All paired differences remained within the upper and lower agreement limits, defined as ±1.96 times the standard deviation of the paired differences, corresponding to approximately ±0.209 cal/cm². This range is similar in magnitude to the ±5% equivalence margin adopted in the TOST, suggesting that the observed dispersion lies within practically acceptable limits. Furthermore, no patterns or systematic deviations were observed across the range of measured IE values, indicating uniform variance.

B. Non-Parametrical Analisys

To complement the parametric evaluations, a non-parametric analysis was conducted by visualizing the distributions through the box plot and kernel density plot shown in Fig. 10.

The box plot in Fig. 10(a) reveals structural similarity between the two methods. Medians are slightly offset, with thermography presenting a lower value. The interquartile range is narrower for IRT, suggesting a tighter clustering of central values—likely influenced by variations in I_{arc} and t_{arc} observed across paired tests. Both methods span nearly the same minimum and maximum values, and the mean markers align closely with the medians, indicating low skewness in both cases. No outliers were identified using the 1.5·IQR criterion, and the general symmetry of the boxes supports the observation that both datasets share a consistent distribution pattern despite minor specific differences between methods.

The kernel density plot in Fig. 10(b) supports these findings through continuous distribution profiles. The

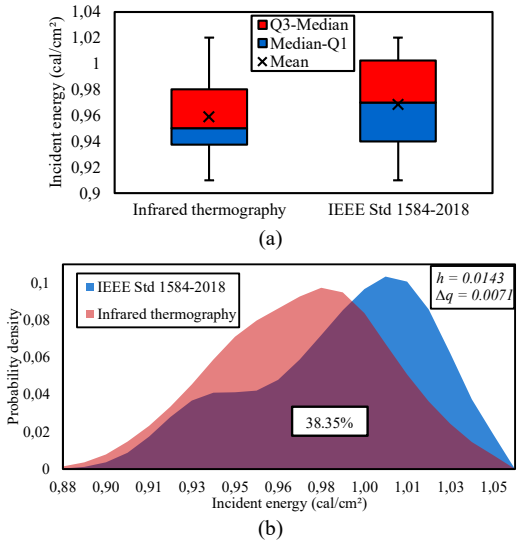


Fig. 10. Non-parametrical analysis. (a) Box plot. (b) Kernel density plot.

thermographic curve is broader and peaks earlier, while the IEEE density is narrower and more centralized. A central overlap of 38.35% between the distributions reflects moderate similarity, particularly around the median region. This overlap reinforces the interpretation drawn from the box plot: despite differences in symmetry and spread, both methods capture a comparable energy distribution in their central values, with variations becoming more evident in the distribution tails.

V. Conclusion

This study investigated the use of infrared thermography as a complementary approach for estimating incident energy in arc flash tests, offering a non-contact alternative to traditional calorimetric techniques, addressing limitations inherent to conventional methods, such as sensor mounting complexity and susceptibility to electromagnetic interference.

Experimental assessments conducted using a vertical electrode in open-air configuration demonstrated that thermographic measurements exhibited behavior consistent with the estimations derived from IEEE Std 1584-2018. Statistical analysis supported this observation: no significant differences were detected via the paired t-test, and the Two One-Sided Test confirmed equivalence under reasonable acceptance margins, suggesting that both methods converge under the evaluated test scenario.

Result obtained indicates that infrared thermography can be a viable complementary method, particularly in environments where conventional sensor deployment is restricted or invasive. Its use may help expand the range of tools available for arc flash diagnostics without compromising measurement accuracy and reliability. Further studies under varied configurations and larger sample sizes are recommended to strengthen the applicability of this methodology.

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Good Practices for Incident Energy Reduction in Electrical Substations at Porto de Tubarão

Thallis H. Felipe Teixeira
Vale S.A
thallis.henrique.felipe@vale.com

Edmilson José de Castro
Vale S.A
edmilson.jose@vale.com

Antonio Silveira Martins
Vale S.A
antonio.silveira.martins@vale.com

Raphael Alasia
Vale S.A
raphael.alasia @vale.com

Moises Cabral
Vale S.A
moises.cabral@vale.com

***Abstract* — This article details the implementation of a comprehensive program for mitigating arc flash risks in industrial electrical substations. The study, focused on reducing incident energy to safe levels, employed a rigorous methodology that included the analysis of 83 critical points. The implemented solutions encompassed the optimization of protection parameters in Intelligent Electronic Devices (IEDs), the implementation of remote tripping logics (transfer trip), which ensure ultra-fast circuit breaker operation, and the installation of dedicated arc flash relays. The results demonstrate a successful reduction of incident energy to values below 8 cal/cm² at all analyzed points, a crucial threshold for operational safety. This work not only validates a structured approach to electrical safety but also serves as a replicable model for similar facilities seeking to enhance their electrical safety practices and operational reliability. The expanded impact analysis reveals significant improvements in worker safety and electrical system resilience.**

***Keywords* —** *Arc Flash, Incident Energy, Electrical Substation, IEDs, Electrical Safety, Risk Mitigation.*

INTRODUCTION

Electrical safety represents an essential element in the operation of large and complex industrial facilities, such as Porto de Tubarão , located in Vitória-Brazil. The presence of extensive power electrical systems with high energy levels introduces significant inherent risks, among which the arc flash phenomenon stands out due to its potential severity. Mitigating the risks associated with this phenomenon goes beyond mere regulatory compliance, becoming a critical operational necessity for preserving workers' physical integrity and ensuring the continuity and reliability of industrial operations. This article presents a case study focused on the good practices implemented to reduce the incident energy associated with arc flashes in the substations of the aforementioned port, detailing the methodology, results achieved, and lessons learned throughout the process.

I. THEORETICAL FOUNDATION AND PROBLEM CONTEXTUALIZATION

A. Theoretical Foundation

Electrical safety in industrial environments is a primary concern, and the risk of arc flash represents one of the most significant hazards. An arc flash is a high-energy electrical discharge that occurs when electrical current jumps from one conductor to another or to ground through the air. This phenomenon can generate extremely high temperatures, explosive pressures, and the emission of intense light and noise, resulting in severe burns, traumatic injuries, and even fatalities for exposed workers.

Incident energy is the amount of thermal energy that can be released onto a surface at a given distance from an arc flash, typically measured in calories per square centimeter (cal/cm²). Assessing incident energy is fundamental for determining Personal Protective Equipment (PPE) requirements and for implementing engineering measures to mitigate risks. Standards such as NFPA 70E [1] and IEEE 1584 [2] provide guidelines for conducting arc flash studies and selecting appropriate PPE.

It is crucial to understand that, in the incident energy analysis process, PPE category is not a calculation premise or an initial selection criterion, but rather a consequence of the calculated incident energy value. NFPA 70E [1] and IEEE 1584 [2] establish methodologies for calculating incident energy (in cal/cm²) at a specific point in the electrical system. Based on this calculated value, and not the other way around, the appropriate PPE category for the task and working distance is determined. The industry commonly adopts the threshold of 8 cal/cm² for implementing additional engineering controls, aiming to reduce incident energy to a level that allows for the selection of more ergonomic and safer PPE, corresponding to the values stipulated for the lower risk categories of NFPA 70E.

Arc flash mitigation measures can be classified into several categories, including:

1) Protection Setting Optimization: Involves recalibrating protective devices (relays, circuit breakers) to operate more quickly in the event of a fault, reducing arc exposure time and, consequently, incident energy. This is often the first and most economical measure to consider.

2) Transfer Trip Logics: Involves communication between protective devices at different points in the system. A relay detecting a fault can send a signal to an upstream circuit breaker, causing it to operate quickly and isolate the fault before incident energy reaches dangerous levels. This solution is particularly effective in complex and interconnected systems.

3) Dedicated Arc Flash Relays: These are devices specifically designed to detect the light and/or current of an arc flash. Their operation is extremely fast, often in milliseconds, making them one of the most effective solutions for drastic incident energy reduction, especially in locations with high short-circuit currents and long operating times for conventional protections.

These approaches, when applied in an integrated and hierarchical manner, enable effective management of arc flash risk, protecting personnel and infrastructure..

II. METHODOLOGY

The starting point for this work was a comprehensive incident energy study encompassing 635 electrical panels distributed across 79 substations. The study followed the IEEE 1584 standard, utilizing PTW SKM Tools for systems up to 15 kV and ArcPro software for 34.5 kV systems. From the total panels analyzed, 83 critical points were identified with incident energy (IE) levels exceeding the 8 cal/cm² threshold. Based on these findings, an internal team was assembled to develop and execute a targeted mitigation action plan.

To manage the process of analyzing and implementing solutions, a detailed control directory was created. This tool proved essential for recording and tracking the progress of each of the 83 critical points. For each point, a row in a spreadsheet contained crucial information, including panel location, nominal voltage, incident energy calculated in the initial study (column “Incident Energy Before”), description of the analysis performed and possible mitigating actions considered (column “Mitigating Action”), the engineering solution effectively implemented (column “Definitive Action”) and, finally, the new incident energy value calculated after implementing the solution (column “Incident Energy After”).

The team responsible for the action plan held weekly meetings to discuss each risk point individually. During these meetings, they analyzed the specific characteristics of the installation, operational conditions, and possible engineering solutions to reduce incident energy. The alternatives considered included adjustments to protection parameters of existing Intelligent Electronic Devices (IEDs), implementation of additional protection logics such as transfer trip, and installation of new protection devices, such as arc relays.

For each of these points, the engineering team applied a technical decision logic to select the most appropriate mitigation measure. This logic can be visualized in the Technical Decision Flowchart (Figure 1), which guided the choice among the different available solutions:

IED Settings Optimization: This was the first and preferred mitigation measure. It consisted of reviewing and adjusting the time and current parameters of existing Intelligent Electronic Devices (IEDs), such as protective relays, to ensure faster operation in the event of a fault. This solution was considered whenever the reduction of incident energy to below 8 cal/cm² could be achieved without compromising the selectivity and coordination of the protection system. This approach was successful in 63 of the 83 critical points, demonstrating its effectiveness and cost-benefit.

Implementation of Transfer Trip Logics: In cases where IED settings optimization was not sufficient to achieve the incident energy target or when it resulted in compromised selectivity, the next step in the decision logic was to evaluate the feasibility of transfer trip logics. This solution involves communication between protective relays and upstream circuit breakers, allowing for ultra-fast tripping of the circuit. This measure was applied at 7 points where coordination with other devices and the system architecture allowed for its effective implementation.

Installation of Dedicated Arc Flash Relays: For the most challenging points, where the first two approaches were not technically feasible or did not provide the necessary incident energy reduction, the installation of dedicated arc flash relays was chosen. These devices, which detect the light and/or current of an arc flash, offer the fastest possible operation, being the last resort solution to ensure safety. This measure was implemented at the remaining 9 points, typically in low-voltage panels with high short-circuit currents and intrinsically longer operating times.

Deactivation and Load Migration: In 4 panels, the adopted strategy was total deactivation, followed by the migration of loads to panels that presented incident energy levels below 8 cal/cm². This measure contributed to eliminating critical points without the need for additional technical interventions, increasing operational safety.

Each proposed change underwent simulation in PTW SKM Tools software to verify its effectiveness in reducing incident energy and ensure there would be no negative impact on the selectivity and coordination of the protection system. In all panels with voltage above 15 kV, the initial study with ArcPro for 34.5 kV resulted in data <8 cal/cm². The validation simulations of mitigations focused primarily on protection adjustments and their impacts on the system, using PTW SKM Tools as the main tool for coordination analysis and verification of operation time reduction, a key factor in IE reduction, regardless of voltage. Only after validation by simulation and approval by the technical team was the definitive action implemented in the field and the new incident energy value recorded in the control spreadsheet (recalculated with the appropriate tool for the point’s voltage, if necessary, or confirmed by the reduction in operation time).

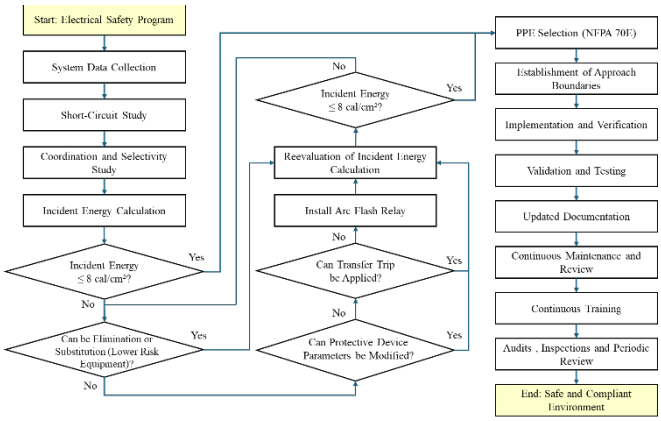

Fig. 1 Tubarão Port's technical decision flowchart for arc flash mitigation

III. RESULTS

A. *Initial Risk Assessment*

The arc flash study of 635 electrical panels across 79 substations at Porto de Tubarão revealed:

- 83 critical panels (13.1%) with incident energy (IE) >8 cal/cm² (per IEEE 1584-2018)
- 3 extreme-risk panels with IE exceeding 36 cal/cm² (maximum: 39.7 cal/cm² at Panel SC-20)
- 78 panels requiring NFPA 70E Category IV PPE
- 18 substations where arc flash boundaries encompassed entire electrical rooms

B. *Mitigation Strategy Implementation*

The application of the described methodology resulted in significant incident energy reduction across all 83 critical points analyzed in the electrical substations of Tubarão Port.

As illustrated in Fig. 2, the hierarchical approach achieved risk reduction through:

1) IED Optimization (63 panels, 76%): Reduced clearing times by 40-60% through coordination studies (PTW SKM Tools)

2) Transfer Trip Logic (7 panels, 8%): Achieved <100 ms fault isolation in interconnected systems

3) Arc Flash Relays (9 panels, 11%): Installed ABB REA-101 (<5 ms operation) in all extreme-risk panels

4) Decommissioning (4 panels, 5%): Load migration to safer panels with IE <4 cal/cm²

C. *Performance Metrics*

This outcome is critical, as it enables maintenance and intervention operations to be performed with lower-risk PPE (typically Category 2), enhancing worker safety and operational efficiency.

- Post-implementation analysis demonstrated:
- 100% compliance with IE <8 cal/cm² across all panels
- Elimination of Category IV PPE requirements
- 83.3% reduction in arc flash boundary distances
- 40% decrease in PPE donning time (from 12.5 to 7.5 minutes)

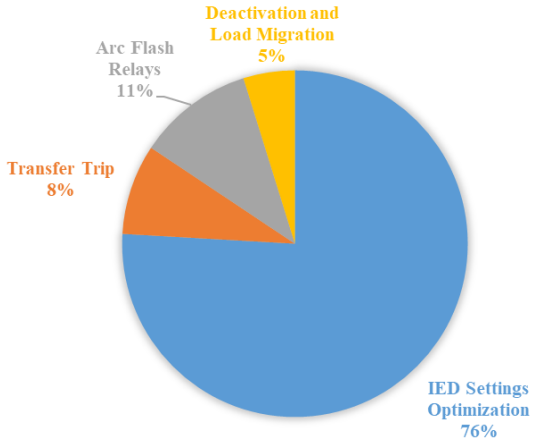

Figure 2 Mitigation Techniques Used

To illustrate the impact of interventions, Table 1 presents a summary of incident energy values before and after implementation for a representative sample of critical points.

TABLE 1 – INCIDENT ENERGY REDUCTION AFTER INSTALLATION OF ARC FLASH RELAYS

Substation	Busbar	Voltage (kV)	IE Level Before	IE Level After
EP-01	CCM-EP-01-B1	0.46	31.3	0.91
RCP-09	CJMB-812I-51	0.46	14.40	3.75
SC-03A	CJM-03AB1	0.46	10.3	6.52
DN-05	CCMBT	0.46	22.12	7.20
DN-06	+EH.T1-T7	0.51	38.25	6.42
DN-07	EHS2	0.60	36.85	4.85
SC-20	CJM-20B1	0.46	39.70	1.07
SC-CM01	CJM-CM1B2	0.46	12.40	3.75
SC-CM01	CJM-CM1B1	0.46	12.40	3.75

D. *Visual Documentation*

Figure 3 ABB REA-01 Arc Flash Relay installed in Panel SC-20

Fig. 3 shows the installed ABB REA-101 Arc Flash Relay in Panel SC-20 (March 2025 deployment). The relay installation reduced SC-20's incident energy by 97.3%, enabling:

- Maintenance under Category II PPE (8 cal/cm² ATPV)
- Elimination of de-energization requirements per NFPA 70E 130.2(A)

Figure 4 ABB REA-01 Arc Flash Relay installed in SCVV04/05 with Transfer trip

Most points were resolved with IED optimization, which represented the most economical and quickly implemented solution. Cases that required *transfer trip* or arc flash relays were those where the system complexity or the need for ultra-fast operation demanded more advanced solutions.

IV. Discussion

This study demonstrates an effective, structured, and replicable methodology for mitigating arc flash hazards in industrial substations. The primary objective of reducing incident energy to below the 8 cal/cm² threshold was achieved across all 83 identified critical points, a significant outcome that directly enhances personnel safety. The success of this project was rooted in a methodical, hierarchical decision-making process, which prioritized engineering controls while preserving the operational integrity of the power system.

The project also proved its worth economically through a clear and quantifiable strategy. By prioritizing IED optimization, which was the most affordable and quickest solution, the team avoided major capital expenses for the majority of the panels. To put this in perspective, the material cost alone for installing a single arc flash relay is around US$ 7,000, and that doesn't even account for the specialized labor and operational downtime needed to de-energize the panels. This stands in stark contrast to the low or zero capital cost of simply re-adjusting the settings of existing protective relays. This disciplined approach ensured that the investment in hardware was only made where it was absolutely necessary, proving the economic efficiency of our methodology.

Beyond the measurable safety improvements, the project also delivered some key operational benefits. Our technicians reported they had more mobility while performing maintenance tasks after switching to Category II PPE. On top of that, maintaining selective coordination prevented costly production shutdowns during fault events. The technical decision flowchart (Figura 1) delivered on its promise, achieving a dual benefit of lower incident energy while keeping the system reliable. Operational data confirmed that our optimized protection settings worked perfectly, with zero misoperations recorded across all 83 modified panels during live work.

The methodology's particular value lies in its adaptability. The technical decision flowchart (Figure 1) proved equally effective across a range of systems, from simple IED optimizations to the targeted installation of Arc Flash relays in extreme-risk locations. This demonstrates the approach is not only effective but also highly scalable and robust, proving its worth for:

- 15kV switchgear with electronic relays
- 34.5kV systems with modern IEDs
- Mixed protection architectures common in brownfield sites

V. Conclusion

This comprehensive arc flash risk reduction program achieved three key milestones at Tubarão Port:

1) Safety Transformation: All 83 critical panels now operate below 8 cal/cm²

2) Operational Integrity: Maintained 100% protection system selectivity

3) Knowledge Transfer: Developed institutional expertise in hierarchical mitigation

The study's most significant insight confirms that existing protection systems, when properly optimized through methodical coordination studies, can address most arc flash hazards without capital-intensive replacements. Future work will explore dynamic protection coordination, but the current methodology already provides facility managers with a proven template for balancing safety and productivity.

Ultimately, the project's legacy extends beyond technical specifications - it has established a new safety culture where risk-aware design decisions become second nature for both engineers and operators.

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Epidemiology of accidents involving electric shocks in residential areas in Brazil.

Wallace Espírito Santo de Oliveira
Interdisciplinary Center for Energy Planning Studies - NIEPE
Federal University of Mato Grosso – UFMT
Cuiabá, Brazil
https://orcid.org/0009-0004-5942-5131

Walter Aguiar Martins Junior
IEEE Member
Brazilian Association for Awareness of Electrical Hazards - Abracopel
Cuiabá, Brazil
https://orcid.org/0000-0003-1134-0548

Edson Martinho
Brazilian Association for Awareness of Electrical Hazards - Abracopel
Cuiabá, Brazil
https://orcid.org/0000-0003-4934-0797

Daniel Majano
Electrical Safety Foundation International – ESFI
Arlington, United States
https://orcid.org/0000-0002-2152-0596

Danilo Ferreira de Souza
Federal University of Mato Grosso – UFMT
University of São Paulo – USP
Cuiabá, Brazil
https://orcid.org/0000-0002-1155-1778

***Abstract*—The widespread use of electricity in society, while beneficial, has led to an increase in electrical accidents, with electric shocks being a significant concern in residential areas. Despite their severity, data on these incidents in Brazil are often underreported, creating a knowledge gap that hinders the development of prevention policies. This study aimed to analyze the epidemiology of electric shock accidents in residences in Brazil from January 2014 to September 2024, focusing on the direct causes and victim profiles (sex, age, profession), aiming to provide a basis for electrical safety policies. Methodologically, 2415 cases were identified through keywords such as "Electric shock", “Electrocution”, and “Residential”, detailing the accident period, location, victim and accident characteristics. The results include 2010 fatalities among 2415 accidents (CFR: 83.2%). The main causes were Contact with Wiring or Internal Electrical Installations (35.0%) and Contact with Home Appliances or Electronics (29.5%). Males accounted for 70.22% of the victims (1696 out of 2415), predominantly in the 21 to 50 age group, while children (0 to 5 years) also emerged as a vulnerable group. In conclusion, residential electric shocks in Brazil represent a serious public health problem.**

Keywords*—*electric shocks, electrical installations, household appliances, electrical safety, residential accident, accident prevention, accident statistics.

I. INTRODUCTION

Among the differences between modernity and contemporary times, the use of electricity stands out. In particular, the breadth of ways in which it was used to replace animal and human power [1]. With the advent of the Second Industrial Revolution at the end of the 19th century, electricity began to be used in daily life, resulting in the electrification of industrial processes, means of communication, transportation, and leisure [2]. With this change, society became more dependent on electricity, causing changes in behavior and consumption. [3], [4]. In residences, the same pattern was perceived, with the appearance of electrical appliances to replace human labor and provide a better quality of life.

However, despite its benefits, the inadequate use of electricity has caused several large and small-scale accidents throughout human history [5]. Currently, it is possible to categorize accidents caused by electricity into three (“3”) major groups:

Electric Shock – Resulting from direct or indirect contact with an electricity source or an object subjected to electricity (e.g., Contact with an energized wire).[6].

Electrical Fire – Resulting from Short Circuits, Overloads, Electric Arcs, etc. (e.g., Sparks from an installation in contact with flammable material)[7].

Lightning – Frictional Sparking and other electrostatic phenomena (e.g., Atmospheric discharge on a day of heavy rain).[8].

Among the categories mentioned, electric shocks stand out as a common situation, with indices pointing to 54.42% of accidents in Brazil [9], [10]. Additionally, such accidents occur mainly in overhead distribution and transmission

lines (38.36%), followed by residential areas (22.36%) and commercial buildings (6.28%)[10], [11]. However, the losses caused by these accidents are underreported and made invisible, resulting in insufficient prevention policies. Despite technological advances involving methods to enhance user safety, few countries have organized data on electrical accidents in residences or scientific literature addressing such events [12], [13]. Consequently, making it impossible to identify the main situations, victims, and affected regions, resulting in difficulties in implementing electrical safety policies. [14].

Using the database provided by the Brazilian Association for Raising Awareness of the Dangers of Electricity (Abracopel), this study aimed to evaluate accidents along three (“3”) central axis:

Direct Causes of Accidents – Proposing specific categories and possible justifications for their occurrence. Victim Profile – Sex, Age, and Profession, cross-referencing demographic and socioeconomic patterns of the occurrences.

The study was organized as follows. Section II presents the methodology used, based on the analysis and processing of news reports involving accidents that occurred in the period from January 2014 to September 2024. This is followed by Section III with results and discussions, where the main data obtained regarding residential electrical accidents are presented, along with justifications for their occurrence. Finally, Section IV is presented, highlighting the study's relevance for the political basis of safety standards.

II. METHODOLOGY

Using an alert monitoring tool, keywords of interest were recorded, namely five (“5”):

1. Electric shock.
2. Short circuit.
3. Overload.
4. Electrical discharge.
5. Electrocuted.

The selection of the five keywords was based on two main criteria. The first was the ability of these terms to cover the widest diversity of recorded electrical accident cases. The second criterion was the high frequency with which these words are used by media outlets to report such occurrences.

In total, Abracopel received numerous emails daily, resulting in the collection of 2415 records between January 2014 and September 2024; however, an extensive review of the emails received was necessary to avoid discrepancies in the database, the main reasons being:

1. More than one e-mail reporting the same case (various sources).
2. Events outside the scope of the search.
3. Lack of information in the description of accidents.

After analysis, the remaining accidents were standardized by inserting relevant information using available sources for the same news item, thus obtaining the maximum amount of relevant data, and finally submitted for registration in the database tool used, where the most diverse information extracted from the received emails was cataloged, among which are:

1. Accident Period.
   a. Date – Day, Month, Year.
2. Accident Location.
   a. Region.
   b. State.
   c. City – Latitude, Longitude, Population.
3. Characteristics of the Victim.
   a. Age.
   b. Sex.
   c. Profession.
4. Characteristics of the Accident.
   a. Activity at the Time of the Accident.
   b. Fatality or Injury.

The fourth stage of the research consisted of processing and analyzing the information obtained, aiming to find inconsistencies or errors in the data set. The fifth stage involved seeking efficient ways to visualize the data obtained and allow for a thorough discussion of the topic. The sixth stage resulted in discussion and strict textual adaptation to scientific literature.

The summarized form of this study's development stages can be seen in Fig. 1.

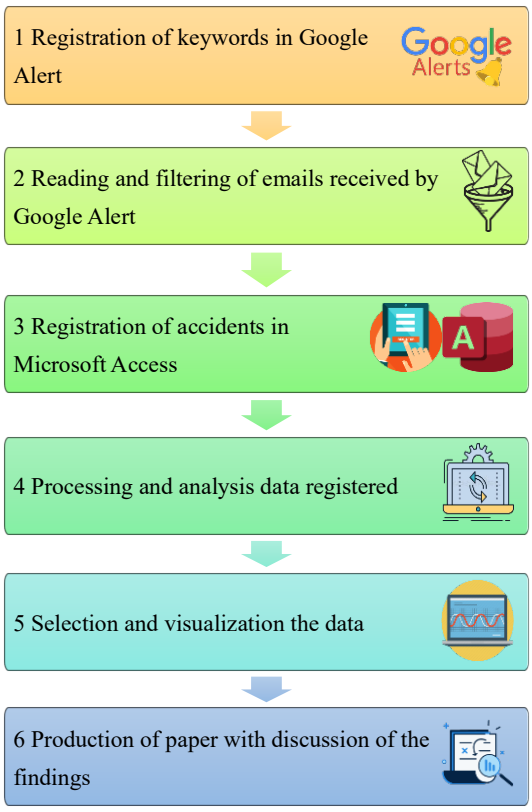


Fig. 1. Flowchart of data collection, processing, and analysis methodology.

III. RESULTS AND DISCUSSIONS

According to Fig. 2, the annual rates of residential accidents involving electric shock have been increasing, demonstrating the population's lack of awareness regarding accidents.

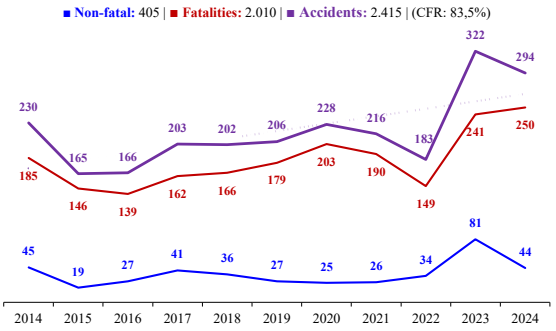
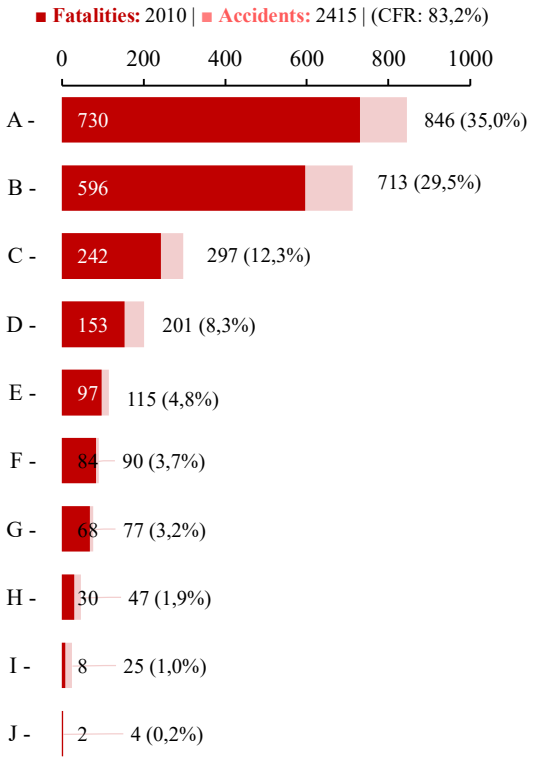


Fig. 2. Annual incidences of electrical origin shocks from January 2014 to September 2024.

As shown in Fig. 3, it is possible to see a stratification of the main occurrence situations of residential electrical accidents during the period from January 2014 to September 2024. Referring to category A, its occurrence represented 35% of the accidents in the period, followed by situation B, representing 29.5%, situation C with 12.9%, situation D with 8.3%, and situation E with 4.8%; the remaining situations did not present a significant quantity.



A - Contact with Wiring and Internal Electrical Installations | **B** - Contact with Home Appliances and Electronic Devices | **C** - Contact with Energized Metal Structures | **D** - Maintenance or Installation Work Involving Electricity | **E** - Illegal Electrical Connections or Theft | **F** - Contact with Electrical Equipment in Wet Areas | **G** - Contact with Water Pump | **H** - Contact with Overhead Power Lines | **I** - Other Known Activities | **J** - Unknown Activities.

Fig. 3. Main causes of accidents of electrical origin occurring in residences from January 2014 to September 2024.

Additionally, Fig. 4 presents detailed information on the sex and age of the analyzed victims; a higher incidence was perceived among male individuals, constituting 70.22% of the obtained data; the accidents had a higher occurrence in the age groups between 21 and 50 years, considered productive age. The higher occurrence among male individuals is linked to their greater exposure to risk situations and the influences of cultural issues. Regarding the general causes, there are unique characteristics for each situation; however, the influence of the quality of residential installations in the country is notable, especially the lack of safety elements, such as Ground Fault Circuit Interrupters (GFCIs) and functional grounding, elements required by Brazilian technical standards, such as NBR – 5410 and NBR – 5339. Abracopel has studies involving the analysis of the presence of those devices in the work titled “Snapshot of Brazilian Residential Electrical Installations,” presenting discouraging rates for the presence of safety devices – lack of the third pin in 48% of residences and the presence of GFCIs in only 21% of residences [11], [15], [16].

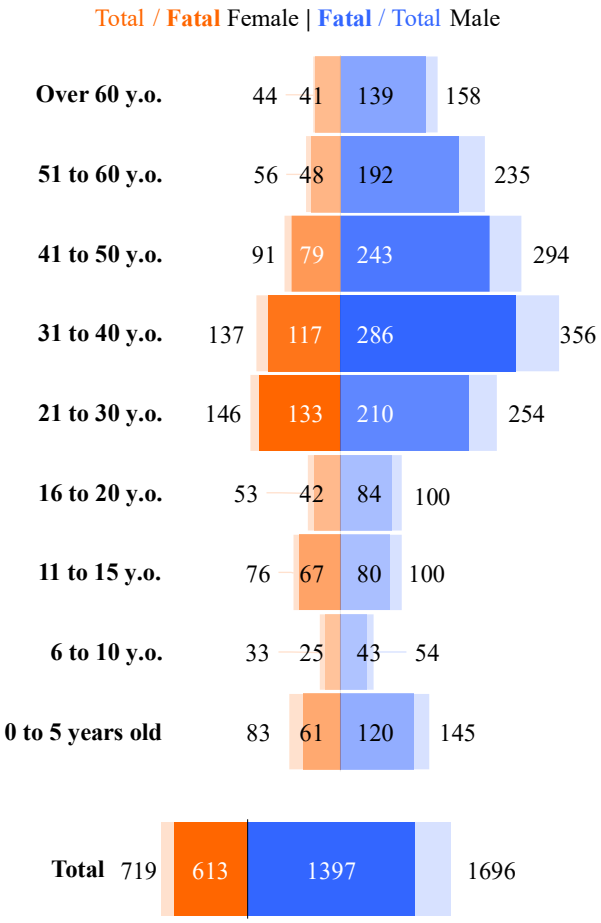
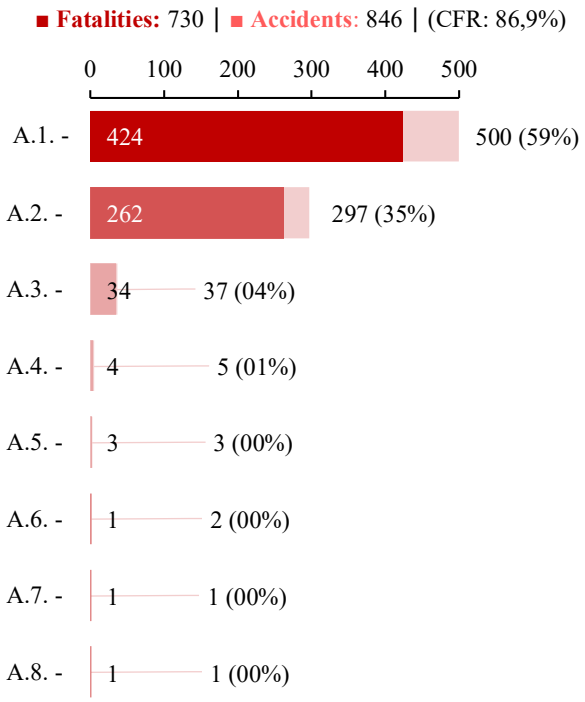


Fig. 4. Correlation between age and sex characteristics in relation to the occurrence of electric shock in Brazilian residences from January 2014 to September 2024.

As shown in Fig. 5, an expansion of the data presented in Fig. 3 is provided. Regarding situation A, where it is possible to see more clearly the elements that it composes.

In situations A.1, higher incidences were observed among males, with a greater occurrence in the 31 to 40 age group; however, differing rates were observed in the 0 to 5 age group, regardless of sex. Among the cases, their high lethality is perceptible, reaching 88%. The incidents are accompanied by various justifications; for older individuals (31 to 40), the accidents occurred during home maintenance on domestic wiring, which is carried out without proper training [17], [18]. Regarding the younger age group (0 to 5 years), curiosity is common to this age, coupled with moments without adult supervision, resulted in cases involving touching electrical outlets. [19]. In general, all cases, regardless of age group, share poor wiring quality, especially without preventive maintenance by professionals; the adoption of measures such as using outlet protectors to prevent accidents involving younger ages and encouraging positive education can create additional layers of protection [16], [19].



A.1 – Damaged Wire (or Lack of Insulation) | **A.2 –** Use of Extension Cord / Power Strip / Adapter | **A.3 –** Wiring of Home Appliances or Electronic Devices | **A.4 –** Contact with Broken Wire in the Street | **A.5 –** Replacing a Light Bulb | **A.6 –** Voltage Surge Caused by Lightning | **A.7 –** Short Circuit in the Internal Electrical Installation | **A.8 –** Electric Vehicles, etc.

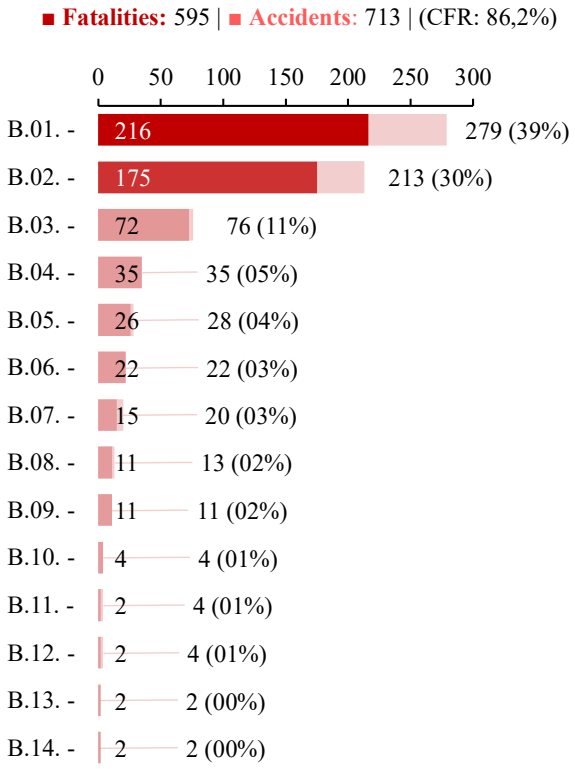
Fig. 5. Details of accidents caused in situation A: contact with wiring or internal electrical installations.

Regarding situation A.2, age and sex profiles were similar to situation A1. Concerning adults, there is not much to discuss; generally, failure in the equipment itself and/or the presence of irregularities were observed, especially live parts with insulation failure. For the 0 – 5 age group, causes similar to those described for situation A1 were found. These elements are hazardous due to the lack of inspection, resulting in equipment that does not comply with the safety standards established by Brazilian Standards.

Figure 6 represents an expansion of the data presented in Fig. 3, regarding situation B, allowing for a clearer visualization of its constituent elements.

It is possible to observe a controversial relationship; high incidence rates are not necessarily accompanied by higher lethality. For example: situations B.04, B.06, B.09, B.10, B.13, and B.14 showed 100% lethality, yet they are not among the most frequent.

Regarding situation B.01, sex was not relevant; however, higher rates occurred for individuals in the 11 to 15 age group. This disparity can be explained by the daily use of cell phones by this age group, exceeding the common usage time of an adult, who shows lower incidences [20], [21]. The accidents are characterized by the use of the device during charging or at the moment it is plugged into the outlet; justifications for the causes of the accidents are difficult to formulate, given the scarcity of information.



B.1 – Cell Phone Charger | **B.2 –** Lawn Mower / Pressure Washer | **B.3 –** Washing Machine | **B.4 –** Refrigerator / Freezer | **B.5 –** Hair Care Devices | **B.6 –** Fan | **B.7 –** Media Players | **B.8 –** Electric Shower | **B.9 –** Electric Tools | **B.10 -** Blender | **B.11 –** Stove | **B.12 –** Water Cooler | **B.13 –** Microwave | **B.14 –** Sandwich Maker.

Fig. 6. Details of accidents caused in situation B: Contact with Home Appliances and Devices.

Accidents in situation B.02 occurred mostly in individuals of active age, not concentrating exclusively in a specific age group. The influence of sex is noted in these cases, affecting the male population more, which in the Brazilian social structure is commonly responsible for such activity, leading to greater exposure to the situation. The accidents occurred when using equipment without proper maintenance or with the presence of inappropriate maintenance; a lack of use of Personal Protective Equipment (PPE) was also observed, resulting in cases where the victim did not use clothing with protection against possible debris or splashes, in addition to the lack of closed-toe shoes with rubber soles.

Regarding accidents caused by situation B.03, higher rates occurred among female individuals, in the 10 to 15 age group. The influence of sex is justified by issues involving the roles played by both sexes in Brazilian society. The accidents can be justified by the nature of the equipment, being accompanied by water during its operation. However, the influence of the quality of installations and lack of safety devices is undeniable [16].

Situation B.04 differs from the others cataloged by presenting 100% lethality. There is no correlation with sex; however, a higher incidence is noted among individuals in the 0 to 5 age group; the curious nature common to this age, combined with a lack of awareness of potential dangers, results in greater exposure to risk situations. The situation is characterized by the presence of a potential difference in the metallic casing of equipment, common in refrigerators and freezers, coupled with problems or lack of the third pin conductor as well as the lack of GFCIs.

Situations B.05 and B.08 require extra attention due to their nature. Accidents in these subdivisions both occur in the same room, the bathroom, during or after bathing. Consequently, the environment is humid, as is the skin. Human skin is not in favorable conditions, reducing its electrical resistance (Ω), consequently resulting in higher current magnitudes (A) [22]. Regarding the victims, there is a predominance of females; however, age was concentrated in the 10 to 15 and 21 to 30 age groups. Due to the low occurrence, it is not possible to affirm justifications. However, it is supposed that in the 10 to 15 age group, the first signs of vanity are present, especially due to puberty.

Analyzing situation C, sex proved relevant, with a predominance of males, especially in the 31 to 40 age group. The most recent occurrences involved contact with Electric Fences, usually installed on top of buildings to deter intruders. In these cases, the shock caused by electrocution resulted in accidental falls. Additionally, situations occurred involving Metallic Clotheslines used for drying clothes in the sun; the presence of wiring with precarious or non-existent maintenance led to the degradation of insulating material, which, upon contacting a nearby metallic clothesline, resulted in electrocution accidents.

While in situation D there was a predominance of males, there was no concentration in a specific age group. However, the presence of youths and children proved abnormal. Justifications for the incidence among such age groups are scarce, possibly ranging from child labor to caregiver neglect. Regarding older age groups, social and economic issues have a greater influence. Commonly, male individuals are responsible for high-risk activities; this situation also occurs in Brazil. Additionally, the country faces high costs for specialized services, coupled with the devaluation of its currency; consequently, it is common to opt for performing services without the necessary technical qualification. Such factors – high pricing, low purchasing power, and the existence of informal alternatives – lead to a high incidence among adult men.

Regarding situation E, sex proved relevant, with victims predominantly male. The accidents were concentrated in the 31 to 40 age group. They are caused by Contact with Clandestine Electric Fences, present in metallic enclosures of private properties; however, unlike traditional electric fences, they are energized directly by the consumer unit, lacking safety devices against overvoltage or short circuits, besides not presenting pulsed voltage coupled with safety indicators, increasing the risk of electrocution and probable fatalities. These structures completely deviate from what is established by Brazilian technical standards (NBR IEC 60335-2-76).

Situation E also involves Wire Theft Attempts, a practice driven by the high value of copper in the Brazilian market, resulting in an attractive product for illegal sale. However, criminals frequently opt to steal residential wiring, which is energized, ignoring the risks; without the use of PPE or prior knowledge of good safety practices, criminals subject themselves to direct contact with the still-energized wiring, resulting in a high mortality rate. Additionally, there are cases of Illegal Connections, made with the intent to bypass electricity bills, motivated by the high price charged per kW/h; however, those involved also subject themselves to the risks without using PPE or knowledge of good safety practices.

Situation F showed a predominance of males. Higher incidence rates were observed in rural residences; however, urban dwellings continue to be the focus of incidence. Age showed various focuses of incidence, not allowing for the outlining of a most affected group. The constant use of this equipment without proper maintenance results in excessive wear, which compromises the integrity of sealing components, leading to interaction between electricity and water, increasing potential risks during indirect contact. Combined with the lack of PPE use during equipment handling, there are few non-fatal occurrences.

Regarding category G, there was a predominance of males. Age proved varied; however, incidences in groups below 20 years were minimal, representing 4.25% of occurrences (2 out of 47). Due to the low incidence, it is not possible to definitively state the cause of these events; however, higher incidence rates were observed in rural dwellings.

IV. CONCLUSION

The study highlighted the severity of residential electrical accidents in Brazil, emphasizing demographic patterns, direct causes, and challenges in data collection. The analysis of 2415 cases, collected through news alerts between January 2014 and September 2024, revealed an

alarming average of fatalities, with a predominance among men of productive age (21 to 50 years), who accounted for 70.22% (1696) of the victims. General explanations point to a greater disposition of these individuals to dangerous situations, in this case, electrocution. Cultural issues are also potential causes for this disparity. Children (0 to 5 years) also emerged as vulnerable groups, especially in accidents related to childhood curiosity and the lack of preventive maintenance. Both male and female sexes showed fatality rates of over 80% (84.22% and 82.55%, respectively).

The main causes point to contact with wiring and internal electrical installation (35% of cases) and contact with home appliances or electronics (29.5%), often associated with the absence of grounding, GFCIs (Ground Fault Circuit Interrupters), and unsafe practices, such as unqualified home maintenance. The high lethality reinforces the urgency for policies that combat the precariousness of electrical installations and promote the inspection of equipment.

V. ACKNOWLEDGEMENTS

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Impact of Using Typical Values for Calculating Incident Energy Using IEEE Guide STD-1584:2018

Filipe Barcelos Resende
VALE/UFMG
Belo Horizonte, Brasil
filipe.resende@vale.com

Márcio Bottaro
IEE/USP
São Paulo, Brasil
marcio@iee.usp.br

Cláudio Sérgio Mardegan
ENGEPOWER
São Paulo, Brasil
claudio.mardegan@engepower.com

Thaísa Rodrigues Loback Durães
PUC-MG
Florianópolis, Brasil
thaisarld@gmail.com

***Abstract* — Among the incident energy calculation methods currently available, the one proposed by IEEE STD 1584:2018 - "Guide for Performing Arc-Flash Hazard Calculations" stands out. In order to apply the method proposed by the IEEE, it is necessary to collect a series of data associated with the model's variables. This will allow the incident energy to be estimated with the appropriate precision. The standard offers suggestions for certain variables to streamline calculations. These include working distance, electrode spacing, and enclosure dimensions. The present paper elucidates the impact of discrepancy between the actual and the standard values on incident energy levels. Furthermore, it is demonstrated the atypical behavior of the model in scenarios involving low voltage, shallow panels, and configurations of vertical electrodes terminated in an insulating barrier inside a metal enclosure.**

Keywords—arc flash, incident energy, arc current, calculation methods

I. Introduction

In industrial contexts, the evaluation of risks pertaining to arc flashes is predominantly concerned with activities occurring within electrical panels, irrespective of the voltage level (low or medium). It is imperative to acknowledge that the most critical accidents, which often result in fatalities and disabling injuries, happen in panel interventions. Considering these circumstances, the methodology outlined in the IEEE STD 1584:2018 standard [1] merits particular attention, given its extensive utilization in industry for calculating incident energy. Therefore, it is useful to analyze the impact of certain variables on the final values of the arc current and of the incident energy. It should be noted that the analysis is most readily conducted at the standardized voltage levels (600 V, 2.7 kV, and 14.3 kV). However, upon validation of the results at the standardized voltage levels, it is assumed that the behavior is appropriate for the interpolations.

The IEEE STD 1584:2018 method evaluates the incident energy for some electrode configuration, assuming electrodes placed in open-air ("OA") or enclosed ("Box") configurations (with open front end). These elements can be oriented in both vertical and horizontal positions, and they can be open-tipped or barrier-terminated. The following electrode configurations are defined and listed according to their order of use within the incident energy model:

- VCB → vertical electrodes inside a metal box.
- VCBB → vertical electrodes terminated in an insulating barrier inside a metal box.
- HCB → horizontal electrodes inside a metal box.
- VOA → vertical electrodes in open air.
- HOA → horizontal electrodes in open air.
- Voc → open-circuit voltage (kV).
- EC → electrode configuration.

II. Influence of the Gap on the Arc Current

Equation (1) of the IEEE STD 1584:2018 standard is presented below.

$$I_{arc_Voc} = 10^{k1+k2\cdot\log(I_{bf})+k3\cdot\log(G)}(k4\cdot I_{bf}^6+k5\cdot I_{bf}^5+k6\cdot I_{bf}^4+ +k7\cdot I_{bf}^3+k8\cdot I_{bf}^2+k9\cdot I_{bf}+k10) \quad (1)$$

where:

I_{bf} → the bolted fault current for three-phase faults (symmetrical rms) [kA].
I_{arc_Voc} → the average rms arcing current at at the chosen voltage level (Voc = 600 V or 2700 or 14300 V) [kA].
G → the gap distance between electrodes [mm].
k1 - k10 → the coefficients provided in Table 1 of IEEE STD 1584:2018.

The calculated arc current (I_{arc_Voc}) is called the intermediate arc current since the final currents (1st and 2nd) are found by interpolating (or extrapolating) to the chosen voltage. It should be remarked, in addition, that the physical model of the arc current is formulated through (1). This equation is used to evaluate the effect of the variables involved

on the final value of the current. Equation (1) can be reformulated as shown in (2).

$$I_{arc_Voc} = 10^{k1} \cdot I_{bf}^{k2} \cdot G^{k3} \cdot Q_0 \quad (2)$$

where:

$$Q_0 = \sum_{n=0}^{n=6} k^{n+4} \cdot I_{bf}^{6-n}$$

Equation (2) is particularly useful for evaluating the effect of the gap (G) and the short-circuit current (I_{bf}) on arc current (1st or 2nd). According to IEEE STD 1584:2018, the gap limits are:

- from 208 V to 600 V: from 6.35 mm to 76.2 mm.
- from 601 V to 15000 V: from 19.05 mm to 254 mm.

The values of k3 (extracted from Table 1 of the IEEE STD 1584:2018) are presented in Table I and range from –0.2400 to –0.0100. Mathematically, as the value of k3 approaches zero, the influence of the gap on the final value of the arc current becomes less significant. It has been observed that enclosed configurations (VCB, VCBB, and HCB) feature k3 values under 0.1 in absolute terms, indicating a reduced influence of the gap on arc current in comparison to open air configurations (VOA and HOA). It is also noteworthy that the k3 value decreases as the voltage increases. The k3 values for 14.3 kV range from −0.0100 to −0.0290. Practically, small gap variations at medium voltage levels have little effect on current values. This phenomenon aligns with the analysis of arc circuits; wherein higher voltage systems exhibit a greater ratio of system impedance to arc resistance. Consequently, small alterations in gap size have a reduced effect on arc current. It is notable that the arc resistance is directly proportional to the gap.

TABLE I. THE VALUES OF K3 EXTRACTED FROM TABLE 1 OF THE IEEE STD 1584:2018

VCB		
600 V	**2700 V**	**14300 V**
–0.0830	–0.0240	–0.0110
VCBB		
600 V	**2700 V**	**14300 V**
–0.0500	–0.0125	–0.0100
HCB		
600 V	**2700 V**	**14300 V**
–0.1100	–0.0249	–0.0200
VOA		
600 V	**2700 V**	**14300 V**
–0.1800	–0.0188	–0.0290
HOA		
600 V	**2700 V**	**14300 V**
–0.2400	–0.0380	–0.0200

Fig. 1, 2, and 3 illustrate the variation of the G^{k3} term for all k3 values listed in Table I. It is evident that for any of the fifteen conditions evaluated, small gap variations do not significantly affect the term and consequently have a minimal impact on the arc current value. It is worth noting that an accurate calculation of I_{arc} is essential for a precise estimate of the incident energy. Equation (2) suggests that variations in the gap have a significant impact on the arc current. However, as illustrated in Fig. 1, 2, and 3, minimal changes in the initial conditions yield only a negligible effect on the final value of I_{arc}.

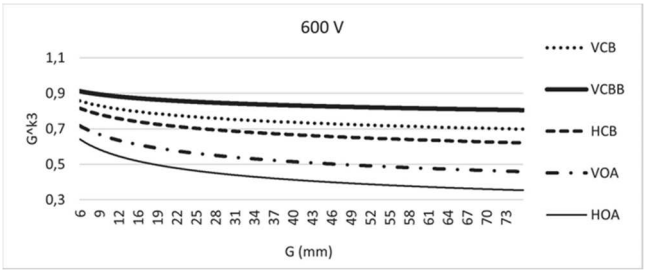

Fig. 1. Influence of gap variation (G) on factor G^{k3} for 600 V

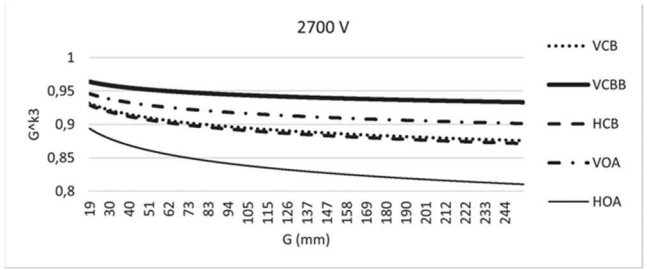

Fig. 2. Influence of gap variation (G) on factor G^{k3} for 2.7 kV

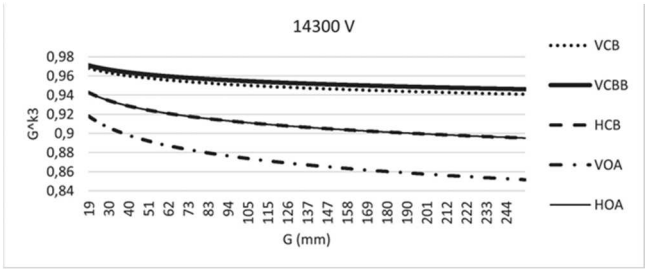

Fig. 3. Influence of gap variation (G) on factor G^{k3} for 14.3 kV

A. *Example 1*

Calculation of I_{arc} using the following data: V_{oc} = 600 V; I_{bf} = 38 kA; G = 32 mm; VCB configuration.

Using (1), I_{arc} = 28.69 kA. A 20% increase in the gap (38.4 mm) or a 20% decrease (25.6 mm) results respectively in I_{arc} values of 28.26 kA and 29.23 kA. This indicates that a 20% variation in gap results in an alteration of less than 2% in the final arc current value. The same effect is observed for the calculation of the second arc current (minimum arc current). Table 2 presents the values of arc currents (1st and 2nd) and their percentage variations for the three gap values.

TABLE II. IARC VALUES AS A FUNCTION OF GAP VARIATION

	G = 32 mm	**G = 25.6 mm**	**G = 38.4 mm**
Iarc1 [kA]	28.69	29.23 (+1.88%)	28.26 (–1.50%)
Iarc2 [kA]	25.34	25.81 (+1.85%)	24.96 (–1.50%)

III. INFLUENCE OF GAP ON THE INCIDENT ENERGY

For the purpose of incident energy calculations, gap variations are more significant in determining the final energy value. Nonetheless, this relationship does not reach a direct proportionality. Analogous to (2), incident energy can be expressed in simplified form as (3):

$$E = G^{k2} \cdot Q_1 \quad (3)$$

where:

Q_1 → Factor that includes all variables except the gap (G)

The values of k3 (extracted from Tables 3, 4 and 5 of the IEEE STD 1584:2018) are presented in Table III and range from 0.1050 to 0.7460. As the value of k2 approaches zero, the influence of the gap on the final value of the incident energy becomes less significant. It is also noteworthy that the k2 value decreases as the voltage increases. It has been observed that incident energy values are more sensitive to gap variation at low voltages than at medium voltages.

TABLE III. THE VALUES OF K2 EXTRACTED FROM TABLES 3, 4 AND 5 OF THE IEEE STD 1584:2018

VCB		
600 V	**2700 V**	**14300 V**
0.5660	0.1650	0.1100
VCBB		
600 V	**2700 V**	**14300 V**
0.2600	0.1850	0.2150
HCB		
600 V	**2700 V**	**14300 V**
0.3440	0.1770	0.1250
VOA		
600 V	**2700 V**	**14300 V**
0.7460	0.1050	0.1200
HOA		
600 V	**2700 V**	**14300 V**
0.4650	0.1490	0.1770

A. Example 2

Table IV presents the data used in Example 2. In order to facilitate the analysis, voltage values of 600 V, 2.7 kV, and 14.3 kV are selected so that interpolation is not necessary. The calculation of the incident energy is also carried out taking into account a variation of ±20% in the gap value to assess the effect on the final value of the incident energy.

TABLE IV. INPUT DATA FOR THE CASE STUDY IN EXAMPLE 2

CASE 1	**CASE 2**	**CASE 3**
Voc = 600 V	Voc = 2700 V	Voc = 14300 V
I_{bf} = 38 kA	I_{bf} = 25 kA	I_{bf} = 16 kA
G = 32 mm	G = 104 mm	G = 152 mm
VCB	VCB	VCB
BOX: 508 x 508 x 508 mm	BOX: 660 x 660 x 660 mm	BOX: 1143 x 762 x 762 mm
D = 457 mm	D = 914 mm	D = 914 mm
$T_1 = T_2$ = 200 ms	$T_1 = T_2$ = 200 ms	$T_1 = T_2$ = 200 ms

The results are presented in Table V. Similarly to the arc current behavior, it can be seen that the percentage variations in the final incident energy value (< 5%) are much smaller than the 20% variation in the gap (G).

TABLE V. INCIDENT ENERGY LEVELS ACCORDING TO ±20% VARIATION IN GAP VALUES FROM TABLE 4 (32 MM, 104 MM, 152 MM)

	G	**0.8*G**	**1.2*G**
E_{600} [cal/cm²]	15.2	14.45 (–4.93%)	15.85 (+4.28%)
E_{2700} [cal/cm²]	5.43	5.28 (–2.76%)	5.55 (+2.21%)
E_{14300} [cal/cm²]	3.6	3.51 (–2.50%)	3.69 (+2.5%)

The equations used to determine the arc currents (1st and 2nd) and the incident energy include the gap as a variable in the calculations. The results elucidate that both the final arc current values and the incident energy values are not highly sensitive to small gap variations. Other cases can also be simulated with similar results.

IV. INFLUENCE OF FAULT CURRENT ON ARC CURRENT

In order to determine the influence of the bolted short-circuit current on the final arc current value, it is necessary to consider two components of (2): $(I_{bf})^{k2}$ and Q_0. Table VI presents the k2 values for different electrode configurations. The values are very close to one, suggesting, at first glance, that the arc current (I_{arc}) is directly proportional to the short-circuit current (I_{bf}). In contrast, for higher current values, the ratio I_{arc}/I_{bf} decreases. This behavior is incorporated into (2) through the Q_0 factor, which adjusts the arc current using a sixth-degree polynomial. The reduction in the I_{arc}/I_{bf} ratio occurs for high level of currents and is more significant for values above 40 kA.

TABLE VI. THE VALUES OF K2 EXTRACTED FROM TABLE 1 OF THE IEEE STD 1584:2018

VCB		
600 V	**2700 V**	**14300 V**
1.0350	1.0010	1.0150
VCBB		
600 V	**2700 V**	**14300 V**
0.9800	0.9950	1.0100
HCB		
600 V	**2700 V**	**14300 V**
0.9880	1.0030	0.9990
VOA		
600 V	**2700 V**	**14300 V**
1.0400	1.0060	1.0102
HOA		
600 V	**2700 V**	**14300 V**
1.0080	1.0060	0.9990

Fig. 4 through 8 illustrate this behavior of arc current (Ia_2018) for 600 V, 25 mm gap, and the five electrode configurations (VCB, VCBB, HCB, VOA, HOA). For comparison, the graphs also show arc current curves disregarding the Q_0 factor (Ia_600). The I_{arc} curves, which are calculated using the methodology proposed by IEEE 1584-2002, are also presented [2] (Ia_2002).

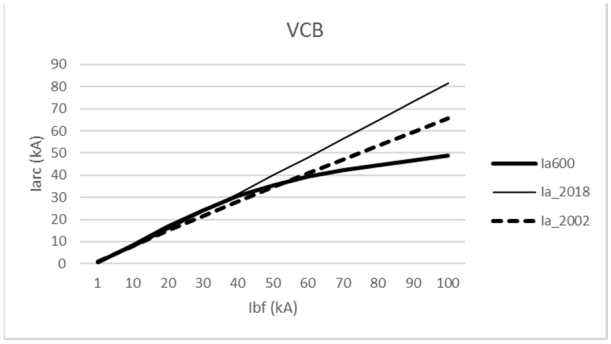

Fig. 4. Arc current variation as a function of bolted short-circuit current for the VCB configuration

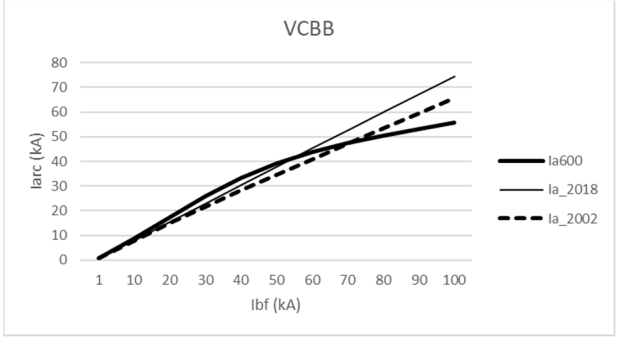

Fig. 5. Arc current variation as a function of bolted short-circuit current for the VCBB configuration

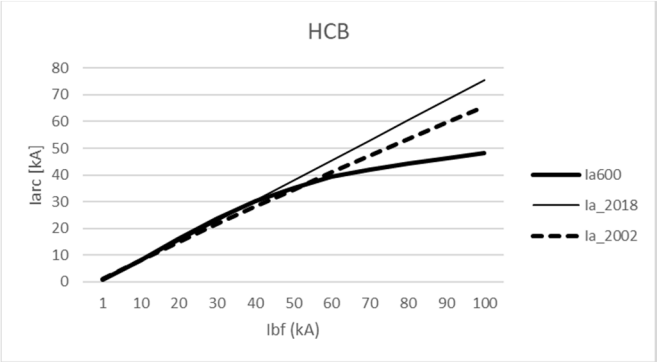

Fig. 6. Arc current variation as a function of bolted short-circuit current for the HCB configuration

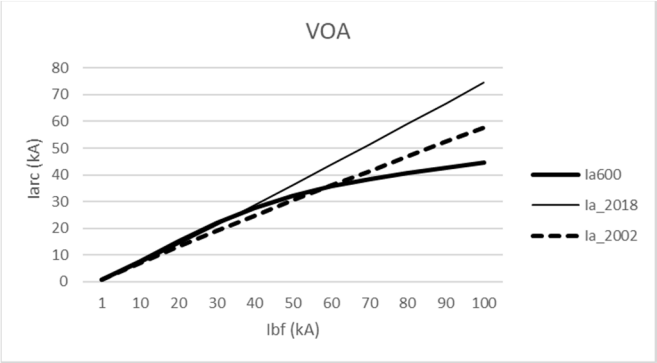

Fig. 7. Arc current variation as a function of bolted short-circuit current for the VOA configuration

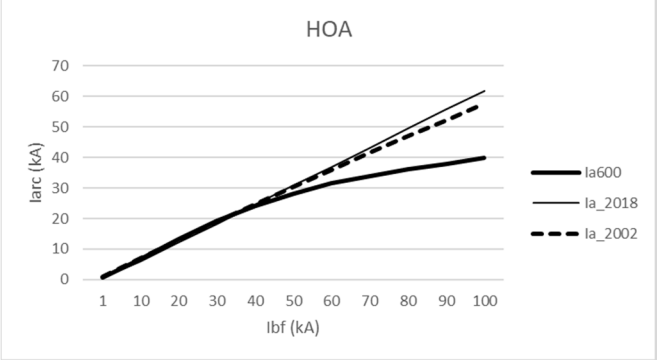

Fig. 8. Arc current variation as a function of bolted short-circuit current for the HOA configuration

One observes that all three currents are very close to each other up to approximately 40 kA. For the VCBB configuration, the results are similar for up values of I_{bf} corresponding to 60 kA. Q_0 can be interpreted as a weighting factor for high current values, reducing the I_{arc}/I_{bf} ratio. It is also noteworthy that the model proposed in IEEE STD 1584:2002 does not reflect this behavior, since the I_{arc}/I_{bf} ratio remains nearly constant across the model's entire current range. The IEEE STD 1584:2018 edition included approximately 1800 additional tests, which improved the robustness of the arc current model.

V. Influence Of Working Distance On Incident Energy

The first model for calculating incident energy, proposed by Ralph Lee [3], considered the decay of incident energy with the square of the working distance. This assumption was based on an isotropic point heat source (which emits energy uniformly in all directions and is considered to have no physical dimensions - infinitesimally small). As the models were refined, other variables were found to influence energy decay, such as arc confinement, electrode configuration and distance to each other. The method developed by Doughty, Neal, and Floyd [4] introduced the effect of arc confinement on incident energy decay, presenting two working distance exponents: –1.9593 for open air configurations and –1.4738 for enclosed ones. Notably, the exponent for open air configurations is very close to –2, supporting Lee's isotropic source assumption. The enclosed configuration's exponent (–1.4738) shows a softer decay due to the "funneling" of energy effect, which characterize this kind of configuration. IEEE STD 1584:2002 further enhanced the first model by incorporating equipment type to determine the distance exponent (according to Table 6 of IEEE STD-1584:2002). Lately the 2018 version went even further, including the electrode configuration [1]. A similar approach is also proposed by Wilkins et al. [5] [6] and Neal et al. [7].

Analogous to the reasoning developed for (2) and (3), the incident energy calculation can be expressed as (4):

$$E=D^{k12}\cdot Q_2 \tag{4}$$

where:

Q_2 → Factor that includes all variables except the working distance (D).

Table VII shows the k12 values extracted from Tables 3, 4 and 5 of the IEEE STD 1584:2018. These values range between –2.030 and –1.515, closely aligning with the values in the Doughty, Neal, and Floyd model. A near-quadratic decay is seen for 600 V in HCB and HOA configurations, although the isotropic point heat source assumption no longer fully applies. For 14.3 kV, k12 shows little variation across configurations, indicating low correlation between energy decay and electrode configuration at higher voltages (values within the established application limits).

TABLE VII. The Values of K12 Extracted From Tables 3, 4 and 5 of the IEEE STD 1584:2018

VCB		
600 V	**2700 V**	**14300 V**
–1.598	–1.569	–1.568
VCBB		
600 V	**2700 V**	**14300 V**
–1.809	–1.742	–1.677
HCB		
600 V	**2700 V**	**14300 V**
–2.030	–1.723	–1.655
VOA		
600 V	**2700 V**	**14300 V**
–1.598	–1.515	–1.534
HOA		
600 V	**2700 V**	**14300 V**
–1.990	–1.639	–1.633

Fig. 9 to 11 illustrate the decay of incident energy as the working distance varies for three voltage levels (600 V, 2.7 kV, and 14.3 kV) and five electrode configurations. The differences in incident energy values are more significant at shorter distances from the arc and decrease as the distance increases. For example, at 2.7 kV and a distance of 305 mm, the HCB configuration results in 147 cal/cm², while the VOA configuration results in 30.7 cal/cm²—almost five times less. At a distance of 1.83 m, the difference decreases to about a factor of three. The incident energy is: 6.7 cal/cm² for HCB

configuration and 2.0 cal/cm² for VOA configuration. This behavior is clearly shown in Fig. 9 to 11.

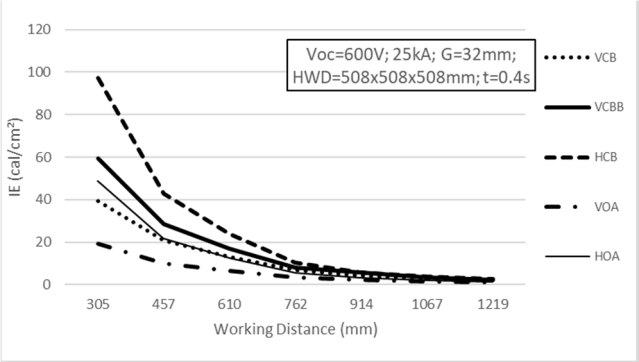

Fig. 9. Incident energy versus working distance (for the five electrode configurations at a voltage of 600 V)

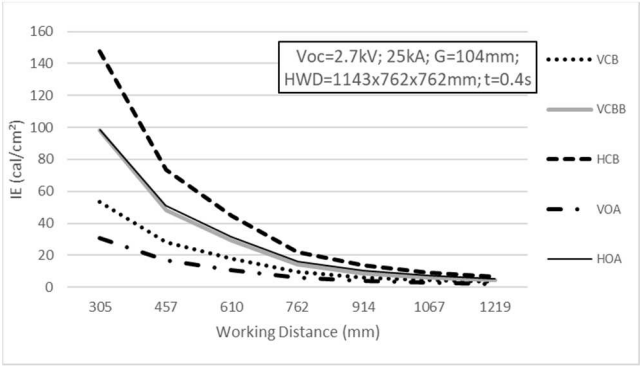

Fig. 10. Incident energy versus working distance (for the five electrode configurations at a voltage of 2700 V)

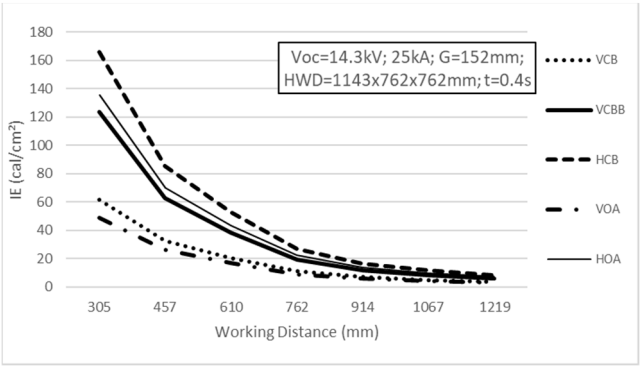

Fig. 11. Incident energy versus working distance (for the five electrode configurations at a voltage of 14300 V)

VI. Influence of the Correction Factor (CF) on Incident Energy

It has been well established that the confinement of arc flash leads to an increase in incident energy. This effect is considered on calculation using the k1 to k13 factors from Tables 3, 4 and 5 of the IEEE STD 1584:2018. The thirteen factors vary for each electrode configuration and voltage level. The enclosure size correction factor (CF) aims to adjust the calculated value of incident energy in function of enclosure dimensions. The sequence for calculating the correction factor is delineated as follows.

- Calculation of the equivalent width (width1) according to Table VIII (Table 6 of the IEEE STD 1584:2018).
- Calculation of the equivalent height (height1) according to Table VIII (Table 6 of the IEEE STD 1584:2018).
- Calculation of the equivalent enclosure size (EES).
- Calculation of enclosure size correction factor (CF).

TABLE VIII. Guidelines for Determining Equivalent Width (W1) and Equivalent Height (H1)

EC	Range	< 508 mm	≥ 508 e ≤ 660,4 mm
VCB	W_1	= 20 (if Typical) = 0.03937 * Width (if Shallow)	= 0,03937 * Width
	H_1	= 20 (if Typical) = 0.03937 * Height (if Shallow)	= 0,03937 * Height
VCBB	W_1	= 20 (if Typical) = 0.03937 * Width (if Shallow)	= 0,03937 * Width
	H_1	= 20 (if Typical) = 0.03937 * Height (if Shallow)	= 0,03937 * Height
HCB	W_1	= 20 (if Typical) = 0.03937 * Width (if Shallow)	= 0,03937 * Width
	H_1	= 20 (if Typical) = 0.03937 * Width (if Shallow)	= 0,03937 * Height
EC	**Range**	**> 660,4 e ≤ 1244,6 mm**	**> 1244,6 mm**
VCB	W_1	obtained from (6) and actual Width	obtained from (6) with Width = 1244.6 mm
	H_1	= 0.03937 * Height	49
VCBB	W_1	obtained from (6) and actual Width	obtained from (6) with Width = 1244.6 mm
	H_1	obtained from (7) and actual Height	obtained from (7) with Height = 1244.6 mm
HCB	W_1	obtained from (6) and actual Width	obtained from (6) with Width = 1244.6 mm
	H_1	obtained from (7) and actual Height	obtained from (7) with Height = 1244.6 mm

$$W_1 = \left(660.4 + (Width - 660.4) \times \left(\frac{V_{oc}+A}{B}\right)\right) \times 25.4^{-1} \quad (5)$$

$$H_1 = \left(660.4 + (Height - 660.4) \times \left(\frac{V_{oc}+A}{B}\right)\right) \times 25.4^{-1} \quad (6)$$

where:

W_1 → equivalent enclosure width;
H_1 → equivalent enclosure height;
Width → actual enclosure width in mm;
Height → actual enclosure height in mm;
V_{oc} → system voltage, in kV;
A → constant equal to 4 for the VCB configuration and equal to 10 for the VCBB and HCB configurations;
B → constant equal to 20 for the VCB configuration, 24 for the VCBB configuration and 22 for the HCB configuration.

Subsequently, the equivalent enclosure size (EES) is determined using (7). Finally, the CF value is obtained using (8) for typical panels or (9) for shallow panels. The coefficients used in (8) and (9) are provided in Table IX.

$$EES = \frac{W_1 + H_1}{2} \quad (7)$$

where:

W_1 → equivalent enclosure width.

H_1 → equivalent enclosure height.
EES → equivalent enclosure size.

$$CF = b_1 \times EES^2 + b_2 \times EES + b_3 \quad (8)$$

$$CF = \frac{1}{b_1 \times EES^2 + b_2 \times EES + b_3} \quad (9)$$

where:

EES → equivalent enclosure size.
CF → enclosure size correction factor.
b1, b2 and b3 → coefficients from Table IX.

TABLE IX. COEFFICIENTS FOR DEFINING THE ENCLOSURE SIZE CORRECTION FACTOR (CF)

Box Type	EC	b_1	b_2	b_3
Typical	VCB	–3.02E–04	3.44E–02	4.33E–01
	VCBB	–2.98E–04	3.20E–02	4.79E–01
	HCB	–1.92E–04	1.94E–02	6.90E–01
Shallow	VCB	2.22E–03	–2.56E–02	6.22E–01
	VCBB	–2.78E–03	1.19E–01	–2.78E–01
	HCB	–5.56E–04	3.72E–02	4.78E–01

As illustrated in Fig. 12, 13, and 14, the CF values are plotted as a function of the width and height of the enclosure for the three standardized voltage levels (600 V, 2700 V, and 14300 V). In these cases, the enclosure's width is considered equal to its height, with a minimum value of four times the gap (G). According to IEEE STD 1584:2018, the minimum width must be four times the gap. Notably, the standard does not present restrictions for minimum height.

The premise of equating height with width is intended to simplify the analysis and facilitate the construction of CF vs. width (or height) curves. While this constitutes a specific instance, given the infinite combinations of height and width, the maximum CF values for each configuration can be extracted from Fig. 12, 13, and 14. Additionally, it is possible to examine how small variations in width (or height) influence the CF value. This analysis is pertinent for comprehending the impact on incident energy when opting to utilize conventional values (as recommended by IEEE STD-1584) for the enclosure dimensions (height and width).

Fig. 12 presents the CF value for the three electrode configurations (VCB, HCB, and VCBB) for 600 V, gap (G) of 25 mm, typical panel (depth > 203.2 mm). For width and height values less than or equal to 508 mm, the CF is one. For values above 1244.6 mm, the CF value reaches its maximum and no longer changes, being 1.33 for VCB configuration, 1.14 for HCB configuration, and 1.25 for VCBB configuration. Between 508 mm and 1244.6 mm, the CF value increases proportionally with the width (or height), with a higher growth rate between 508 mm and 660.4 mm. The growth rate exhibits a decline between 660.4 mm and 1244.6 mm. From 660.4 mm onward, the voltage levels and electrode configuration influence the calculation of equivalent width (width1) and equivalent height (height1), reducing the CF growth rate. Similar behavior occurs for voltages of 2700 V and 14300 V, as shown in Fig. 13 and 14.

Fig. 13 presents the CF value for the three electrode configurations (VCB, HCB, and VCBB) for 2700 V, gap (G) of 100 mm. For width and height values less than or equal to 508 mm, the CF is one. For values above 1244.6 mm, the CF value reaches its maximum and no longer changes, being 1.34 for VCB configuration, 1.15 for HCB configuration, and 1.27 for VCBB configuration.

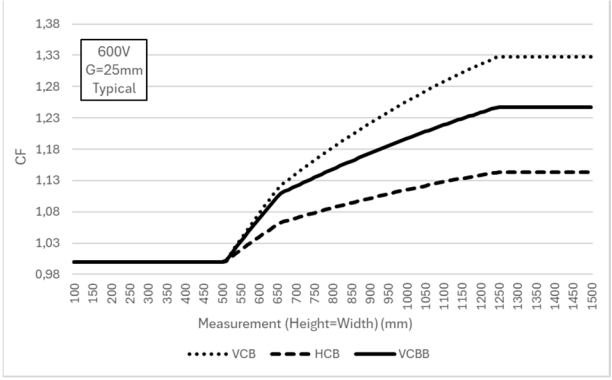

Fig. 12. CF values for the three electrode configurations at a voltage of 600 V and width ranging from 100 mm to 1500 m

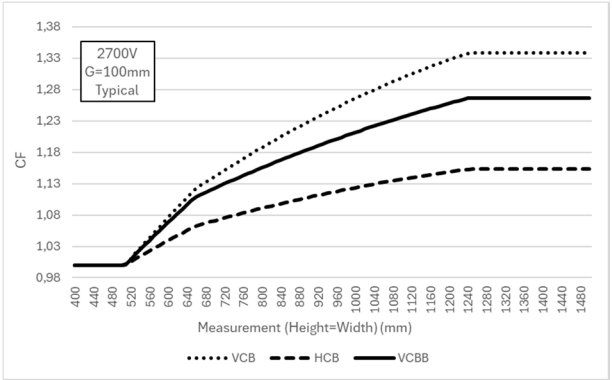

Fig. 13. CF values for the three electrode configurations at a voltage of 2700 V and width ranging from 400 mm to 1500 mm

Fig. 14 presents the CF value for the three electrode configurations (VCB, HCB, and VCBB) for 14300 V, gap (G) of 150 mm. For width and height values less than or equal to 508 mm, the CF is one. For values above 1244.6 mm, the CF value reaches its maximum and no longer changes, being 1.39 for VCB configuration, 1.18 for HCB configuration, and 1.33 for VCBB configuration.

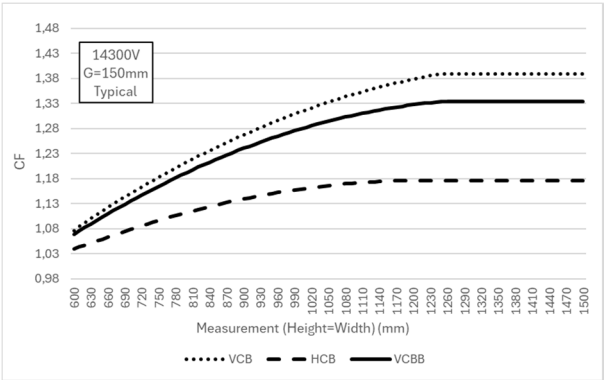

Fig. 14. CF values for the three electrode configurations at a voltage of 14300 V and width ranging from 600 mm to 1500 mm

Fig. 12, 13, and 14 are particular cases for voltages of 600 V, 2700 V, and 14300 V, respectively. Height and width are also considered equal in all cases. Nevertheless, one of the core conclusions drawn from Fig. 12, 13, and 14 concerns the maximum CF values. In a practical sense, CF values range from 1 to 1.39 when considering the three electrode

configurations (VCB, HCB, and VCBB) and the three voltage levels (600 V, 2700 V, and 14300 V). This implies that the incident energy calculated for the standard box is divided by a maximum of 1.39 (VCB at 14300 V). For the model's maximum permitted voltage, 15000 V, under the VCB configuration, the CF value increases negligibly and remains at 1.39 (to two decimal places). Another relevant analysis is to understand how small changes in dimensions (height, width) affect the final incident energy value. Table X presents in Case 1 the incident energy results for typical panels using the standardized dimensions provided by IEEE STD 1584:2018. As illustrated in Table X, the incident energy results for Cases 2 and 3 vary by 20% in dimensions. In Case 2, each dimension (height and width) is reduced by 20% compared to Case 1. In Case 3, each dimension is increased by 20% in relation to Case 1. All the cases in Table X were simulated with I_{bf} = 10 kA and a duration of 0.5 s.

It is evident that the final incident energy values did not vary significantly due to the changes in dimensions (height and width). Variations ranged from -1.5% to +5.3%. For the last three lines (MCC LV, Panelboard, and Cable junction box), the final incident energy values remain constant because the CF value remains unchanged. As demonstrated in Table X, utilizing typical values for the dimensions can serve as a plausible solution, since minimal variations in dimensions (height and width) do not lead to substantial alterations in the final incident energy values.

TABLE X. INCIDENT ENERGY RESULTS FOR TYPICAL PANELS, VARYING ENCLOSURE DIMENSIONS BY ± 20 %

Typical	DATA				CASE 1			
	Voc [kV]	WD [mm]	G [mm]	EC	Height [mm]	Width [mm]	CF	IE [cal/cm²]
Swg 15kV	14	914	152	HCB	1143	762	1,15	**33,6**
MCC 15kV	14	914	152	HCB	914,4	914,4	1,14	**33,9**
Swg 5kV	4,2	914	104	HCB	914,4	914,4	1,12	**28,6**
MCC 5kV	4,2	914	104	HCB	660,4	660,4	1,06	**30,0**
Swg LV	0,5	609	32	HCB	508	508	1,00	**26,9**
MCC LV	0,5	457	25	HCB	355,6	304,8	1,00	**45,2**
Panelboard	0,4	457	25	VCBB	355,6	304,8	1,00	**28,2**
Cab. junc. box	7,2	457	13	VCB	355,6	304,8	1,00	**36,4**
Typical	**DATA**				**CASE 2**			
	Voc [kV]	WD [mm]	G [mm]	EC	Height [mm]	Width [mm]	CF	IE [cal/cm²]
Swg 15kV	14	914	152	HCB	914,4	609,6	1,10	**35,1**
MCC 15kV	14	914	152	HCB	731,5	731,5	1,09	**35,5**
Swg 5kV	4,2	914	104	HCB	731,5	731,5	1,08	**29,5**
MCC 5kV	4,2	914	104	HCB	528,3	528,3	1,01	**31,6**
Swg LV	0,5	609	32	HCB	406,4	406,4	1,00	**27,0**
MCC LV	0,5	457	25	HCB	284,5	243,8	1,00	**45,2**
Panelboard	0,4	457	25	VCBB	284,5	243,8	1,00	**28,2**
Cab. junc. box	7,2	457	13	VCB	284,5	243,8	1,00	**36,4**
Typical	**DATA**				**CASE 3**			
	Voc [kV]	WD [mm]	G [mm]	EC	Height [mm]	Width [mm]	CF	IE [cal/cm²]
Swg 15kV	14	914	152	HCB	1372	914,4	1,17	**33,1**
MCC 15kV	14	914	152	HCB	1097	1097	1,17	**33,0**
Swg 5kV	4,2	914	104	HCB	1097	1097	1,14	**27,9**
MCC 5kV	4,2	914	104	HCB	792,5	792,5	1,09	**29,2**
Swg LV	0,5	609	32	HCB	609,6	609,6	1,04	**25,9**
MCC LV	0,5	457	25	HCB	426,7	365,8	1,00	**45,2**
Panelboard	0,4	457	25	VCBB	426,7	365,8	1,00	**28,2**
Cab. junc. box	7,2	457	13	VCB	426,7	365,8	1,00	**36,4**

VII. CONSIDERATIONS ON CF FOR SHALLOW PANELS

Four conditions are necessary for a panel to be considered shallow: voltage < 600 V; width < 508 mm; height < 508 mm; and depth ⩽ 203.2 mm. CF values for shallow panels are more sensitive to changes in dimensions (height and width) when compared to typical panels. The calculation of CF for shallow-type panels does not consider the panel's voltage level in any case.

Another relevant point concerns the change in the behavior of the incident energy delivered by the electric arc for shallow panels as the dimensions of the panel are reduced. In the case of shallow panels, the incident energy decreases with the reduction in size, unlike typical panels.

Fig. 15 presents the variation in CF as a function of the variation in height (and width). For the VCB and HCB configurations, the CF values are between 0.99 and 1.82, a much wider range than that found for typical panels. For the VCBB configuration, the CF behavior becomes quite peculiar, with its value increasing sharply for smaller dimensions, as shown in Fig. 14.

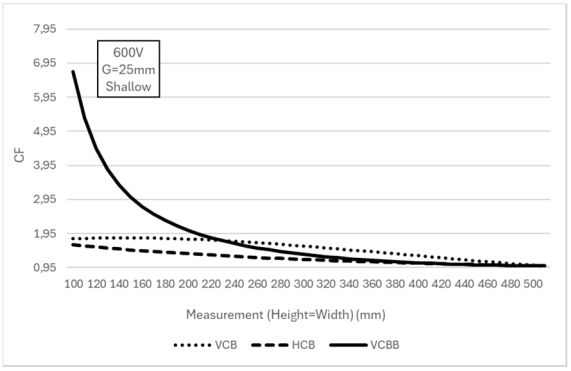

Fig. 15. CF values for the three electrode configurations in shallow panels and width ranging from 100 mm to 508 mm.

The CF value for a shallow panel with height and width equal to 120 mm, for example, is 4.46. For a 100 mm x 100 mm panel, the CF is 6.70 and for 63 mm x 63 mm, the CF is 794.

An analysis of (5) and (10) reveals that if the denominator of (5) approaches zero, CF will tend to infinity and the incident energy will tend to zero, regardless of the other variables in (5), represented by the numerator Q3. This case, CF→∞ and E→0, occurs for an enclosure with dimensions close to 62.7 mm (width=height). This behavior certainly differs from reality and is a point of attention when using the standard in similar scenarios. It should be noted that there are no restrictions in the IEEE STD 1584:2018 standard for minimum width and height values.

Fig. 16 shows the behavior of the incident energy as the dimensions of the box are reduced.

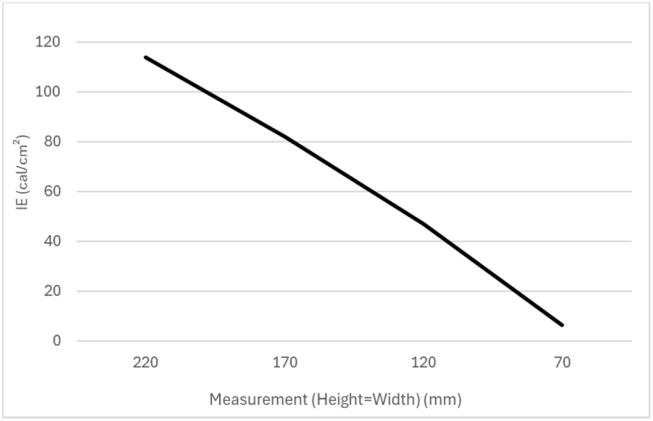

Fig. 16. Incident Energy Variation – Case: Voc = 480 V, I_{bf} = 100 kA, shallow panel, WD = 457 mm, G = 13 mm, EC = VCBB, t = 1,5 s

Table XI presents the incident energy results for shallow panels in case 1, using the standardized dimensions provided by the IEEE STD 1584:2018. Cases 2 and 3 in Table XI present the incident energy results with a 20% variation in dimensions. For case 2, there is a 20% reduction in each of the dimensions (height and width) compared to case 1. For case 3, there is a 20% increase in each of the dimensions (height and width) compared to case 1. All the cases in Table XI were simulated with I_{bf} = 10 kA and a duration of 0.5 s.

Unlike typical panels, shallow panels are more sensitive to variations in enclosure size. Variations of up to 17.5% can be seen. It is important to highlight the CF value for very small panels in the VCBB configuration. In these cases, the CF value becomes very high, quite different from the CF value of the other configurations (VCB and HCB).

TABLE XI. INCIDENT ENERGY RESULTS FOR SHALLOW PANELS, VARYING ENCLOSURE DIMENSIONS BY ± 20%

Shallow	DATA				CASE 1			
	Voc [kV]	WD [mm]	G [mm]	EC	Height [mm]	Width [mm]	CF	IE [cal/cm²]
MCC LV	0,48	457	25	HCB	355,6	304,8	1,15	**11,9**
Panelboard	0,22	457	25	VCBB	355,6	304,8	1,24	**4,0**
Cab. junc. box	0,38	457	13	VCB	355,6	304,8	1,50	**3,6**
Shallow	**DATA**				**CASE 2**			
	Voc [kV]	WD [mm]	G [mm]	EC	Height [mm]	Width [mm]	CF	IE [cal/cm²]
MCC LV	0,48	457	25	HCB	284,5	243,8	1,24	**11,0**
Panelboard	0,22	457	25	VCBB	284,5	243,8	1,51	**3,3**
Cab. junc. box	0,38	457	13	VCB	284,5	243,8	1,68	**3,2**
Shallow	**DATA**				**CASE 3**			
	Voc [kV]	WD [mm]	G [mm]	EC	Height [mm]	Width [mm]	CF	IE [cal/cm²]
MCC LV	0,48	457	25	HCB	426,7	365,8	1,08	**12,7**
Panelboard	0,22	457	25	VCBB	426,7	365,8	1,10	**4,5**
Cab. junc. box	0,38	457	13	VCB	426,7	365,8	1,31	**4,1**

VIII. CONCLUSION

This paper demonstrates the utilization of typical values in the execution of an incident energy study. Variations in the gap of ± 20%, compared to typical values, have little effect on the final values of the arc current and incident energy. In the context of dimensional parameters (height and width), the utilization of typical values yields satisfactory results.

According to IEEE 1584:2018, when bolted fault currents exceed 40 kA, the arc resistance tends to increase, reducing the ratio between the arc current and the bolted fault current, indicating the influence of arc current under the arc resistance.

Regarding the working distance, it has been observed that the difference in incident energy values, depending on the electrode configuration, decreases as the distance increases, resulting in a closer proximity of the incident energy values.

It is relevant to acknowledge that shallow panels require a modicum of additional attention, given that the final value of the incident energy is more sensitive to variations in dimensions. The present study provides a degree of confidence in using typical values, particularly beneficial for large industry, with hundreds or thousands of electrical panels, especially for field data that is more difficult to obtain.

Additionally, this paper highlights the peculiar behavior that manifests in shallow panels with the VCBB electrode configuration. In this specific scenario, a reduction in incident energy is observed as the dimensions of the enclosure are decreased, thereby leading to a zero-incident energy condition when the width and height are nearly equal to 62.7 millimeters.

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Lightining Protection for Lifelines - Considerations

Jobson Modena
GUISMO Engenharia
UNIPOTENCIA
Santa Isabel, Brasil
jomodena@gmail.com

Hélio E. Sueta
Instituto de Energia e Ambiente-USP
São Paulo, Brasil
sueta@iee.usp.br

Luiz C. Ferraro
L. C. Ferraro Engenharia
IEC Young Professional Leader
Valinhos, Brasil
ferraroeletrica@gmail.com

***Abstract*— Lifelines are critical components for fall protection, specifically used in work-at-height activities. However, when exposed to adverse weather conditions, such as lightning strikes, they may suffer structural damage that compromises their safety.**

This study analyzes the impacts of lightning discharges on lifelines, discusses damage mechanisms, presents experimental evidence regarding the vulnerability of the materials used, and proposes practical protection measures.

Keywords — *Lifelines, LPS, Lightning strikes on lifelines, Safety of lifelines after lightning strikes, Regulatory Standard NR-35.*

I. Introdução

Work at height inherently presents a high level of risk, requiring the implementation of Fall Protection Systems, as established in NR-35 [01]. Within this context, lifelines — whether fixed or mobile — play a central role in fall restraint system.

They may be temporary or permanent and are made of metallic cables or synthetic materials. However, a growing concern lies in the exposure of these structures to lightning strikes, which can cause damage that is not always visible but may critically compromise their mechanical strength.

The lifeline may be installed at different stages of the structure's life cycle: during construction, prior to maintenance work on rooftops or equipment installed on the roof, or even before or after the implementation of the Lightning Protection System (LPS). As a result, it is common for part—or even the entirety—of the lifeline to remain outside the protected volume provided by the LPS, thus becoming vulnerable to potential direct lightning strikes.

This paper addresses the impacts of lightning effects on lifelines and proposes mitigation measures for these effects.

II. Types of Lifelines and Materials Used

The Brazilian standard that establishes the requirements for lifelines is ABNT NBR 16325-2:2014 – Type C Anchorage Devices [2].

Lifelines are classified according to:

Purpose:

- Permanent (permanently installed)
- Temporary (used only during the execution of specific tasks)

Material type:

- Metallic (mainly galvanized steel cables, with steel or fiber cores);
- Synthetic (webbing or ropes made of weather-resistant artificial fibers).

Metallic materials offer greater tensile strength but are electrically conductive, which makes them susceptible to lightning strikes and current conduction.

On the other hand, synthetic materials, although non-conductive, have shown thermal vulnerability in tests involving electrical current injection.

When a lightning strike hits a lifeline composed exclusively of synthetic material, the resulting damage—such as fire or breakage—is usually visible and easily identifiable.

For this reason, this study focuses on lifelines made primarily of metallic materials, in which the effects of lightning discharges may not be immediately noticeable.

This characteristic creates uncertainty about whether a lightning-related event has occurred and may compromise the structural reliability of the lifeline, preventing it from providing the expected level of safety.

III. Impacts of Lightning Discharges

When lifelines are installed externally on buildings or structures, they become exposed to various effects of lightning discharges:

- Direct Strike: Full or partial transfer of lightning current to the cable, causing wire fusion, material loss, and changes in mechanical properties.
- Dangerous Flashover: Electric arc jumps between the Lightning Protection System (LPS) and the lifeline, especially when the safety distance is not maintained.
- Hidden Damage: Microcracks, changes in structural properties (e.g., corrosion), and thermal degradation without immediate visual evidence, compromising the safety of the system.

Accidental damage may also occur due to the improper use of the lifeline with incompatible Personal Protective Equipment (PPE), the action of tools, or the installation of equipment that causes cuts or deformations in the cables. Mechanical impacts from falling branches or nearby structures, among other factors, may also contribute. These damages, combined with natural aging over time, can significantly reduce the mechanical robustness of the lifeline.

If this structure is struck by lightning—even with current levels lower than those applied in laboratory testing—its integrity may be further compromised, rendering it unable to ensure protection in the event of a fall by a worker connected to it.

Tests conducted on cables with steel cores and fiber cores, subjected to continuous current pulses (simulating the long-duration component of a lightning discharge) [03], yielded the following results:

- Applied current: up to 634 A, with total charges reaching 343 C and durations exceeding 600 ms.
- Observed effects:
    - Formation of fusion marks and material loss (see Figure 1);
    - Presence of self-extinguishing flames on fiber-core cables (see Figure 2);
    - Changes in electrical resistance of the conductors after discharge, with variations of up to 19.9%;
    - In dynamic tests, the integrity of cables exposed to discharges was visibly compromised (see Figure 3).

Fig. 1: Example of damage after laboratory testing.

Fig. 2: Self-extinguishing flame during test

Fig. 3: Dynamic test: failure after continuity current test

The tests were carried out at the Structures and Materials Laboratory of the Polytechnic School of the University of São Paulo (see Figure 4) and at the High-Current Laboratory of the Institute of Energy and Environment of the University of São Paulo (see Figures 1, 2 and 3). The results showed that the effects of lightning discharges tend to concentrate on specific points along the cable, causing localized damage that, in some cases, may critically compromise its integrity.

Fig. 4: Static tensile test

Although conducted with a limited number of samples and only two types of cables (with steel core and with synthetic fiber core), the tests indicated that lifelines made of these materials may lose their mechanical properties—and, consequently, their functionality—when subjected to lightning discharges containing a long-duration current component equal to or greater than 170 Coulombs.

This performance loss was demonstrated in the dynamic tests, in which a 100 kg mass was attached to one end of a cable previously subjected to continuous current arcs with a charge of 170 C. The mass was then lifted to a height of one meter and suddenly released.

All samples exposed to charges of 170 C or higher failed during the test, revealing the material's vulnerability under such conditions.

IV. Damage Assessment

Inspection following a suspected lightning strike must be immediate and thorough. The main methods include:

- Direct Visual Inspection:

This involves a careful observation for signs such as melting, discoloration, characteristic odors of burned material, or charring marks. It is important to note that evidence left by lightning discharges is not always easily noticeable. Therefore, inspections must be conducted with extreme caution, using a temporary lifeline whenever necessary to ensure the inspector's safety.

If broken steel wires, scorched areas, or any indication of damage are found, mechanical integrity should be presumed compromised, and the lifeline must be taken out of service until a more detailed technical evaluation is carried out.

- Electrical Resistance Measurement:

This consists of comparing the electrical resistance values of the cable before and after a suspected event. It is a more complex assessment, requiring highly sensitive measuring equipment capable of detecting small variations.

Subtle differences in the measured values may indicate internal damage to the conductor, even in the absence of visible signs

- Static and Dynamic Mechanical Analysis:

This involves checking for elongation, permanent deformation, and the residual strength of the lifeline. In practice, this analysis can be performed by attaching a mass of approximately 100 kg to a PPE device connected to the lifeline and simulating a free fall of at least one meter.

It is essential to understand that the lifeline must ensure complete safety: it must either be fully capable of withstanding the impact load in the event of a fall or it cannot be considered reliable at all. There is no such thing as a "partially safe" lifeline.

- Preventive Monitoring:

Current sensors, commonly known as lightning counters, serve as an effective tool for detecting lightning discharges that may have struck the lifeline.

Based on the information provided by these devices—combined with the other inspection techniques mentioned—it is possible to more accurately determine the need for corrective actions, ranging from localized maintenance to complete system replacement.

The tests specified in the standards for the design, installation, testing, and maintenance of lifelines must also be taken into account.

V. Protection Strategies

Effective protection of lifelines against lightning discharges involves the adoption of a set of coordinated technical measures:

- External LPS:

It must include an air-termination subsystem with conductors properly positioned to ensure that the lifelines remain entirely within the protected volume generated by the system.

Many LPS installations, as illustrated in Figure 5, use metal roofs as an integral part of the natural air-termination subsystem. In such cases, lifelines are often installed directly on the metal roof itself and, in many situations, end up outside the protected volume defined by the LPS.

To ensure user safety, air terminals must be strategically positioned and properly dimensioned—preferably based on the Rolling Sphere Method—to ensure that the entire length of the lifeline remains within the lightning protected volume.

Fig. 5: Lifeline installed on metal roof

- Safety Distance:

It is essential to maintain adequate separation between the LPS conductors and the lifelines, including their supports, in accordance with the calculation criteria established in NBR 5419-3 [4].

Failure to observe this minimum distance may result in disruptive discharges between the LPS conductors and the metallic elements of the lifeline. Such discharges produce marks similar to those caused by direct lightning strikes, although—depending on the fraction of lightning current involved—they may be less extensive and visible.

Nevertheless, even these partial discharges can compromise the mechanical integrity of the lifeline and pose a significant safety risk to users.

- Avoid Unintended Equipotential Bonding:

The portion of lightning current that flows through the lifeline due to its direct equipotential connection to the LPS may severely compromise the structural and functional integrity of the system.

In addition to the risks of excessive heating and mechanical failure, corrosive processes may occur at bonding points due to high current density, persistent moisture, or galvanic reactions between dissimilar materials.

Therefore, direct equipotential bonding between the lifeline and the LPS should be avoided, except in cases that are properly designed and technically justified.

- Regular Inspections:

Adopt preventive maintenance plans after storms and ensure that lightning counters are installed and inspected.

- Qualified Technical Design:

Lifeline project specifications must mandatorily include an analysis of interactions with the structure's LPS, in order to ensure system compatibility and safety.

VI. Conclusions

- This technical study reinforces that lifelines composed predominantly of metallic elements, when exposed to lightning discharges, may suffer significant damage—even in the absence of visible signs—that compromises their ability to provide fall protection.

- Laboratory tests confirm the loss of structural performance in cables subjected to impulse currents from lightning discharges, especially in fiber-core models, which demonstrated greater vulnerability to mechanical degradation;

- To ensure system integrity and, consequently, worker safety in the event of lightning strikes, it is imperative that lifelines be fully contained within the protected volume of a properly designed external LPS, with strict adherence to the safety distances established by ABNT NBR 5419-3;

- The immediate execution of inspections—preferably supported by lightning strike counters—after electrical storms is an effective strategy to preserve the integrity of lifelines and ensure the safety of workers at height.

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Impact of Internal Electrical Safety Audits on the Safety of Petrobras ES Oil Platforms

Abrahão Fontes
Unidade do Espírito Santo/Engenharia de Produção/Engenharia de Facilidades, Equipamentos Dinâmicos, Sistemas Elétricos e Automação
Petrobras
Vitória, Brasil
abrahaofontes@petrobras.com.br

Renan Pin
Unidade do Espírito Santo/Engenharia de Produção/Engenharia de Facilidades, Equipamentos Dinâmicos, Sistemas Elétricos e Automação
Petrobras
Vitória, Brasil
renan.pin.prestserv@petrobras.com.br

Silvana Ramos
Unidade do Espírito Santo/Engenharia de Produção/Engenharia de Facilidades, Equipamentos Dinâmicos, Sistemas Elétricos e Automação
Petrobras
Vitória, Brasil
silvanaramos@petrobras.com.br

Abstract—**In an internal Electrical Safety audits context, it was found that a systematic approach to periodic and active implementation of these audits has a significant impact in the industrial sector. This is because they aim to identify and propose solutions for systemic and specific deviations in safety management, compliance, and, most importantly, in electrical installations. The research emphasizes the importance of regular and structured audits to identify and mitigate risks, implement a safety culture on platforms, and standardize the understanding and application of safety norms and guidelines. The methodology will present the systematic approach adopted in conducting internal audits, explaining the management framework used. The guidelines, application methods, verification, and critical analysis will be detailed. The understandings and consensus used, as well as the best practices adopted within Petrobras' oil production platform system, will be explained. The impact of this systematic approach will be presented based on historical data analysis of internal audits, safety indicators, the gradual reduction in the number of deviations found, the evolution in addressing these deviations, and the improved adherence to Regulatory Standard 10 (NR-10) and other compliance items over time. Since the audits cover different platforms with distinct topologies and management systems, the results will provide a global overview of Petrobras Espírito Santo's entire platform system while also highlighting specific noteworthy guidelines. It is expected that the presented results can serve as a reference for other companies seeking to enhance their electrical safety management systems.**

Keywords—Internal Audits, Electrical Safety, Safety Indicators, Electrical Installations, NR-10 Compliance.

I. INTRODUCTION

Regulatory Standard No. 10 (*Norma Regulamentadora NR-10*), established by the Brazilian Ministry of Labor and Employment (*Ministério do Trabalho e Emprego* - MTE), is an essential normative instrument for promoting the safety and health of professionals working with electricity [1]. Focused on accident prevention, this standard covers aspects ranging from worker qualification to the maintenance of electrical installations, emphasizing the need for collective and individual protective measures. The NR-10 2004's update introduced minimum technical requirements and consolidated the mandatory nature of specific training to ensure professionals are adequately prepared to identify and intervene in risk situations. In this context, NR-10 becomes a cornerstone in structuring safer and technically qualified work environments.

One of the central elements of NR-10 is the mandatory technical training for professionals interacting with electrical systems, with a minimum initial instruction period of 40 hours [2]. This training must be renewed periodically, with refresher courses every two years, ensuring continuous updating of knowledge applicable to electrical safety. The training covers fundamental topics such as first aid principles, fire containment and extinguishing strategies, and methodologies for risk analysis and control [2]. These contents are structured to promote safe professional practices in all stages of electrical work. Additionally, the standard proposes for integration among engineering, occupational safety, and human resources departments, fostering an organizational culture focused on prevention. In addition, is mandatory the usage of Personal Protective Equipment (PPE) and Collective Protective Equipment (CPE) further underscores the role of technical responsibility in electrical safety practices.

Beyond individual and collective worker protection, NR-10 reflects an institutional commitment to social responsibility and the preservation of a safe organizational environment. Documenting activities and rigorously complying with normative requirements are essential for mitigating risks

inherent to electrical installations. Research indicates that inadequate training and ineffective preventive measures are predominant factors in the high occurrence of electrical accidents [3]. Therefore, implementing systematic inspection and maintenance routines is considered indispensable both for ensuring normative compliance and for preserving the physical integrity of involved professionals.

The organization, through the employer or a formally designated professional, is responsible for preparing and continuously updating the Electrical Installations Handbook [4]. This document must be accessible to workers operating the installations to ensure full awareness of operational conditions and risks. However, the isolated application of NR-10 is insufficient to guarantee an effective management system. Integration with others regulatory standards, such as NR-01 (General Provisions), NR-35 (Work at Height) and NR-37 (Safety and Health on Oil Platforms), is recommended to form a cohesive and extensive normative framework [1]. Proper implementation of NR-10 positively impacts safety workplaces, contributing to the reduction of labor liabilities and increased organizational productivity. Simultaneously, the standard encourages a systemic approach to occupational risk management, requiring updated technical documentation available for audit and inspection purposes. Thus, compliance with NR-10 promotes not only legal conformity but also responsible and technically qualified professional practices.

Unfortunately, NR-10 compliance is not adequately observed in Brazil, as evidenced by the high rate of accidents involving electrical risks. According to the Brazilian Association for Awareness of Electrical Hazards (*Associação Brasileira de Conscientização para os Perigos da Eletricidade* - ABRACOPEL), over the past five years, the country recorded 9,360 electrical accidents resulting in 3,832 deaths. These data include electric shocks, overload-related fires, and atmospheric discharges [5], [6]. Analyzing the historical average between 2013 and 2024, 18,662 electrical accidents and 8,741 deaths were reported, representing an annual average of approximately 1,555 accidents and 728 deaths. The following table presents annual data from 2020 to 2024, comparing them with the historical average.

TABLE I. STATISTICS OF BRAZILIAN ELECTRICAL ACCIDENTS

YEAR	Accidents	Deaths
2020	1.502	764
2021	1.585	761
2022	1.828	686
2023	2.089	781
2024	2.356	840
Historical Average (2013-2024)	1.555	728

A significant portion of these accidents is related to domestic incidents, underscoring the importance of awareness among residential users, as well as in power generation, transmission, distribution, and electrical poles [5], [6]. However, it is noteworthy that some economic sectors, such as the Oil and Gas industry, which operate in highly hazardous areas, also report significant numbers. The Brazilian National Agency of Petroleum, Natural Gas, and Biofuels (*Agência Nacional do Petróleo, Gás Natural e Biocombustíveis* -ANP) reported that in 2024, 2,106 incidents were recorded, including 731 accidents and 1,375 near-misses in offshore oil exploration activities [7]. Although the report does not detail specific causes, it is plausible that a portion is related to electrical failures, given the complexity of operations and the presence of electrical equipment in maritime and terrestrial environments. As an area for improvement, it was not possible to obtain nationally segregated data provided by ANP. Such data would enable a historical analysis, helping to identify behavioral patterns and providing a basis for implementing new practices aimed at mitigating these electrical risks. This lack of data was one of the factors motivating this work.

Internationally, although specific data are scarce, in the United States, between 2014 and 2019, there were 470 fatalities in oil and gas extraction, of which 16 (3.4%) were caused by electrocutions [8]. A 2010 report by the International Oil & Gas Producers Association indicated that 16.1% of all fatalities in oil fields were caused by electrical accidents, explosions, or burns originating from electrical equipment failures, such as short circuits or electrical arcs [9].

Regarding Petrobras, considering its onshore and offshore operations, in 2024, several accidents causing harm to people and/or property were recorded, of which a small portion involved electricity, corresponding to 2.32% of total accidents. Thus, comparing electrical accident data in Brazil with the global oil and gas sector average, Petrobras exhibits significantly lower rates. This reflects the company's strong commitment to the safety of its employees and facilities, particularly concerning electrical safety.

That said, one of the pillars of Petrobras' process, compliance, and safety management system relies on conducting and monitoring internal and external audits. Auditing, as a management tool, is a systematic, documented, and independent process aimed at verifying organizational processes' compliance with current norms [10]. It is an instrument applicable to different areas—including finance, quality, environment, and occupational safety—and seeks to identify failures, risks, and improvement opportunities. In the organizational context, auditing fulfills a strategic role by ensuring institutional transparency and accountability, enabling continuous process improvement, and providing technical support for managerial decision-making. Through critical analysis of organizational performance, auditing strengthens internal control and ensures regulatory compliance.

In management systems based on standards such as ISO 9001 (quality), ISO 14001 (environment), and ISO 45001 (occupational safety), auditing is an indispensable mechanism for verifying compliance with normative requirements [10], [11]. Identifying non-conformities and proposing corrective measures drive the consolidation of an organizational culture focused on continuous improvement. Regular audit execution promotes operational gains while reinforcing institutional credibility before clients, regulatory institutions, and other stakeholders. Thus, auditing is not limited to an evaluative function but decisively contributes to the maturity of management systems.

In this context, auditing is a relevant tool for assessing compliance of internal procedures with the standard's guidelines and verifying whether involved professionals have received the required training and are qualified to perform their duties safely. From this perspective, NR-10 auditing represents a crucial mechanism for ensuring that electrical safety requirements are adequately implemented in

organizations [12]. As mentioned earlier, the standard establishes guidelines aimed at protecting workers from risks arising from electricity in installations and electrical services. In this scenario, auditing enables the evaluation of whether safety measures have been effectively applied. Beyond verifying compliance, the process identifies improvement opportunities, endorsing a safer and more efficient work environment.

Although NR-10 does not explicitly mandate periodic audits, the item 10.2.4 of the standard recommends implementing an electrical safety management system [1]. This recommendation indirectly implies adopting systematic verification practices—typical characteristics of audits. Such evaluations can be conducted by internal occupational safety teams, electrical engineers, and/or specialized external auditors, covering the analysis of mandatory documents such as the Electrical Installations Record and training records, for example. Therefore, auditing becomes essential for verifying the level of adherence to NR-10 and, consequently, preventing operational failures and accidents.

The periodic conduct of NR-10 audits indicates the organization's commitment to occupational safety and sustainable management practices. Beyond facilitating the identification of non-conformities, this process contributes to strengthening a prevention culture and promoting corporate social responsibility. Although not compulsory, NR-10 auditing is widely recognized as a good management practice, especially in companies with high electrical complexity or operating in critical sectors. Its implementation allows for correcting failures before they escalate into severe accidents, thus promoting a continuous cycle of improvement and compliance.

Finally, NR-10 auditing also stands out as a tool for documentary support in inspection processes, technical expertise, or corporate audits. Although the term "audit" is not explicitly present in the normative text, the requirement for systematic and documented control justifies its practical application. It is concluded, therefore, that auditing, when applied within the scope of NR-10, has a strategic role in legal compliance, worker safety, and organizational management efficiency. Reinforcing, thus, that NR-10 auditing is one of the pillars of Petrobras' process, compliance, and safety management system.

II. METHODOLOGY

At Petrobras, internal NR-10 compliance audits are governed by corporate procedures that establish the criteria and conditions necessary for their execution, management, and follow-up. Within the scope of offshore exploration and production units, which include the *Espírito Santo's* (ES) platforms, the systematic application and monitoring of NR-10 audits are conducted through a risk management system called *Audit Management System*. For each audited platform, a Risk Project is generated, consisting of an adherence to NR-10 analysis. Based on MTE Ordinance No. 143/2005 and NR-28 (Inspection and Penalties) [13], 119 auditable items were defined, which compose the Checklist (*Lista de Verificação* - LV) used in the Risk Project for audits.

To ensure standardization and uniformity in evaluating the standard's auditable items, a Consensus List was developed, establishing the corporate understanding of the evidence required for full compliance of each auditable item in light of NR-10.

In the LV within the Risk Project, each auditable item is evaluated for its Urgency (U), Severity (S), and Relevance (R), receiving a value from 1 to 10 and resulting in a weight (USR) that is the product of U, S, and R. Thus, the weights have standardized values of 3, 6, 15, and 30, which are related to the degrees of infraction under NR-28, from one (01) to four (04), respectively. Therefore, each auditable item directly influences the audit performance indicator and the deadlines for correcting non-conformities by the audited units. This is because the higher the USR weight, the greater its degree of infraction and, consequently, the greater the negative impact on NR-10 adherence and the shorter the deadline for addressing the Non-Conformity (NC).

From a practical standpoint, to better evaluate NR-10 adherence during the audit, the LV was subdivided and categorized into two groups:

- **Management Items:** Related to the administrative compliance of the standard, covering documentation, certificates, and controls required to meet legal requirements.
- **Field Items:** Relating to inspections of electrical installations, conducted on-site by auditors.

Each LV item is classified as Implemented, Not Implemented, or Not Applicable. At the end of the audit, the IA-NR10 indicator is calculated, which defines a score of the audited platform's adherence to NR-10, according to the formula:

$$IANR10 = \frac{PSR_{Control}}{PSR_{Applied}} \quad (1)$$

Where:

- PSRcontrol = Sum of USRs of all Implemented Items
- PSRapplied = Sum of USRs off all Applicable items

For each identified non-conformity, whether field or management, an Event is opened in Audit Management System, and the units have a determined deadline to provide evidence of correction. The Legally Qualified Professionals (*Profissional Legalmente Habilitado* - PLHs), formally designated by each platform, are responsible for these Events registered in Audit Management System and for the electrical installations handbook. The IA-NR10 indicator is updated as Events are resolved, reflecting compliance progress. When multiple deviations are identified for the same item, associated Events are created, and the indicator is only updated after all are resolved. Corporately, it was established that an IA-NR10 index of 95% is the target to be achieved, representing a low-risk threshold for the audited unit.

So far, the entire methodology detailed above refers to what is adopted corporately. This can be described as having a co-participative and with an external view of the Unit, meaning auditors conduct the audit, point out NCs, and issue the final report, leaving it to those responsible for addressing NCs to carry out the necessary actions to achieve the target and the corporate team begins to monitor and issue alerts through weekly spreadsheets, sent via email, regarding the expiration of the non-conformities (NCs) within the next 30 days. Within the active management system of NR-10 audits

on Petrobras ES platforms, other complementary initiatives can be listed:

- **Dedicated NR-10 Team:** In the Petrobras ES structure, there are electrical engineers who act as NR-10 auditors and are responsible for managing this topic;
- **Technical Support:** The same team mentioned above serves as a focal point for clarifying normative, compliance, and technical questions related to resolving field issues;
- **Periodic Meetings with PLHs:** Meetings are held periodically to discuss encountered difficulties, conduct analyses, and seek solutions;
- **Monitoring of Audit Management System Event Deadlines:** Monthly, deadlines expiring in 30 and 60 days are analyzed in collaboration with Event responsible, with item-by-item follow-up.;
- **Event Closure Quality Verification on Audit Management System:** Monthly, Events closed in the last 30 days are verified for effective resolution of identified non-conformities. If the solution is deemed unsatisfactory, the Event is reopened, and clarification is provided to the responsible party;
- **Supplementary NR-10 Checklists:** In Petrobras ES, supplementary checklists exist for inspections of electrical equipment in operational areas, accommodations, and platform common areas. These checklists are preferably executed by the platform's electrical supervisor on a half-yearly basis. For each identified issue, a maintenance note is opened via the SAP system (Systems, Applications, and Products in Data Processing) with an NR-10 identifier in its status;
- **Monitoring and Management of NR-10 Notes:** NR-10 maintenance notes originating from supplementary checklists are managed and monitored by the platform's PLHs, with support from Petrobras ES's dedicated NR-10 team;
- **Temporary Electrical Installations and Monitoring of Specific Maintenance Plans Standardization for Equipment Used in These Installations:** Temporary electrical installations in Petrobras ES follow a specific standard defining technical requirements to be met by executors. Additionally, the equipment used, such as mobile panels, have periodic maintenance plans to verify their integrity and functionality, conducted by equipment responsible. Furthermore, Petrobras ES' dedicated NR-10 team monitors these points;
- **Specific Treatments for Recurring Complex Electrical Problems:** Ground leakage in electrical circuits is a challenging fault to diagnose and address, with a significant history of accidents/incidents at Petrobras. Therefore, standardizations, training with equipment detection manufacturers, and periodic inspection routes for electrical circuits displaying ground leakage in their fixed monitors were implemented;
- **Technical Alert Issuance:** Technical alerts are regularly issued, guiding on major electrical safety issues, the most recurrent failures in the Petrobras system, and their scopes.;
- **ES Electrical Safety Committee:** Petrobras ES has a formally designated committee, composed of electrical and safety engineers, which meets periodically to discuss technical and management issues, aiming for improvements in electrical safety conditions;
- **Equipment Technology Changes:** In Petrobras ES, as electrical equipment and accessories become obsolete, initiatives are launched to study and evaluate the implementation of new technologies. Examples include fiber poles, replacement of Ex d junction boxes with Ex e type, and new luminaires.;
- **Management Meetings with Assets (Comprising a Set of Platforms):** When necessary, meetings are held with asset leadership, including maintenance and technical support managers, as well as high-level Petrobras ES managers, to align technical and management issues on the main challenges faced by that set of platforms and discuss guidance for improvements.

These initiatives aim to improve the degree of compliance and adequacy to Regulatory Standards, resulting in greater electrical safety on the platforms. To evaluate the actions implemented by the team responsible for the topic on Petrobras ES platforms, a critical analysis of historical data from the last audit cycle was conducted to identify the effectiveness of the adopted measures and the challenges faced in achieving even higher levels of electrical safety.

A. Database and Collection

This work used historical data from internal NR-10 audits conducted on Petrobras ES platforms from 2021 to 2024, extracted from the Audit Management System responsible. The data included:

- **Checklist (LV) Responses:** Classified by type (Management or Field), application date, and auditor comments;
- **Initial Scores (Initial IA-NR10):** Representing the percentage of compliance at the audit's conclusion.;
- **Non-Conformity Events (NCs):** With opening and closing dates, constituting auditable management and field items, as well as their associated Events in Audit Management System;
- **IA-NR10 Indicator Evolution:** Temporal tracking of the indicator's evolution for each Risk Project.

The selection criteria adopted were all completed audit projects in the period (21 audits conducted on 14 audited platforms).

B. Tools and Analysis

- **Power BI:** Used for data consolidation, creation of interactive dashboards, and graphical visualization.;
- **Excel:** Employed for statistical calculations (averages, standard deviations) and complementary analyses;

- **Quantitative Analysis**;
    - Annual averages of initial scores calculation;
    - Average time (in days) to achieve 95% (corporate target) and 100% compliance
    - NCs openings and closures rates per year;
    - Comparison of the number of electrical accidents involving people between the Petrobras system and Petrobras ES;
    - Comparison of the number of electrical accidents involving property between the Petrobras system and Petrobras ES
- **Qualitative Analysis**;
    - Identification of behavioral patterns (e.g., stagnation after reaching IA-NR10 = 95%).

C. *Limitations*

- **Temporal Bias:** Ongoing 2024 projects may distort averages;
- **External Variables:** Changes in the auditor team or corporate policies were not controlled.

III. Results and Discussion

A. *Continuous Improvement in Initial IA-NR10 Scores*

This section presents the graphs of IA-NR10 score evolution year by year. Fig. 1 shows that the average initial scores increased from **82.32% (2021)** to **91.29% (2024)**, indicating significant progress in NR-10 compliance. Fig. 2 reveals that, for Management Items, the average rose from **87.82% (2021)** to **97.96% (2024)**, highlighting advancements in the standard's documentary and administrative management.

The continuous growth in scores suggests that platforms are internalizing safety best practices and improving their legal compliance, especially in management aspects.

B. *Addressing NCs efficiency*

This section presents the graphs of average time (in days) to achieve 95% (corporate target) and 100% compliance year by year. Fig. 3 shows that the average time to achieve **95% compliance reduced by 72.7% (from 275 days in 2021 to 75 days in 2024).** Fig. 4 indicates that, for **100% compliance**, the reduction was **43.5% (from 391 days in 2021 to 221 days in 2023)**. It is worth noting that 2024 was not analyzed in Fig. 4, as audits conducted that year, despite reaching the 95% target, had not yet achieved 100%.

The difference between the time period to achieve 95% and 100% suggests that units prioritize items with higher impact on the indicator to accelerate reaching the 95% target, while complex or less critical issues are addressed later. Factors such as resource availability or technical difficulties may also explain the slowdown between 95% and 100%.

C. *Dynamics of Non-Conformities*

This section presents the graphs of NC opening and closure rates per year. Fig. 5 illustrates the number of NCs identified per year, predominantly field items (main and associated Events). The graph shows a slight downward trend in new NCs between 2021 and 2024, reflecting a modest preventive evolution in addressing problems. Fig. 6 demonstrates that the average time to close NCs decreased from **237 days (2021)** to **69 days (2024)**, indicating greater efficiency.

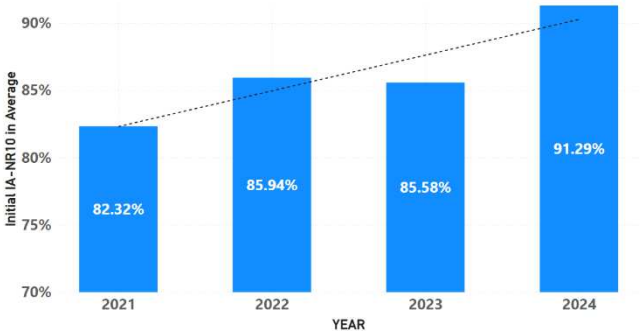

Fig. 1. Average Initial Audit Scores by Year

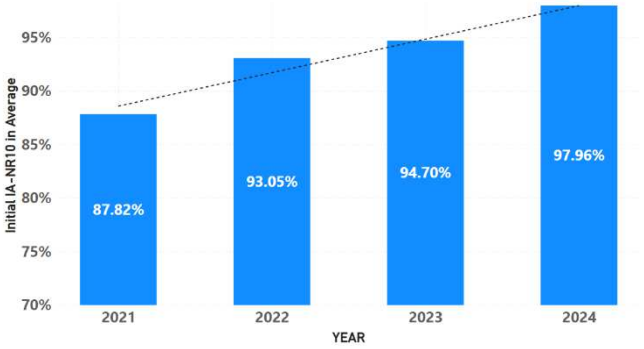

Fig. 2. Average Initial Audit Scores by Year – considering only management items.

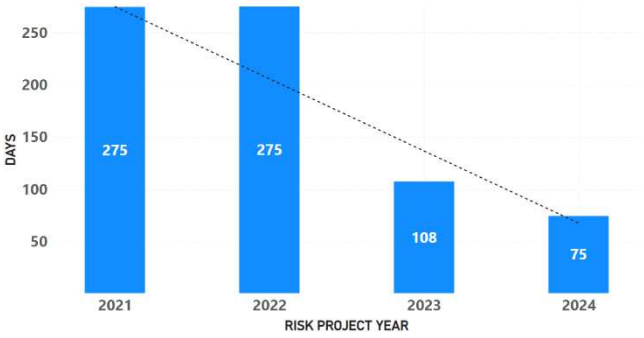

Fig. 3. Average Time to Achieve IA-NR10 Target = 95% by Year.

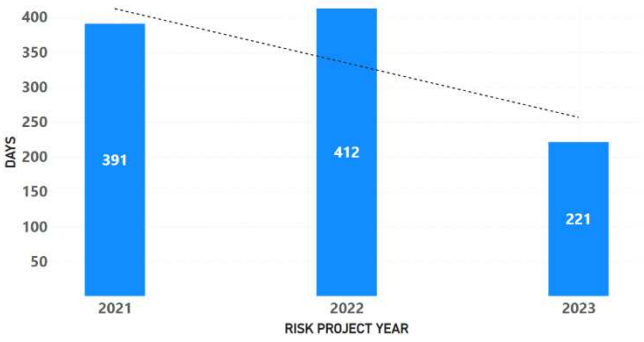

Fig. 4. Average Time to Achieve IA-NR10 Target = 100% by Year.

Regarding field non-conformities (NCs), it is observed that platforms still face challenges in performing preventive

maintenance work to ensure safe electrical conditions. This occurs mainly due to the natural degradation of equipment over time, especially in a maritime environment, along with other difficulties related to activity prioritization. However, a slight downward trend in NCs can be perceived, as illustrated in Fig. 5. On the other hand, Fig. 6 demonstrates excellent reactive readiness, indicating clear prioritization in resolving NCs that directly affect compliance and platform indicators. This is positive, as it contributes to increasing the level of electrical safety on the platform.

Fig. 7 and 8 present the temporal evolution of Events created, closed, and the accumulated volume of Non-Conformities (NCs) in the periods of 2021/2022 and 2023/2024, showing a consistent resolution pattern. It is observed that, after NCs are opened, there is an initial period of high resolvability, with a significant volume being addressed in the first months, followed by stabilization in closure rates (*plateau*). This behavior suggests an efficient reactive approach but with challenges in fully eliminating the backlog over time.

A relevant aspect identified in the analysis is the progressive reduction in the time required to stabilize the NC volume. This trend is evident in Fig. 9, which shows increasing slope coefficients in the trend lines associated with each NC peak for its return to the average NC level in the period [14]. This increase in slopes indicates a more agile response to new volumes of open NCs, reflecting possible improvements in management processes or prioritization over the years.

However, Fig. 7 to 9 also highlight a difficulty in fully liquidating NCs, resulting in a residual volume that persists or even grows after initial periods of high resolvability. This phenomenon may indicate the existence of chronic NCs or a lack of dedicated resources for their definitive resolution.

D. Impact Analysis on Accident Rates

As a means of analyzing the applied measures, a quantitative analysis of electrical accidents involving people and property at Petrobras can be conducted, along with the percentage impact that ES platforms had on these values. Fig. 10 shows the evolution of numbers of electrical-origin accidents (short circuits, arcs, or electric shocks) causing harm to people at Petrobras, in ES, and the percentage impact each year. Fig. 11 presents the same analysis for electrical accidents causing property damage (equipment damage, fire outbreaks, among others).

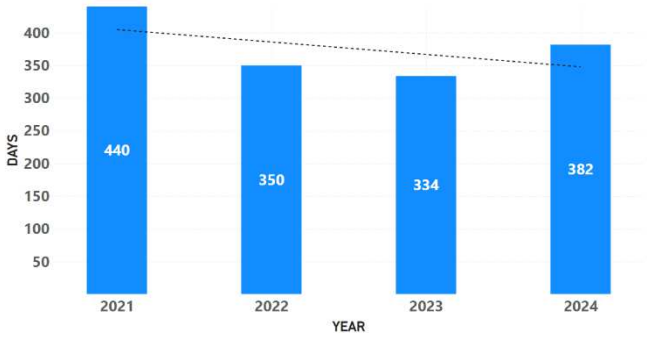

Fig. 5. Number of Created Events by Year

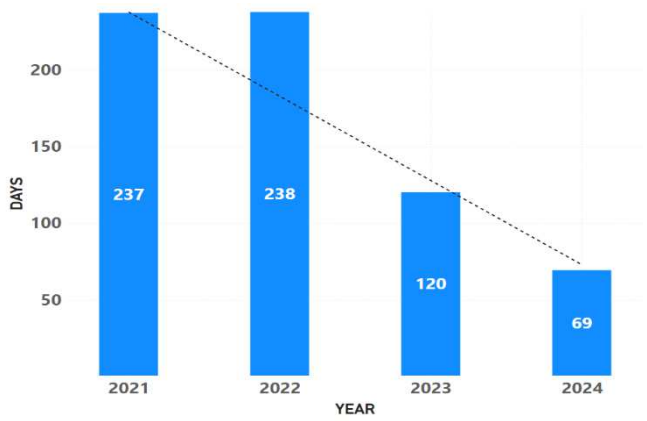

Fig. 6. Average time of NC closure in Days

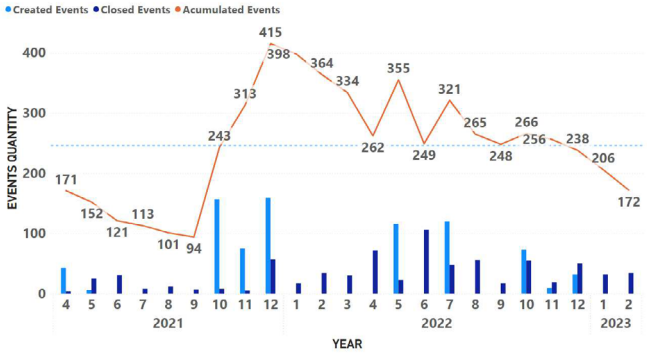

Fig. 7. Time-series analysis of opened events, closed events, and cumulative Non-Conformity (NC) volume for 2021-2022.

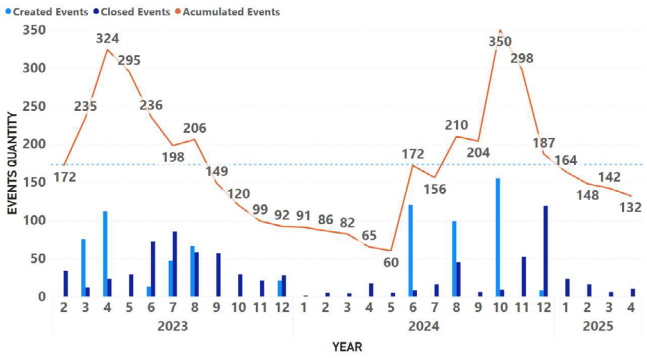

Fig. 8. Time-series analysis of opened events, closed events, and cumulative Non-Conformity (NC) volume for 2023-2024.

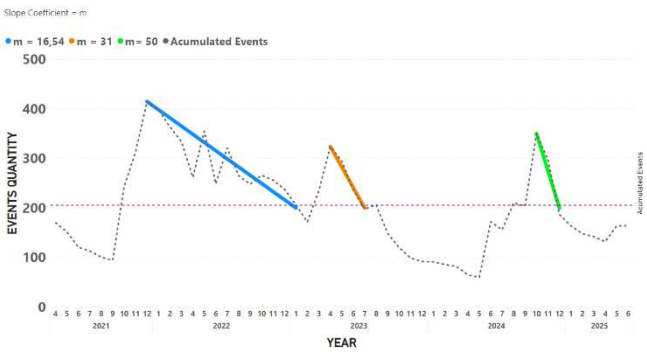

Fig. 9. Slope coefficients of trend lines for achieving the average number of NCs.

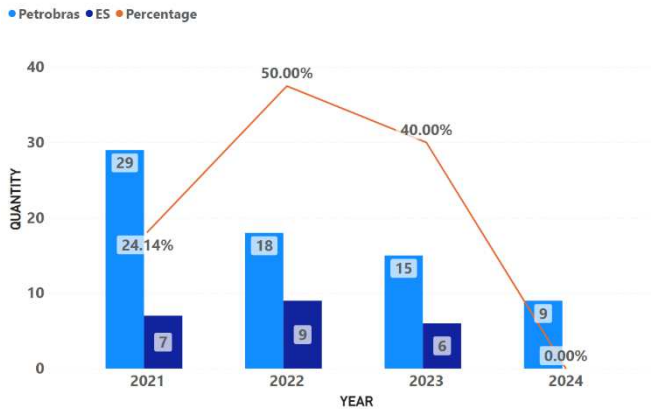

Fig. 10. Number of accidents involving people

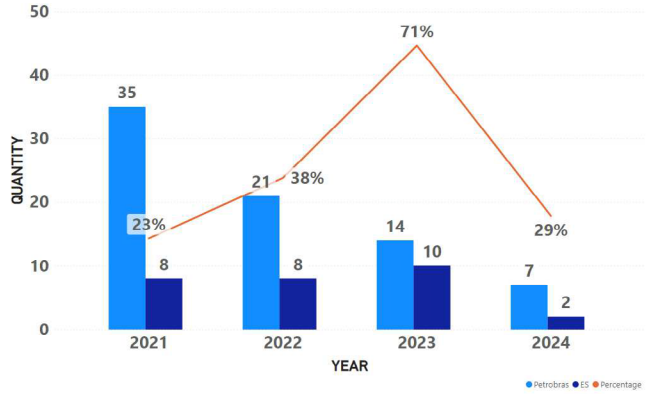

Fig. 11. Number of accidents involving property

CONCLUSION

At the corporate level, a general downward trend is observed in both accidents involving people and property damage. However, ES units maintained relatively stable rates until 2023.

The year 2024 marked a significant turning point, with a sharp drop in accidents in ES. This reduction coincides temporally with the implementation of active safety management measures, suggesting a cause-and-effect relationship. Additionally, the improvement observed in IA-NR10 indicators (Fig. 1-2), response time to achieve safe levels (Fig. 3-4), and NC management patterns (Fig. 7-9) reinforces the hypothesis that these metrics can be considered leading indicators, as proposed by [15].

These results indicate that the proactive approach to electrical safety management is generating measurable impacts. The reduction in correction time suggests greater maturity in risk management and efficient resource allocation. On the other hand, the persistence of a plateau visualized in Fig. 7-8 indicates systemic challenges in achieving 100% compliance, representing a critical focus for future cycles.

The correlation between improvement in process indicators and the subsequent reduction in accidents suggests that deepening these metrics, as advocated by [16], may bring even greater benefits. The experience of ES platforms serves as a demonstrative case of how evolution in management systems can directly reflect on operational safety.

ACKNOWLEDGMENT

We thank Petrobras for its institutional support and our immediate manager for sponsoring and encouraging this work. We extend our recognition to colleagues directly involved in NR-10 and electrical safety activities at Petrobras ES, whose collaboration was essential.

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What Science Says about the Injury Mechanisms described in "*When thunder roars go indoors!*"

Hélio Eiji Sueta
Institute of Energy and Environment (IEE)
University of São Paulo (USP)
São Paulo, Brazil
https://orcid.org/0000-0002-3079-2040

Danilo Ferreira de Souza
Federal University of Mato Grosso (UFMT)
Institute of Energy and Environment (IEE), University of São Paulo (USP)
São Paulo, Brazil
https://orcid.org/0000-0002-1155-1778

Miltom Shigihara
Institute of Energy and Environment (IEE)
University of São Paulo (USP)
São Paulo, Brazil
https://orcid.org/0000-0001-6907-062X

Roberto Zilles
Institute of Energy and Environment (IEE)
University of São Paulo (USP)
São Paulo, Brazil
https://orcid.org/0000-0002-5195-1493

***Abstract*—The book "*Um caminho quase suave*" (English version "When thunder roars go indoors!") published in December 2024 by the Institute of Energy and Environment of the University of São Paulo (IEE/USP), is a popular science booklet aimed at children. It serves as an educational resource introducing fundamental concepts of lightning protection. The booklet presents the main mechanisms of lightning-related injuries using accessible language and storytelling techniques to help children and laypersons understand how to protect themselves from lightning and its effects. This article examines how science has addressed and studied these injury mechanisms, drawing from technical standards and scientific literature. It discusses key publications related to topics such as upward unconnected leaders (UULs), touch and step voltages, side flashes, and overvoltage issues affecting plugged-in equipment. Technical recommendations and scientifically grounded safety tips are provided for minimizing lightning-related risks in both open areas and buildings. These include the use of thunderstorm warning systems and surge protection measures (SPMs), especially the application of Surge Protective Devices (SPDs) in electrical installations. Particularly noteworthy is IEC Technical Report TR 60479-4 (Effects of current on human beings and livestock – Part 4: Effects of lightning strokes), published in 2020, which outlines various discharge mechanisms and their potential effects on living beings, including conditions and calculations related to direct lightning strikes, touch voltages, side flashes, step voltages, and upward leaders. It also details how these mechanisms can impact the human body. In addition, this work presents key statistics related to lightning-induced injuries and fatalities.**

Keywords*— *Lightning injuries, touch voltage, step voltage, upward leader, side flashes

I. Introduction

The book *"Um caminho quase suave"* was developed as an educational booklet on lightning protection for children, introducing various concepts related to atmospheric discharges. To engage its target audience—laypeople, children, and teenagers—the content is presented as a children's story, following an adventure experienced by adolescents, children, and pets as they confront the dangers of lightning.

This paper presents the main concepts featured in the book and references the technical standards and scientific articles that address these topics. The sections analyzed, in the same order they appear in the booklet, are as follows:

- High-speed cameras, electric field sensors, and upward leaders
- Touch voltage
- Damage and shock hazards in equipment plugged into outlets
- Side flashes
- Step voltage for impulse currents
- Step voltage for alternating currents
- Hazardous voltages in the human body

- The effect of object height on lightning strike location
- Lightning protection systems
- Myths and misconceptions related to lightning
- Safety actions to take indoors before thunderstorms
- Surge Protective Devices (SPDs)
- Thunderstorm detection systems

Each topic is accompanied by simplified and didactic explanations of the associated technical studies and standards, aiming to make the content accessible and educational for the booklet's intended audience.

II. Topics Addressed

A. *Research Using Ultra High-Speed Cameras for the Study of Lightning Strikes*

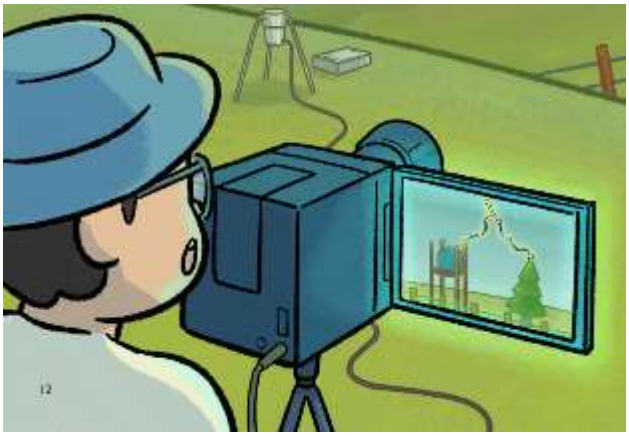

Fig. 1. High-speed camera for lightning capture.

Numerous research centers are utilizing ultra-high-speed cameras to study lightning strikes. Recent advancements in high-speed photography have significantly expanded our understanding of lightning, revealing dynamic features previously unobservable with conventional imaging. Cameras operating at tens of thousands of frames per second have enabled researchers to capture in detail the behavior of upward leaders, current zones, attachment processes, and recoil leaders.

For instance, Saba *et al.* used recordings at 40,000 fps to show multiple upward leaders competing to connect with a descending leader, providing unprecedented insight into the attachment process and the fine structure of current zones [1], [2]. Ding *at al*. combined high-speed imaging in the ultraviolet and visible bands to investigate positive and negative leaders, revealing pulsing current zones at the tips of positive leaders that are not observable in the visible spectrum alone [3].

Research centers such as the Lightning Observatory in Gainesville (LOG) employ ultra high-speed cameras (e.g., TSI – Total Sky Imager; Phantom v310; MegaSpeed) alongside ultraviolet cameras (Corona Finder/Phantom v711), infrared and thermal cameras (FLIER), electric field and X-ray sensors, long-range microphones, various antennas, and GPS devices to study lightning formation processes.

In another milestone, Abbasi *et al.* captured the first-ever video of a lightning flash associated with a terrestrial gamma-ray flash (TGF), using cameras operating at 40,000 fps to shed light on the connection between electrical discharges and high-energy radiation [4].

These developments demonstrate how modern imaging technologies are essential for bridging observational gaps and refining lightning protection models.

B. *Upward Leaders*

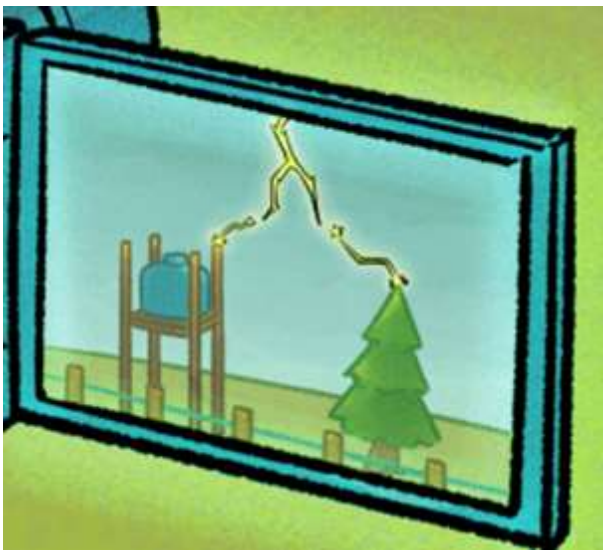

Fig. 2. Upward leaders captured by high-speed camera.

Thunderstorms contain strong electromagnetic fields. As a storm passes over a region, opposite charges are induced in objects on the ground beneath the cloud, including trees, towers, people, and animals. Upward leaders typically emerge from these objects as discharges propagating upward, seeking to connect with the descending lightning channel. Even if a connection with the downward leader does not occur, the upward leader—then referred to as an unconnected upward leader (UUL)—can carry enough energy to cause clinically documented injuries.

Fig. 3 illustrates a scenario involving multiple unconnected upward leaders (UULs), including one emerging from a victim's head, which can result in severe injuries or even death [5], [6], [7], [8].

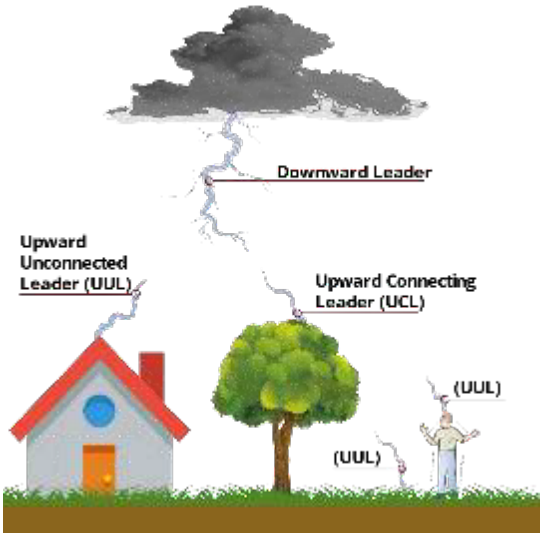

Fig. 3. Upward and downward leaders.

Using ultra high-speed cameras (above 10,000 frames per second), it is possible to capture upward leaders. Fig. 4 shows at least nine upward leaders recorded by a camera operating at 40,000 frames per second, with only one of them (highlighted in the image) successfully connecting to the downward leader [1], [2].

Fig. 4. Connected upward leader, unconnected upward leaders, and downward leader (Photo by Marcelo Saba).

The electric currents associated with Unconnected Upward Leaders (UULs) have been measured by researchers [5], [9] and are characterized by two distinct phases: a development phase and a collapse phase (see Fig. 5).

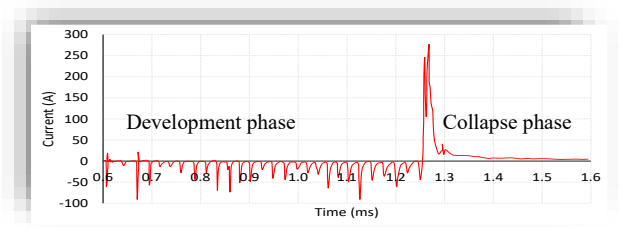

Fig. 5. Development phase and collapse phase (adapted from [9]).

- Negative peak current: –30.1 A.
- Interval between negative peak currents: 20 µs.
- Duration of each negative peak current: 10 µs.
- Duration of the development phase: 789 µs.
- Charge transferred during the development phase: –6.4 mC.
- Positive peak current: 283 A.
- Duration of the collapse phase: 388 µs.
- Charge transferred during the collapse phase: 4.7 mC.

C. Touch Voltage

Fig. 6. Touch voltage.

Touch voltage occurs when a person comes into contact with conductive paths, such as metal pipes, corded phones or devices, wired headphones, or electrical wiring—whether outdoors or indoors—or with external structures such as metal fences or bleachers. Touch voltage can also occur when animals gather near long, ungrounded wire fences [10], [11], as illustrated in Fig. 6.

Recent studies [12] present modeling approaches to estimate electric currents reaching the human heart in scenarios where a person is using a smartphone connected to a wall outlet while a lightning strike hits the medium-voltage line supplying the residence. Fig. 7 shows the full circuit used in this model.

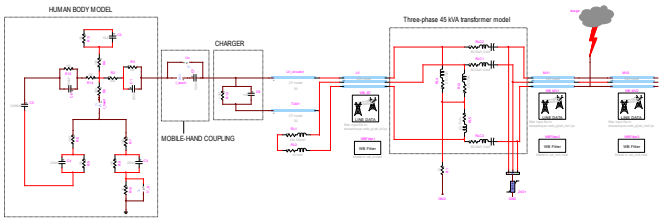

Fig. 7. Complete circuit modeled in EMTP.

Reference [12] analyzes heart currents in a victim touching a refrigerator plugged into an outlet during a lightning strike on the medium-voltage line. The study highlights how the presence or absence of surge protective devices (SPDs) installed in the distribution panel affects the amplitude of these currents. Figure 8 shows a current oscillogram through the heart obtained from the simulation.

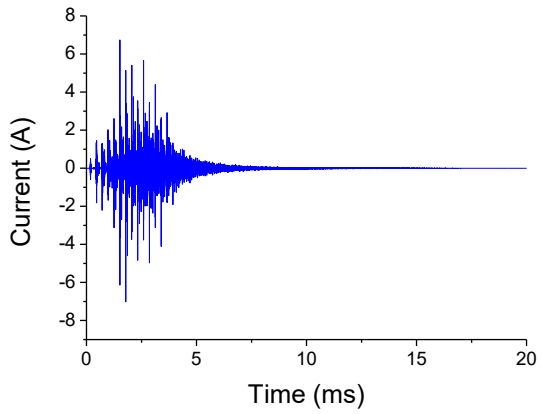

Fig. 8. Current through the heart without SPD in the distribution panel.

The inclusion of SPDs in the distribution panel showed a significant reduction in the peak current values through the heart.

Fig. 9. Smartphone connected to a wall outlet.

Fig. 9 shows a scene from the book in which a smartphone connected to a wall outlet explodes and starts a fire due to a lightning strike on the power line. It would be considered a touch voltage incident if the character had been holding the smartphone.

D. Side Flashes

Fig. 10. Side flash hazard.

Side flashes occur when trees, poles, towers, or other tall objects are struck by lightning, and part of the lightning current arcs to a nearby person. Examples include someone seeking shelter from rain under a tree (see Fig. 10), standing in a parking lot with a metal structure (Fig. 11), or standing too close to the down conductors of a Lightning Protection System (LPS) [13], [14].

Fig. 11. Side Flashes.

Figure 11 is included in Annex G of NBR 16785 [14], [15], [16], which presents safety procedures for reducing risk outside the structure. This annex also includes recommendations related to the other mechanisms described in this study.

E. Step Voltage for Impulse Currents

Fig. 12. Step voltage from impulse currents.

Step voltage occurs when lightning strikes the ground or an object connected to the ground, and its current spreads through the Earth. This current creates ground potential that can injure nearby individuals. It can affect many people both indoors and outdoors in unprotected buildings. Typical examples include field workers, children in classrooms, people engaged in outdoor sports, or congregants at open-air churches. Animal fatalities due to step voltage are also common. Since the distance between a quadruped's front and rear legs is significant (compared to a human), and the current path often involves the heart, animal deaths in open fields caused by lightning (Fig. 12) are frequently observed [17].

Many injuries and fatalities from lightning, when there is no observed direct strike to the individual, are classified as "step voltage" incidents. More recent studies [17], [18] have shown that the hazardous potentials from step voltage are particularly dangerous when a person is located relatively close to the point where the lightning current enters the ground—within about 20 meters—depending on the current magnitude. Figure 13 shows a voltage-versus-distance curve for a 10 kA current in soil with a resistivity of 100 Ω·m, as provided in IEC TR 60479-4:2020 [18].

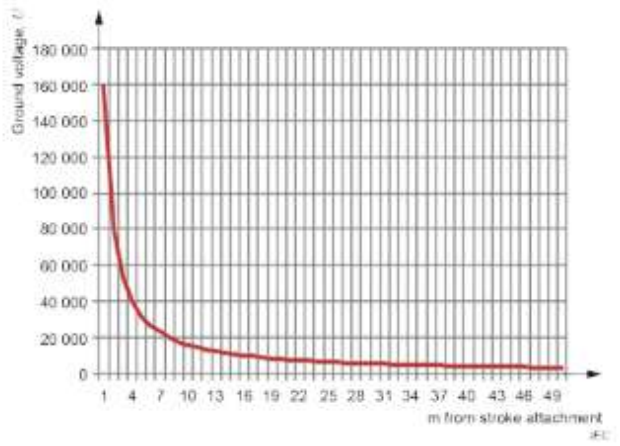

Fig. 13. Ground potential vs. distance. (adapted from [18]).

F. Step Voltage from Alternating Currents

Fig. 14. Step voltage from alternating currents.

Unlike step voltage from lightning strikes—which lasts only a few milliseconds—short-circuit currents in high-impedance circuits can persist much longer, potentially lasting minutes. Considering Fig. 14, the safest action would be to wait for professional emergency services before attempting to exit the vehicle. The recommendation from the book applies to scenarios where the short-circuit current does not trigger protective devices (due to high impedance) and where help is not readily accessible—such as in a rural property far from the city.

In cases where energized power lines fall onto vehicles, São Paulo's Civil Defense advises the following: if a power line falls on the vehicle, the driver should not attempt to exit. Instead, emergency services should be contacted. Because the entire vehicle is likely energized, one must avoid touching any external part of the vehicle or any metallic interior surfaces. Additionally, no one outside the vehicle should approach within a 10-meter radius, as they could be electrocuted. If the vehicle catches fire, the driver and passengers must exit by jumping with both feet together, avoiding contact with the vehicle exterior. Then, they should either shuffle their feet or make small jumps until they are at least 10 meters away from the car.

G. Hazardous Voltages on the Human Body

Fig. 15. Possibility of impulse voltage on the human body.

A study from the Universidad Nacional de Colombia, developed as the doctoral thesis of Jorge Alejandro Cristancho Caviativa and titled "Analysis and development of a personal portable lightning protection system", investigates the use of conductive fabrics to mitigate hazardous voltages on the human body. The research explores the potential application of such materials as personal protection in extreme situations, such as remote camping areas far from lightning-safe structures. The work includes experimental tests conducted with conductive textiles, measuring the voltages that may appear on the body of a person lying on the fabric while a lightning current flows through the ground beneath it.

H. Effect of Height on Lightning Strike Points

Fig. 16. Height effect.

Numerous safety guidelines emphasize that individuals should avoid increasing their effective height when exposed to the risk of direct lightning strikes. Holding umbrellas, fishing rods, metal pipes, or even placing another person on one's shoulders in such conditions can be extremely dangerous. Lightning typically strikes the tallest objects—or people/animals in contact with the ground—within the vicinity of the impact point.

Standards for lightning protection of structures [19], [20], [21], [22], [23] generally recommend the use of rods properly positioned on rooftops to serve as the preferred strike points for lightning strikes.

I. Lightning Protection Systems (LPS)

Fig. 17. Lightning Protection System (LPS).

An effective Lightning Protection System (LPS) must comply with applicable technical standards. In Brazil, the relevant standard is ABNT NBR 5419, which is structured into four parts. Internationally, the corresponding standard is IEC 62305 [24], [25], [26], [27], also organized into four parts.

J. Myths and Misconceptions Related to Lightning

Fig. 18. Myths and Misconceptions.

Numerous books and technical publications have documented the myths and misconceptions that have developed over time regarding lightning. The chapter "Lightning: Public Concepts and Safety Education" by Chandima Gomes and Ashen Gomes, published in the book "Lightning – Science, Engineering, and Economic Implications for Developing Countries"[28], edited by Chandima Gomes, as well as the introduction of "Proteção contra descargas atmosféricas" by Duílio Moreira Leite [32] and "Lightning – Vol. 1: Physics of Lightning" by R. H. Golde [33], discuss a variety of popular beliefs surrounding lightning.

Examples of such misconceptions include covering mirrors, hiding knives and scissors during thunderstorms—practices, which are still common today, particularly among older generations. In ancient Rome, it was believed that wearing seal skin during storms offered protection against lightning. Similarly, carrying a "lightning stone"—a fulgurite formed when lightning strikes the ground—was once thought to offer safety.

K. Actions to Be Taken Indoors Before Thunderstorms

Fig. 19. Unplugging Devices from Outlets.

When inside a structure, it is highly advisable to unplug major electronic and electrical devices from power outlets. If the equipment has other signal inputs—such as antenna, network, or telephone lines—those should also be disconnected. These precautions must be taken before the thunderstorm reaches the area, as there is always a risk that lightning could strike the power line at the exact moment someone is unplugging a device, potentially causing serious injury.

L. Surge Protective Devices (SPDs)

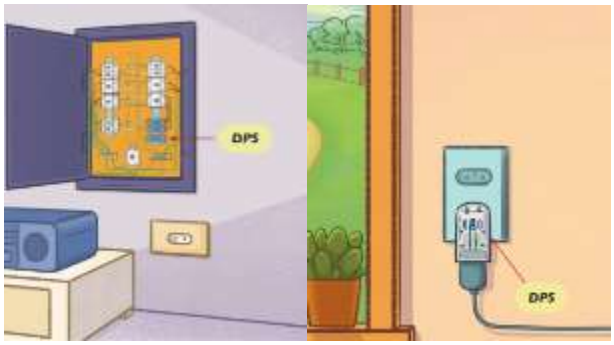

Fig. 20. SPDs.

The use of Surge Protective Devices (SPDs) is highly recommended, in most cases, mandatory — for both power, and signal systems. These devices are essential for mitigating damage caused by transient overvoltages. The applicable standards for these products in Brazil are outlined in the ABNT NBR IEC 61643 series [28], which includes multiple parts addressing various types and applications of SPDs.

M. Thunderstorm Detection Systems

Fig. 21. Thunderstorm Warning System.

Thunderstorm warning systems must comply with the guidelines established in the standards ABNT NBR 16785 [16] and IEC 62793 [30]. These standards define the requirements for thunderstorm detection systems, including specifications for sensor types and the functional characteristics of software used to detect lightning-related storm activity in specific geographic areas. Such systems are critical for early warning and risk mitigation associated with lightning hazards.

III. Essential Documents On The Subject

Two documents previously mentioned in this work are important for the topics addressed in the book under discussion. The Brazilian standard ABNT NBR 16785:2019 [16], particularly Annex G, provides safety procedures for reducing lightning risks in open areas. This annex, based on [31], introduces definitions of the main types of lightning injuries in living beings, describes the principal injury mechanisms, and offers guidance on how to assist injured individuals and act in the presence of a thunderstorm.

The IEC TR 60479-4 [18] presents the main effects of lightning currents on living beings. It explains key definitions and characteristics of lightning, including its formation and occurrence. The document focuses specifically on injury mechanisms, presenting formulas and scenarios that support a better understanding of the phenomena and protection strategies.

IV. Conclusions

The main objective of this paper was to analyze, from a scientific and engineering perspective, the injury mechanisms caused by lightning strikes as introduced in the children's educational booklet A Nearly Smooth Path. By confronting the narrative elements of the book with the state of the art in technical standards and scientific literature, it became evident that—even when conveyed in simplified and accessible language—it is possible to develop technically sound concepts of lightning safety for general audiences, particularly children and adolescents.

The analyzed mechanisms — including upward unconnected leaders (UULs), touch and step voltages, side flashes, and surge effects on electronic devices — were supported by national and international standards and by recent experimental studies, some conducted by Brazilian researchers. This scientific foundation lends credibility to the book's content and enhances its potential as a tool for preventive education.

The intersection between scientific communication and consolidated technical knowledge has proven to be an effective strategy for increasing risk awareness and promoting safe behaviors during electrical storms. Including practical guidance, such as the importance of surge protection devices (SPDs), thunderstorm warning systems (TWS), and safety procedures for buildings and open areas, contributes not only to disseminating knowledge but also to effectively reducing lightning-related incidents.

It is concluded that initiatives like A Nearly Smooth Path hold strategic value for promoting a culture of electrical safety, mainly when supported by robust and up-to-date technical references. The technical insights provided in this article serve as a foundation for future booklet editions and inspire the development of new educational materials grounded in scientific evidence.

Acknowledgment

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Integrated lightning prediction system: Technological advances for safety and efficiency in mining

Soares, Waterson
dept. of Electrical Engineering, Instrumentation and Automation
VALE SA
São Gonçalo do Rio Abaixo, Brazil
https://orcid.org/0000-0002-1966-6465

Fonseca, Fabricio
dept. of Electrical Engineering, Instrumentation and Automation
VALE SA
Itabira, Brazil
fabricio.fonseca@vale.com

Guerra, Luciano
dept. of Electrical Engineering, Instrumentation and Automation
VALE SA
Mariana, Brazil
luciano.guerra@vale.com

Castro, Edmilson
dept. of Electrical Engineering, Instrumentation and Automation
VALE SA
Vitória, Brazil
edmilson.jose@vale.com

Araujo, Guilherme
dept. of Electrical Engineering, Instrumentation and Automation
VALE SA
São Gonçalo do Rio Abaixo, Brazil
guilherme.araujo@vale.com

***Abstract*— The phenomena of nature are still a great mystery to the scientific community, and we are sometimes surprised by uncertainties. Predicting lightning strikes is a critical need, especially in sectors such as mining, where workers are often exposed to open field conditions. To ensure the safety of these professionals, it is essential to use technologies that allow lightning to be accurately anticipated and effective alerts to be issued. This article highlights the importance of prediction systems that combine different technologies, such as weather radars, satellites, electric and magnetic field sensors, wind speed and relative humidity measurements, all in line with the NBR-16785 and IEC-62793 standards. The proposed methodology aims to optimize alert times, increasing safety and operational efficiency. The previous system, which relied mainly on weather radars, satellites and long-distance electromagnetic field measurements, was improved with the installation of point sensors that measure electric field, magnetic field, wind speed and relative humidity. This integration resulted in an average 80% reduction in the duration of alerts, providing significant gains in operation, maintenance and production in the mineral extraction and processing process. The model was implemented in several mines and evaluated during the full rainy season between 2024 and 2025, demonstrating its effectiveness in protecting workers and improving productivity. This innovative approach not only increases safety, but also contributes to the optimization of mining processes, showing that the combination of technologies can be the key to predicting and mitigating the risks associated with lightning strikes.**

Keywords—Lightning strike prediction, Lightning early warnings, Mining safety, Electric and magnetic field sensors, Alert optimization.

I. INTRODUCTION

Despite the great advances in the specialized literature on lightning, whether in relation to the physical phenomenon itself or its causes, as a natural phenomenon, it cannot be neutralized or ignored. Therefore, mining operations need to learn to deal with the problem and mitigate the impact, either for individual or collective protection, or to protect the company's operations.

There are between 30 and 100 cloud-to-cloud (CC) and cloud-to-ground (CG) lightning strikes per second worldwide [1], with Brazil having the highest incidence [2]. The complex nature of lightning, such as its random spatio-temporal occurrence, makes it challenging to study.

The lightning forecasting system must fully meet the criteria established by the technical standards [5] and [6]. With this in mind, local electric field, magnetic field, wind speed and relative humidity sensors were installed, allowing us to monitor weather conditions in each region in real time. To ensure good accuracy in the forecasting process, it is also necessary to monitor the weather using satellites and weather radar. This information together helps meteorologists make decisions about issuing alerts for the monitored areas. All monitoring is continuous, 24 hours a day, 365 days a year.

II. Theorical Background

A. Minimum Requirements for Early Warning Systems

In [5], establishes the minimum requirements for early warning systems and their application in outdoor environments, especially in activities involving exposure to electrical storms. It defines criteria for reliability, lead time, maintenance and operating procedures.

B. Efficiency, calibration and response of sensors according to standard

The criteria detailed in [6], complements the international normative approach by dealing with the efficiency, calibration and response of electric field sensors. It establishes guidelines for lightning detection, integrated sensors and criteria for issuing warnings.

C. Mining environment and related risks

In open-cast mining and mineral processing activities, the need for early warning of lightning is critical and complex to predict, since the phenomenon is influenced by various factors which need to be monitored and correlated so that the prediction is reliable to ensure the safe evacuation of people, controlled shutdown of machinery and protection of teams. Exposure is increased by the conductivity of metal structures and the difficulty of finding immediate shelter.

III. Methodology

A. Sensor Installation and Data Integration

Point sensors have been installed in critical areas of the mines, with the following functions:

Electric Field Sensor: Point electric field measurement (V/m) (key meter for lightning prediction).

Magnetic Field Sensor: Detection of nearby electromagnetic pulses.

Ultrasonic Anemometer: Monitoring wind speed and direction, for analyzing the movement of convective cells.

Humidity and Temperature Sensor: For correlation with atmospheric instability indices.

External data: Integration with weather radar systems and satellite images via reliable APIs.

B. Integration between the sensor network at iron ore mines, satellites and meteorological radar

At each iron ore mine, sensors were installed to monitor electric and magnetic fields, wind speed, and relative humidity, which are integrated with meteorological information from the satellite and weather radar network. These variables are analyzed and strongly correlated for decision-making and subsequent dispatch of lightning warnings.

C. Analysis and Alert Issuing Methodology

Measurements of electric and magnetic fields, wind speed, relative humidity, information from weather radars and satellites are analyzed by meteorologists and correlated to predict lightning strikes, and this information is sent to employees via app, SMS and email. The system generates alerts on three levels:

Pre-alert (blue): Atmospheric instability detected with predictability of 60 minutes.

Alert (yellow): Anomalies detected, but no imminent risk, 30-minute forecast.

Critical Alert (red): Detection of an electric field above the risk threshold, lightning in the vicinity, or instability detected by radar or satellite. Significant probability of discharge within 20 minutes.

Clearance alert (green): No instability in the vicinity.

IV. Results and Discussion

A. Assertiveness assessment

The implementation of this lightning prediction model achieved an average assertiveness rate of 83.09% in the alerts issued compared to the previous system, which used information from weather radars and satellites.

B. Reduced exposure and unnecessary downtime

The comparison with the previous method (alerts based only on weather forecasts from radars and satellites) showed:

Average percentage of optimization of alert efficiency was 83.09% in the Southeast Corridor Mines, totaling 980 hours and 25 minutes of avoided downtime.

C. Performance of Local Sensors

The field sensors proved to be more effective in anticipating lightning strikes, since we obtained the point values which are the best references when correlated with the meteorological radar data and these were important in confirming and tracking the direction of the storm.

D. Time of red warnings per month

The following graphs show a comparison between the previous system, represented by the red color, and the new prediction methodology used, represented by the green color. These graphs show the time of red warnings per month for each mine where the point sensors were installed. The results show that the percentage of optimized alert efficiency between the previous methodology and the new methodology for Cauê Mine was 84.21%, for Conceição Mine was 78.75%, for Água Limpa Mine was 81.07%, for Brucutu Mine was 83.34%, for Capanema Mine was 76.43%, for Fazendão Mine was 90.25%, and Timbopeba Mine was 83.35%.

The results are shown in Figures 1, Figure 2, Figure 3, Figure 4, Figure 5, Figure 6, Figure 7.

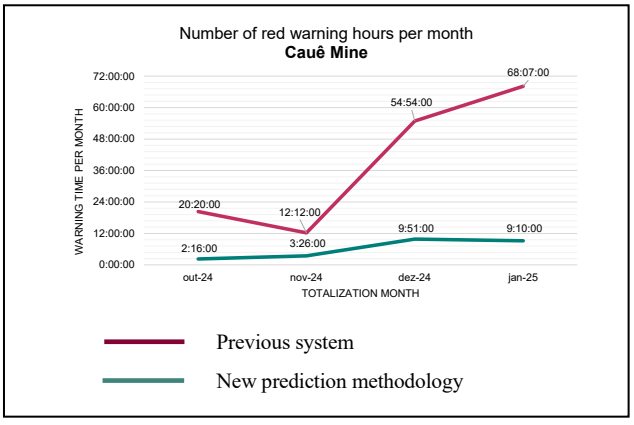

Fig. 1. Number of red warning hours per month at Cauê Mine

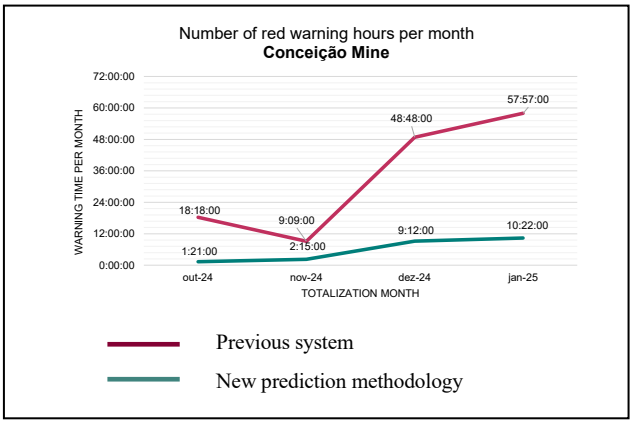

Fig. 2. Number of red warning hours per month at Conceição Mine

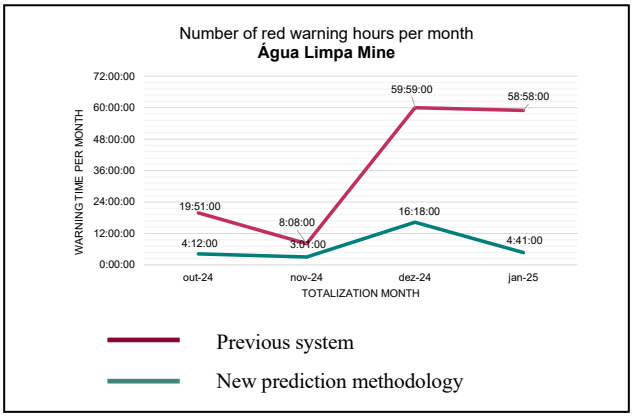

Fig. 3. Number of red warning hours per month at Água Limpa Mine

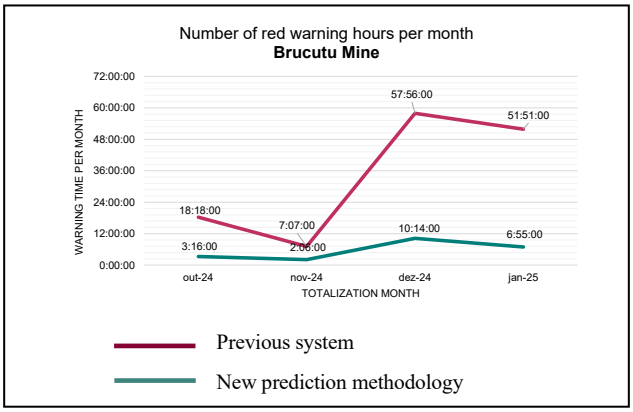

Fig. 4. Number of red warning hours per month at Brucutu Mine

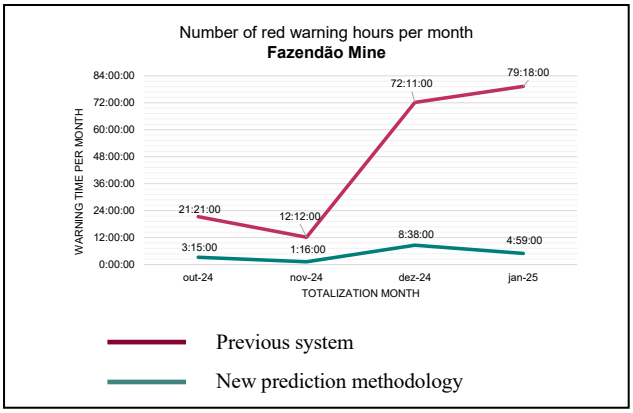

Fig. 5. Number of red warning hours per month at Fazendão Mine

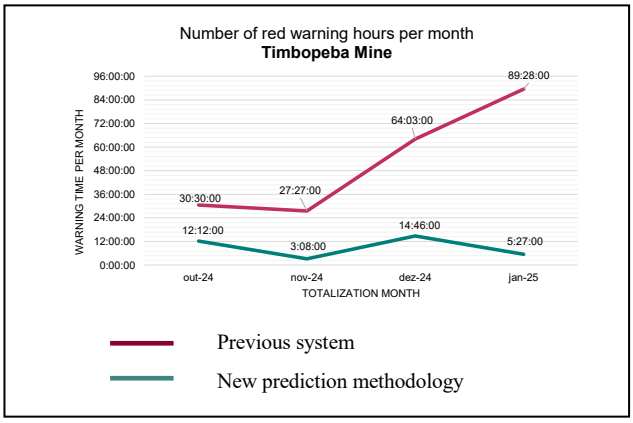

Fig. 6. Number of red warning hours per month at Timbopeba Mine

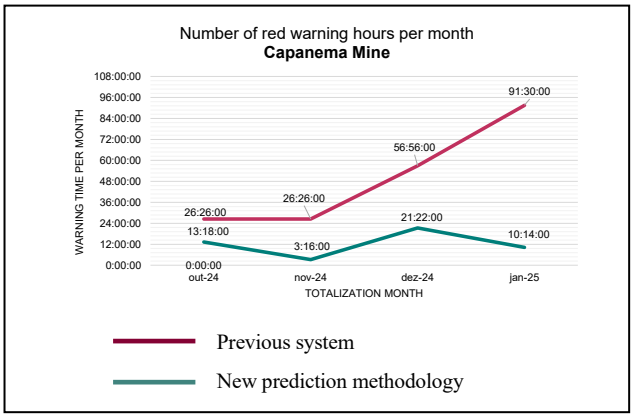

Fig. 7. Number of red warning hours per month at Capanema Mine.

V. Concluding Remarks

The combined application by standards [5] and [6] in mining environments, supported by sensors, weather radars, and satellites, demonstrated high potential for optimizing lightning warnings. The installed system demonstrated high accuracy, directly contributing to safety. It is recommended that the model be extended to other operational units.

Acknowledgment

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Inspeção em Equipamentos Elétricos e Não-elétricos em Áreas Classificadas Offshore – Bacia de Santos, Brasil

Carlos José da Silva Matos Pombo
PETROBRAS
Santos, SP - Brasil
cjpombo@gmail.com

Rogélio Gongora da Silva
PETROBRAS
Santos, SP - Brasil
rogelio.gongora@gmail.com

Franco Almir de Melo
PETROBRAS
Santos, SP – Brasil
francoalmir2@yahoo.com.br

***Resumo*—As instalações elétricas "Ex" e mecânicas "Ex" (não-elétricas) que compõem o processo produtivo das plataformas de produção de óleo e gás, principalmente as plataformas flutuantes do tipo FPSO (Floating Production Storage and Offloading) da Bacia de Santos, mais recentes e de alta capacidade de produção, trazem um parque instalado de milhares de equipamentos elétricos e não-elétricos inseridos em áreas classificadas. A gestão do ciclo total de vida de tais equipamentos é, portanto, um atributo crítico para que a instalação permaneça segura e em conformidade com as normas e regulamentos vigentes no Brasil e também praticados no exterior, principalmente as normas regulamentadoras NR-10 e NR-37 do Ministério do Trabalho e Emprego. Esse trabalho traz um apanhado geral das últimas campanhas de inspeção de equipamentos elétricos "Ex" e não-elétricos para uso em atmosferas explosivas com base nas normas ABNT NBR IEC 60079-17 e ABNT NBR ISO 80079-36, respectivamente, trazendo os principais aspectos técnicos e gerenciais deste tipo de serviço, resultados e lições aprendidas, cujo serviço deve estar criticamente adimplente as normas técnicas aplicáveis, pessoal competente e empresa prestadora de serviços certificada.**
Palavras-chave—atmosferas explosivas, "Ex", área classificada

I. Introdução

Tem-se, ao longo dos anos, um crescente interesse da indústria, das autoridades regulatórias e das demais partes interessadas e interatuantes para com instalações "Ex" que tais áreas classificadas estejam de fato seguras, algo que depende da correta execução de serviços de campo, incluindo serviços de montagem, inspeção e manutenção "Ex" dos equipamentos elétricos, de instrumentação, de automação, de telecomunicações e mecânicos "Ex". A execução correta destes serviços de campo contribui para que os equipamentos com certificação "Ex" não representem possíveis "fontes de ignição" ao longo de toda sua vida útil operacional.

Os profissionais "Ex" que executam ou supervisionam estes serviços de campo necessitam possuir os devidos conhecimentos, experiências, treinamentos e certificação de suas competências pessoais, de forma a proporcionar a necessária confiança que os serviços de campo "Ex" serão realizados de forma correta, atendendo aos requisitos indicados nas respectivas Normas Técnicas Brasileiras da Série ABNT NBR IEC 60079 - Parte 14 (Serviços de projeto e montagem "Ex"), Parte 17 (Serviços de inspeção e manutenção "Ex") e Parte 19 (Serviços de reparo e recuperação "Ex") e, mais recentemente, inclui-se a normatização referente a equipamentos "Ex" não-elétricos com base na Série ABNT NBR ISO 80079, a partir da Parte 36 (Métodos e Requisitos Básicos).

Para o caso das plataformas flutuantes tipo FPSO (Floating, Production, Storage and Offloading), a prática de projeto, seleção e montagem de equipamentos elétricos "Ex" já é bem estabelecido pela indústria naval, citando-se principalmente o controle dos certificados "Ex" oriundos dos fornecedores dos respectivos equipamentos certificados através das Sociedades Classificadoras que atuam no nome da Autoridade Marítima Brasileira na regularização, controle e certificação de tais embarcações.

Porém, o continuar da vida útil de tais equipamentos "Ex" padece de um cuidado especial, ainda mais estando os mesmos em operação nos ambientes agressivos (elevada umidade, salinidade, abrasividade etc) tipicamente observados em uma unidade marítima. Situações comuns são de corrosão severa, quebras no invólucro e/ou sua suportação, degradação das vedações e consequente penetração de intempéries no interior do equipamento, modificações não autorizadas e/ou simplesmente falta de manutenção e/ou preservação generalizada que conduzem tais equipamentos, num horizonte de médio prazo, a serem impactados negativamente no conceito ou mecanismo de proteção "Ex" de seu projeto original certificado, constituindo-se numa potencial fonte de ignição caso não sejam devida e regularmente inspecionados e corrigidos.

A norma ABNT NBR IEC 60079-17 traz o conceito deste "médio prazo" a uma inspeção periódica tipicamente trienal, em que tais equipamentos "Ex" devem ser revisitados ciclicamente dentro deste prazo, trazendo uma sistemática de Lista de Verificação padronizada para cada tipo de proteção, bem como tipo e grau da inspeção praticada.

O desafio é, portanto, realizar ciclos de inspeção trienais num acervo de cerca de 15 mil equipamentos elétricos "Ex" e cerca de 1200 equipamentos mecânicos "Ex" selecionados em

uma plataforma flutuante de alta capacidade em operação, bem como organizar o processo de lançamento de notas de manutenção com base em regras de priorização e atingimento do encerramento técnico das mesmas num ambiente restrito de recursos técnicos e humanos. Trata-se do objetivo deste artigo, portanto, mostrar os aspectos de gestão e produtividade esperada para esta atividade, bem como compartilhar algumas lições aprendidas no histórico da adoção de contratos com este escopo.

II. Aspectos Contratuais

Se cercar dos melhores recursos técnicos e humanos é primordial para este tipo de serviço. Não obstante, a utilização de uma empresa com Sistema de Gestão da Qualidade certificada no escopo da ABNT NBR IEC 60079-17 é fundamental para que se tenha fidúcia satisfatória na qualidade técnica nos serviços de inspeção e manutenção "Ex", com práticas técnicas e de gestão procedimentadas e de qualidade.

Os recursos humanos, por outro lado, são igualmente importantes. Uma vez que o controle estrito de recursos na plataforma simplesmente não permite "uma segunda chance" de se realizar uma avaliação ou correção num equipamento "Ex" elétrico ou não-elétrico, é indispensável que um nível mínimo de peritagem do profissional seja assegurado através de avaliação por terceira parte especializada, no que os esquemas de certificação de competências pessoais disponíveis no mercado nacional, oriundos de uma base normativa internacional, são utilizados neste tipo de contratação.

Citam-se para tais aspectos os documentos operacionais do IECEx OD 314-4 (Requisitos do Sistema de Gestão da Qualidade para Empresas de Serviços) e OD 504 (Especificações para a avaliação dos resultados das Unidades de Competências "Ex"), existindo no país algumas entidades de terceira parte que certificam profissionais e empresas neste escopo, bem como noutros processos subjacentes a tais requisitos.

Neste caso, a empresa faz uso de inspetores "Ex" certificados nas competências Ex 001, Ex 007 e Ex 008, bem como mantenedores "Ex" certificados nas competências Ex 001, Ex 003 e Ex 004. Para o caso da avaliação de conformidade dos equipamentos mecânicos "não-elétricos", faz-se uso do mesmo paradigma de inspetores "Ex" elétricos, ou seja, exige-se o mínimo certificação nas competências Ex 001, Ex 007 e Ex 008. As equipes são bem reduzidas, compostas basicamente por dois especialistas de cada atividade acima descrita, um vez que o acesso a área operacional na plataforma é bem restrito.

A não adoção de empresa e/ou colaboradores com um nível mínimo adequado de conhecimento desta disciplina implica em deficiências irrecuperáveis nos processos de inspeção e manutenção, por exemplo, erros de avaliação, subnotificações de desvios, imperícias nas manutenções etc, por conseguinte, assunção dos mesmos e de novos riscos na instalação "Ex".

III. Inspeção em Equipamentos Elétricos "Ex"

A Bacia de Santos traz uma diversidade de plataformas de produção de petróleo associadas principalmente ao desenvolvimento do "pré-sal" brasileiro, desde plataformas fixas com perfil de produção de gás até a série "replicantes", estas últimas de alta capacidade e do tipo FPSO.

Tais plataformas são de tecnologia recente, datadas principalmente da segunda década dos anos 2000, sendo que o conteúdo elétrico é importante e associado desde grandes máquinas de geração, bombeamento e compressão, bem como distribuída em diversas cargas elétricas menores locais, em todo caso, grande parte delas instaladas em áreas classificadas.

Os ciclos de inspeção "Ex" tal como prescritos pela ABNT NBR IEC 60079-17 normalmente vem sido obedecidos desde a fase do estaleiro, em que as replicantes da série P-66 a P-71 foram submetidas a inspeção tipo inicial grau detalhado ainda em fase de integração e no estaleiro. Desde o primeiro óleo de cada uma delas, qual ocorreu principalmente a partir de 2019, desde então tem-se estabelecido os ciclos de inspeção trienais, sendo que cada plataforma já se encontra entre o segundo e terceiro ciclos de inspeção trienais, conforme sua campanha de produção em andamento.

Por outro lado, as plataformas fixas em operação na Bacia de Santos são mais antigas (início dos anos 2000) e não foram submetidas aos ciclos de inspeção periódica, sequer a inspeção inicial de estaleiro, porém as mesmas já atendiam aos critérios de projeto da série ABNT NBR IEC 60079 e portarias INMETRO vigentes à época de projeto e comissionamento, não estando tão defasadas tecnologicamente do caso das replicantes acima descrito.

A. Características Gerais das Inspeções "Ex" - Elétricos

Conforme requisito contratual prevê o uso de sistemas automatizados para registro e controle dos dados das inspeções, o uso de "tablets" ou "smartphones" certificados "Ex", com interface a um sistema em nuvem para aporte em tempo real dos resultados das inspeções foi essencial para obter uma relativa alta produtividade de inspeção e manutenção a bordo.

Fig. 1. Exemplo do uso de tablet "Ex" em área e recorte da Lista de Verificação automatizada

As Inspeções "Ex" foram controladas através de etiquetas afixadas nos equipamentos, rastreáveis ao respectivo relatório, uma para cada equipamento.

Fig. 2. Exemplo de etiqueta de inspeção "Ex" rastreável ao relatório

Para os casos de equipamentos elétricos “Ex” que por algum motivo perderam sua plaqueta de identificação, são produzidas novas plaquetas de marcação em aço inoxidável conforme requisitos da ABNT NBR IEC 60079-0 Requisitos Gerais.

Fig. 3. Exemplo de plaqueta “Ex” substituta

Foi também escopo contratual a adoção de inspeção e manutenção de equipamentos elétricos em locais de difícil acesso, através de acesso por cordas, em conformidade com a ABNT NBR 15595 – Acesso por Cordas.

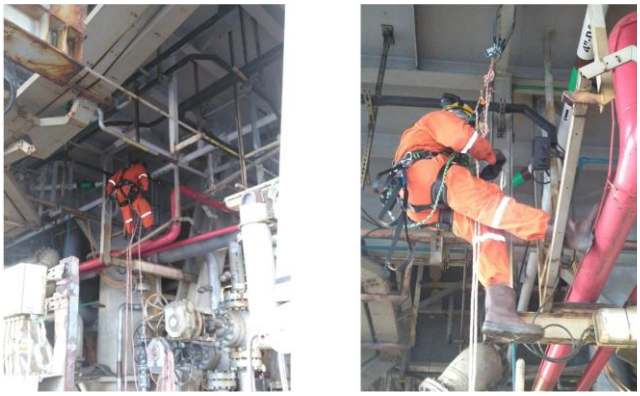

Fig. 4. Inspeção e Manutenção através de acesso por cordas

Foram produzidas ao final de cada inspeção as seguintes entregas:

- Inspeção e manutenção dos cerca de 15000 equipamentos elétricos “Ex” com base na padronização normativa da ABNT NBR IEC 60079;
- Inventário atualizado dos equipamentos elétricos “Ex” com dados completos de marcação, certificado, localização, confirmação do EPL apropriado para a respectiva área classificada em planta, dentre outros registros;
- Elaboração de banco de dados de desvios “Ex” dos equipamentos elétricos impactados, com categorização, prazo inicial e recomendações para manutenção corretiva;
- Gestão de notas corretivas junto ao Planejamento de Manutenção de Base de cada plataforma;
- Sinalização de equipamentos e circuitos;
- Fixação de novas plaquetas de marcação “Ex”;
- Avaliação de equipamentos elétricos industriais adequados para o uso em Zona 2 (avaliação conforme portaria INMETRO);
- Realização de eventos de conscientização da segurança em atmosferas explosivas nas plataformas de produção (diálogos de segurança, workshops, etc).

B. Resultados de uma plataforma fixa, não comissionada “Ex”

O primeiro ciclo de inspeção periódica numa plataforma fixa a qual não foi submetida a uma inspeção inicial grau detalhada na fase de estaleiro produziu um número significativo de desvios, cerca de 45% do total de equipamentos “Ex” inspecionados, no entanto, a maior parte se deu por falta de artigos de sinalização prescritos nas normas (falta de identificação do circuito e/ou plaqueta “Ex”).

Os desvios da categoria leve, conforme padrão interno para categorização de desvios “Ex”, indica presença de anomalias que não impactam diretamente a proteção “Ex” do equipamento no momento da inspeção, porém, caso não sejam corrigidos, poderão agravar e conduzir o equipamento para uma condição de risco.

TABELA I. PLATAFORMA FIXA, NÃO COMISSIONADA “EX”

Sem Desvio	**Total de Equipamentos: 4448[a]**		
	Sinalização	***Leve***	***Moderada+***
2462	1029	924	53

[a.] Produtividade/equipe – 57 Equipamentos “Ex”/dia

Por outro lado, os desvios categorizados como moderados, graves ou críticos, foram priorizados e tratados ao longo da campanha de inspeção deste ciclo, pois impactam o tipo de proteção “Ex” e ensejaram uma correção imediata.

O “Pareto” de desvios categorizados “Ex” são conforme os casos; falta de condutor de aterramento – 51%, falta/dano no bujão/prensa-cabos – 27%, dano no invólucro/vedações – 15%, dano em parafuso/cabo – 4%, dentre outros.

Os casos em que a continuidade operacional do equipamento e do sistema operacional subjacente não permitem a manutenção imediata, estes são geridos através dos processos de Gestão de Mudanças da plataforma, dando origem a adoção de algum tipo de medida contingencial e/ou de monitoramento adicional, conforme o caso.

C. Resultados de uma FPSO não comissionada “Ex”

O primeiro ciclo de inspeção periódica numa plataforma tipo FPSO de alta capacidade a qual não foi submetida a uma inspeção inicial grau detalhada na fase de estaleiro produziu anotação de desvios em cerca de 28% do total dos equipamentos elétricos “Ex” inspecionados, no entanto, a maior parte se deu também por falta de artigos de sinalização tal como no caso da plataforma fixa anterior.

TABELA II. PLATAFORMA FPSO, NÃO COMISSIONADA “EX”

Sem Desvio	**Total de Equipamentos: 15504[b]**		
	Sinalização	***Leve***	***Moderada+***
11209	3542	707	46

[b.] Produtividade/equipe – 60 Equipamentos “Ex”/dia

O “Pareto” de desvios categorizados “Ex” é diferente do caso da plataforma fixa, a saber; falta de condutor de aterramento – 36%, falta/dano no bujão/prensa-cabos – 37%, dano no invólucro/vedações – 16%, dano em parafuso/cabo – 4%, dentre outros.

Comparativamente, uma FPSO de alta capacidade possui cerca de três vezes mais equipamentos elétricos “Ex” que a plataforma fixa do caso anterior, no entanto, a quantidade de desvios nesta plataforma mais complexa apenas escalou linearmente na proporção de desvios de sinalização (3542 *versus* 1029), porém se manteve proporcionalmente menor nos demais desvios categorizados (707 *versus* 924 leves, 46 *versus* 53 moderados+).

Uma explicação plausível para tal constatação se deve ao fato da plataforma fixa estar operando a mais de uma década relativamente ao primeiro óleo da FPSO de alta capacidade, em que um acumulado de degradações nos equipamentos “Ex” devido a exposição ao ambiente agressivo marítimo bem como sucessivas intervenções malconduzidas no equipamento é esperada, especialmente para os casos de falta do condutor de aterramento e também falta/dano no bujão/prensa-cabos.

D. Resultados de uma FPSO comissionada “Ex”

O primeiro ciclo de inspeção periódica numa plataforma tipo FPSO de alta capacidade a qual foi submetida a uma inspeção inicial grau detalhada na fase de estaleiro produziu uma anotação de desvios de cerca de 19% do total dos equipamentos elétricos “Ex” inspecionados.

TABELA III. PLATAFORMA FPSO COMISSIONADA “EX”

Sem Desvio	**Total de Equipamentos: 12447[c]**		
	Sinalização	***Leve***	***Moderada+***
10110	1506	744	87

[c.] Produtividade/equipe – 90 Equipamentos “Ex”/dia

A inspeção não atingiu a 100% do acervo de equipamentos “Ex” devido a pelo menos dois módulos e alguns sistemas operacionais não estarem em condição operacional durante a janela de embarques alocada para inspeção, em que o escopo do contrato somente abrange áreas comissionadas e em operação.

O “Pareto” de desvios categorizados “Ex” é diferente do caso da FPSO anterior, a saber; falta de condutor de aterramento – 54%, falta/dano no bujão/prensa-cabos – 27%, dano no invólucro/vedações – 13%, dano em parafuso/cabo – 4%, dentre outros.

Percebe-se neste ciclo de inspeção que a produtividade por dia e por equipe foi maior que nos casos anteriores, uma vez que o número de desvios encontrado foi significativamente menor que nos casos anteriores, bem como aprimoramento da curva de aprendizado das equipes ao longo das inspeções, sendo esta inspeção a mais recente dentre os casos anteriores.

A adoção da inspeção inicial grau detalhada ainda na fase de estaleiro produziu um número menor de não conformidades de sinalização a partir deste novo ciclo de inspeção, já em fase operacional, porém o número de não conformidades do tipo leve e moderada+ foram proporcionalmente maiores que a FPSO anterior devido a idiossincrasias do comissionamento desta plataforma (vários sistemas operacionais foram comissionados a bordo somente após a fase do estaleiro, agregando desvios “Ex” não previamente controlados em estaleiro).

IV. INSPEÇÃO EM EQUIPAMENTOS MECÂNICOS “EX” (NÃO-ELÉTRICOS)

O advento da série ABNT NBR ISO 80079 trouxe um novo paradigma para a disciplina de atmosferas explosivas: a avaliação de risco de ignição (em inglês, Ignition Hazard Assessment, ou IHA) de equipamentos não-elétricos (os ditos “mecânicos” Ex).

Não era incomum surgirem inconsistências de abordagem do risco de ignição da atmosfera explosiva entre as disciplinas técnicas de um mesmo projeto de instalação: por um lado, a disciplina de elétrica, com todo arcabouço regulatório e normativo desde o projeto, seleção, instalação e gestão da vida útil dos equipamentos elétricos para uso em atmosferas explosivas, bem como os requisitos de certificação de produtos, serviços e competências pessoais e, por outro, o contraste da simples falta de abordagem metodológica da questão “Ex” pelas demais disciplinas compartilhadas do mesmo projeto.

Uma vez que ainda é incipiente a certificação de equipamentos não elétricos no âmbito da série ABNT NBR ISO 80079, não obstante ainda perdura a necessidade de avaliação dos riscos de ignição e do EPL (Equipment Protection Level, ou Nível de Proteção do Equipamento) resultante de tais equipamentos “não elétricos” já presentes na instalação, o que se transformará num relatório técnico de adequação, tal como prescreve o item 5.2.6 e respectivos anexos da norma ABNT NBR ISO 80079-36.

O equipamento mecânico em área classificada é submetido a uma avaliação documentada de risco de ignição para identificar as possíveis fontes potenciais de ignição que podem ocorrer em operação normal, mau funcionamento previsto e mau funcionamento raro. Busca-se, portanto, a confirmação do EPL do equipamento mecânico instalado ou utilizado em área classificada sob avaliação, e sua compatibilidade com área classificada propriamente dita.

A avaliação dos equipamentos mecânicos “Ex” instalados ou utilizados em áreas classificadas se faz através de duas análises: a primeira, referente a documentação técnica do equipamento e do projeto, a ser feita em terra e a segunda que se constitui numa avaliação física operacional, nos locais onde os equipamentos se encontram instalados ou utilizados, a bordo. A convergência destas análises dará origem ao relatório da avaliação de risco de ignição e a confirmação do EPL para este equipamento não-elétrico, trazendo eventuais recomendações adicionais para obtenção dos níveis de proteção de equipamento desejável para a classificação de área.

Um exemplo de relatório de avaliação do risco de ignição e confirmação do EPL para o equipamento mecânico “Ex” pode ser visualizado na Figura 5.

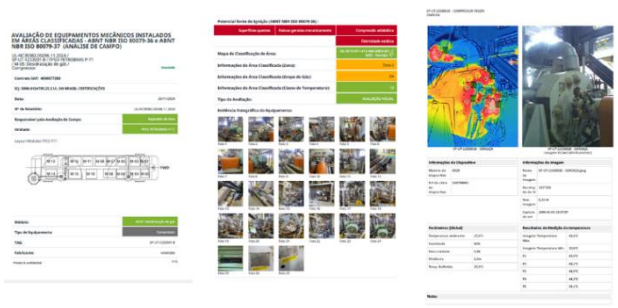

Fig. 5. Exemplo de relatório de equipamento “Ex” não-elétrico

A. Resultados Parciais em FPSO para não-elétricos “Ex”

O primeiro ciclo de avaliação do risco de ignição numa plataforma tipo FPSO de alta capacidade produziu uma seleção inicial de cerca de 1200 equipamentos mecânicos “Ex” em condição operacional.

São exemplos de equipamentos “Ex” não elétricos: Bombas, compressores e ventiladores (centrífugos, alternativos, de engrenagens, de deslocamento axial etc.), corta chamas, caixas de engrenagens, acoplamentos, agitadores, impelidores, freios, motores hidráulicos/pneumáticos, motores a combustão interna, guindastes, elevadores, combinações diversas de dispositivos para fabricação de máquinas, tubulações não-fixas, mangotes, etc. Não são considerados equipamentos estáticos bem como equipamentos mecânicos do escopo acima instalados fora de área classificada e/ou não operacionais.

TABELA IV. AVALIAÇÃO DO RISCO DE IGNIÇÃO, FPSO

Sem Desvio	**Total de Equipamentos: 1261[d]**		
	Desvio em Zona 1	***Desvio em Zona 2***	***Desvio de Documentação***
1148	2	111	*sob avaliação

[d] Produtividade/equipe – 23 Equipamentos Mecânicos “Ex”/dia

Os resultados preliminares até o momento indicam uma importante aderência de projeto dos equipamentos “não elétricos” a classificação de área das instalações da FPSO de alta capacidade, sendo que foram identificados desvios em menos de 9% dos equipamentos mecânicos avaliados a bordo, e mesmo nestes casos, sem impacto na definição do EPL resultante uma vez atendidas as recomendações técnicas do avaliador (por exemplo, instalação de monitoramento, isolamento de superfície aquecida, etc).

CONCLUSÕES

A evolução das normas e critérios de avaliação para equipamentos elétricos e não elétricos instalados em áreas classificadas “Ex” traz um histórico crescente de exigências técnicas e regulatórias cujo atendimento só é possível através do emprego de recursos técnicos e humanos cada vez mais especializados e inovadores.

Não é mais admissível a simples falta de explicação em eventos de explosão, tais como ocorridos no passado, motivados pela ausência ou ineficiência de processos de projeto, seleção, instalação, inspeção, manutenção e reparo de equipamentos destinados ao uso em atmosferas explosivas, sejam elétricos ou não-elétricos.

Dois conceitos importantes advém destas avaliações: “ausência de acidentes não é evidência de conformidade, mas sim a presença de controles eficazes” e “somente é possível controlar aquilo que é mensurado”. Os grandes números produzidos nestas inspeções indicam a complexidade destas instalações, seus riscos associados e confirmam a real necessidade da adoção continuada de tais processos, a fim de se obter o nível de segurança necessário nas atividades de exploração e produção de petróleo e gás em unidades estacionárias de produção.

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Qualidade e segurança: Uma análise do arco elétrico nas distribuidoras de energia sob a perspectiva do cynefin e das normas regulamentadoras

1st Júlia Possebon Spellmeier
Instituto de Redes Inteligentes
Universidade Federal de Santa Maria
Santa Maria, Brasil
julia.possebon@acad.ufsm.br

2nd Carmen Brum Rosa
Instituto de Redes Inteligentes
Universidade Federal de Santa Maria
Santa Maria, Brasil
carmen.b.rosa@ufsm.br

3rd Vitor Cristiano Bender
Instituto de Redes Inteligentes
Universidade Federal de Santa Maria
Santa Maria, Brasil
vitor.bender@ufsm.br

4th Marina Camponogara
Instituto de Redes Inteligentes
Universidade Federal de Santa Maria
Santa Maria, Brasil
marina.camponogara@acad.ufsm.br

5th Gilnei José Gama dos Santos
Engineering Department
CPFL Energia
Campinas, Brasil
gilnei.santos@cpfl.com.br

line 1: 6th Xinjian Chen
Generation & Renewable Department
CPFL Energia
Campinas, Brasil
chenxinjian@cpfl.com.br

7st Fu Li
Transmission Department
CPFL Energia
Campinas, Brasil
lifu@cpfl.com.br

8rd Carlos Almeida Simões
Engineering Department
CPFL Energia
Campinas, Brasil
cas@cpfl.com.br

***Abstract*— Atividades de manutenção e operação de redes elétricas expõem trabalhadores a riscos, como explosões de arco elétrico, que podem resultar em queimaduras graves e lesões fatais. No entanto, a NR 10 apresenta lacunas sobre o tema, tornando necessária a adaptação às normas internacionais, como a NFPA 70E. Diante disso, a pesquisa busca responder: Como promover a gestão da segurança do trabalho em atividades com risco de arco elétrico nas distribuidoras brasileiras de energia? O objetivo geral é analisar a situação da segurança do trabalho frente ao risco de arco elétrico em distribuidoras de energia, considerando a natureza do risco e as regulamentações envolvidas. A metodologia adota o ciclo PDCA (*Plan, Do, Check, Act*), combinando Revisão Sistemática de Literatura e pesquisa na literatura cinza como coleta de dados. Como resultado, a revisão revelou uma lacuna de estudos que abordem a segurança do trabalho relacionada ao arco elétrico sob a perspectiva da gestão da segurança do trabalho nas distribuidoras de energia. Os estudos existentes concentram-se em setores industriais específicos, sem explorar adequadamente decisões gerenciais dessas empresas. Assim, a pesquisa se destaca por buscar soluções inovadoras que promovam a melhoria contínua da gestão da segurança e contribuam para ambientes de trabalho mais seguros e eficientes. Por fim, cabe ressaltar que essa pesquisa faz parte do projeto PD-00063-3104/2024, que conta com apoio técnico e financeiro Programa de Pesquisa, Desenvolvimento e Inovação (PDI) do órgão regulador do setor elétrico ANEEL.**

Palvras-chave*— *Arco elétrico; Segurança do trabalho; Melhoria contínua; Distribuidoras de energia; Ciclo PDCA

I. Introdução

As distribuidoras de energia elétrica são uma parte importante da indústria de energia e seu modo de gerenciamento afeta diretamente a qualidade e a eficiência do fornecimento de energia. Segundo a Agência Nacional de Energia Elétrica (ANEEL) [1], práticas de manutenção eficazes são fundamentais para evitar apagões e minimizar as perdas técnicas no sistema. Durante a execução das atividades de manutenção e operação de redes elétricas, o colaborador que as realiza fica exposto a perigos elétricos [2]. Dentre os perigos elétricos, os mais comuns são choque elétrico, arco elétrico e explosão de arco elétrico, os quais juntamente com os efeitos fisiológicos no corpo humano devem ser compreendidos pela gerência das distribuidoras de energia elétrica, bem como por todos que trabalham próximos a circuitos elétricos e linhas aéreas energizadas [3].

Em 1982 o engenheiro Ralph Lee abordou o tema arco elétrico e seus riscos para as pessoas e trouxe pela primeira vez uma modelagem matemática consistente para o cálculo da energia incidente. Em seu trabalho The Other Electrical Hazard: Electric Arc Blast Burns, mostrou que a temperatura do arco elétrico, durante um curto-circuito, pode alcançar 4 vezes a temperatura da superfície do sol, chegando a 20.000 °C, sendo o fenômeno com maior elevação de temperatura produzido pelo homem. Essa elevada temperatura pode causar graves queimaduras no corpo humano mesmo à distância de poucos metros e até levar o indivíduo a óbito.

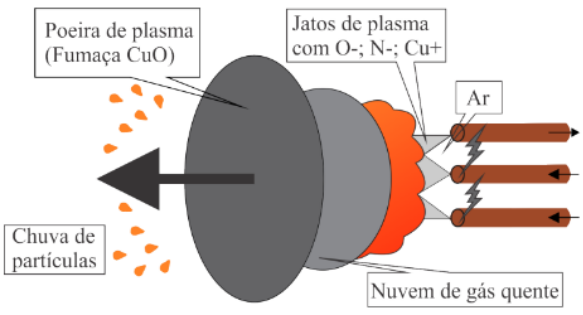
A atual lacuna enfrentada pelas distribuidoras em garantir a segurança dos seus colaboradores em atividades com risco de arco elétrico está intrinsecamente ligada às estratégias de gestão eficazes em conformidade com as normas regulamentadoras de segurança do trabalho que regem o setor. Este estudo tem como objetivo solucionar um problema real enfrentado por uma distribuidora brasileira de energia elétrica no que se refere à segurança do trabalho em atividades com risco de arco elétrico, no contexto de um projeto de Pesquisa, Desenvolvimento e Inovação (P,D&I). Ainda que a investigação se concentre em uma empresa específica, seus resultados possuem potencial de aplicação em outras distribuidoras de energia no Brasil, contribuindo para o avanço do conhecimento e o aprimoramento das práticas de segurança no setor elétrico nacional. Essas discussões iniciais remetem a um problema de pesquisa: Como promover a gestão da segurança do trabalho em atividades com risco de arco elétrico nas distribuidoras brasileiras de energia? Para responder a esse problema, o objetivo geral desse artigo é analisar a situação da segurança do trabalho frente ao risco de arco elétrico em distribuidoras de energia, considerando a natureza do risco e as regulamentações envolvidas.

II. Referencial teórico

A. Arco elétrico e seus perigos

O arco elétrico (AE) pode ser definido como a energia luminosa, térmica e sonora produzida como parte de uma falha, um tipo de explosão ou uma descarga elétrica, resultante da ruptura dielétrica do ar ou de outro meio isolante, sendo uma das fontes de calor mais intensas [4]. Tal intensidade térmica é capaz de provocar queimaduras fatais em um raio de até 1,5 metros, e queimaduras graves a distâncias de até 3 metros do ponto de ocorrência [5]. Em outra definição, o arco elétrico pode ser definido como o fenômeno produzido quando a tensão entre dois pontos condutores (chamados eletrodos) separados por um gás dielétrico (normalmente ar) é tal que esse elemento supera sua capacidade dielétrica e o ioniza, tornando-se condutor. Nessas condições, produz-se uma passagem de corrente elétrica entre esses eletrodos através do gás que os separa[6].

Fig. 1. Comportamento de um arco elétrico



Fonte: Adaptado de Lang e Jones (2015).

A primeira forma de energia liberada por um arco elétrico é a luz intensa, que pode causar danos à visão, desde efeitos temporários, como ofuscamento, até lesões permanentes na retina. A segunda forma de energia, e a mais destrutiva, é a energia térmica: as temperaturas em torno do arco podem atingir cerca de 20.000°C, enquanto nos terminais do arco chegam a até 50.000°C [7], valores superiores à temperatura da superfície do Sol, estimada em cerca de 5.000°C. Queimaduras de alta gravidade podem ocorrer pela exposição direta ou indireta ao arco elétrico, sendo essa última relativa ao contato da pele com vestimentas que entram em ignição e continuam em chamas mesmo após cessado o arco [8]. As altas temperaturas dão origem à terceira forma de energia que são as ondas de pressão causadas pela violenta expansão do ar e pela sublimação dos terminais metálicos do arco (o cobre se expande 67 mil vezes em volume) [5]. Essas ondas de pressão podem causar concussões, lesões auditivas devido ao ruído excessivo, ferimentos por estilhaços e intoxicação por gases tóxicos.

As altas temperaturas produzidas pelos arcos elétricos causam a vaporização dos materiais próximos de onde ele ocorre, podendo causar a liberação de vapores tóxicos e a projeção de metal fundido, uma geração de luz intensa que pode causar cegueira e, associadas as altas temperaturas, o ressecamento do globo ocular, um estampido que pode exceder 160 decibéis no momento em que ocorre a ruptura do dielétrico, prejudicando temporariamente a audição e uma onda de pressão devido à expansão instantânea do ar e dos metais condutores próximos, gerada pelo grande aumento de temperatura em um espaço muito curto de tempo, podendo causar ferimentos por queda e colisão [5].

Na maioria das vezes, o arco elétrico se origina a partir da ocorrência de um curto-circuito (entre fases ou fase-terra), sendo que ele pode iniciar através de um curto-circuito monofásico e evoluir para um curto-circuito bifásico ou trifásico rapidamente [9]. O comportamento do arco elétrico é considerado estocástico, pois envolve rápidas mudanças em sua projeção devido às trocas de calor por convecção, jatos de plasma e forças eletromagnéticas, além das constantes extinções e reignições [10].

B. Qualidade e segurança

Um sistema de fornecimento e distribuição de energia elétrica confiável e seguro é essencial para indústrias altamente produtivas [11]. A ideia de vincular as práticas empresariais de qualidade e segurança não é nova e foi identificada por [12] que afirmou que a qualidade e a segurança seriam valores mais fortes dentro de uma organização se sua gestão estivesse em harmonia e não desconectada. É importante notar que embora existam muitas semelhanças entre as funções organizacionais de gestão da qualidade e da segurança, existe uma grande diferença de foco entre elas [13]. A qualidade está focada na melhoria do produto ou serviço fornecido ao cliente [14], e a segurança está focada na melhoria das condições existentes na produção do produto ou serviço [15]

Os fatores de “Melhoria Contínua” e “Realização do Funcionário” [16] representam as adaptações evolutivas feitas aos métodos operacionais e à cultura para melhorar ambos os métodos e alinhar os trabalhadores com a visão e direção da liderança. A melhoria contínua segue o ciclo PDCA: “planejar, fazer, verificar e agir”, que representa “qualidade cada vez melhor, [com] cada vez menos variação”[12,16]. O ciclo PDCA inclui decidir o que fazer, fazê-lo, implementá-lo e, em seguida, testar o sistema para determinar seu nível de sucesso [12]. Embora o ciclo PDCA tenha sido originalmente focado na melhoria da qualidade, ele está completamente alinhado com as melhorias na segurança do trabalhado [17].

Com vistas ao discutido acima, a melhoria contínua, tema base da qualidade, integrado à segurança do trabalho, pode ser

um recurso chave para as melhores práticas de gestão. Dessa forma, este estudo busca contribuir para a gestão da segurança do trabalho em distribuidoras de energia elétrica, estruturando-se a partir do ciclo PDCA de Deming. A proposta integra práticas de gestão, estratégia, qualidade e segurança em cada uma das etapas do ciclo, com o objetivo de promover uma gestão mais eficaz, assegurando tanto a proteção dos trabalhadores, quanto a continuidade do fornecimento de energia elétrica. A descrição detalhada da aplicação de cada etapa do ciclo PDCA no escopo de estudo, encontra-se apresentada na seção de metodologia. Este artigo concentra-se nas etapas "*Plan*" e na fase inicial da etapa "*Do*" do ciclo PDCA.

Para aprimorar um sistema, é essencial, antes de tudo, identificar claramente o problema, compreender o contexto em que está inserido e, a partir dessa análise, direcionar seu desenvolvimento [18]. A etapa "*Plan*" dessa pesquisa tem como objetivo central realizar esse processo, utilizando para isso, a estrutura do modelo *cynefin*. Desenvolvido por Snowden, o modelo *cynefin* classifica os problemas em cinco domínios: simples, complicado, complexo, caótico e desordem. Cada domínio apresenta diferentes relações de causa e efeito, exigindo abordagens específicas de tomada de decisão, conforme mostra a figura abaixo.

Fig. 2. Estrutura do modelo *cynefin*

Fonte: Adaptado de Snowden (2010)

- Domínios ordenados (simples e complicado) permitem decisões baseadas em boas práticas e análises técnicas;
- Domínios não ordenados (complexo e caótico) requerem experimentação e ação imediata, respectivamente, devido à imprevisibilidade;
- Desordem representa a ausência de clareza sobre qual domínio se aplica, sendo um estado a ser evitado.

Para essa pesquisa, o uso da estrutura *cynefin* tem como premissa classificar o problema da segurança do trabalho com risco de arco elétrico nas distribuidoras de energia, de forma que a desordem não seja alcançada, visto que a segurança dos trabalhadores é um tema sensível do ponto de vista humano, pois trata-se da vida das pessoas. A ideia central é permear um caminho no ciclo PDCA para que o problema se torne simples.

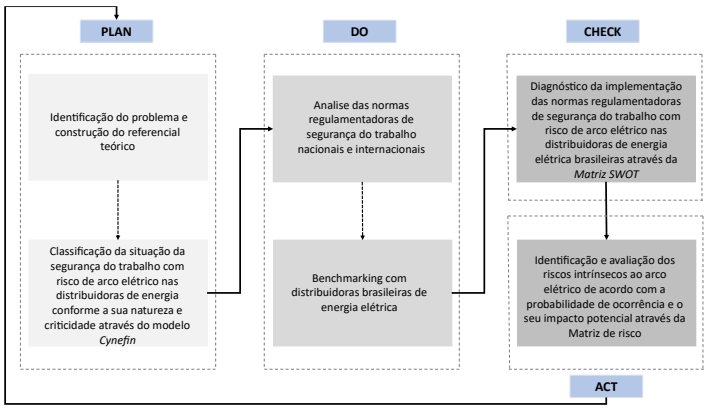
Na primeira fase da etapa "*Do*", o foco está na análise das principais normativas voltadas à segurança do trabalho com risco de arco elétrico. O objetivo é compreender como normas técnicas internacionais e nacionais – como NFPA 70E, IEEE Std 1584, IEC 61482 e NR-10 – orientam práticas para mitigar riscos e garantir a integridade dos trabalhadores. Essas normas oferecem diretrizes sobre cálculo de energia incidente, definição de categorias de Equipamentos de Proteção Individual (EPIs), distâncias seguras, treinamentos e medidas preventivas.

A análise normativa constitui um elemento fundamental para subsidiar a construção de um sistema de gestão eficaz, pautado em requisitos técnicos e em boas práticas reconhecidas internacionalmente. Tal abordagem visa assegurar a conformidade regulatória, ao mesmo tempo em que fomenta uma cultura organizacional orientada à prevenção de acidentes e à preservação da vida. As etapas "*Plan*" e a fase inicial do "*Do*" do ciclo PDCA orientam a estruturação das etapas subsequentes do ciclo, contribuindo para a consolidação de um modelo de gestão sistemático e contínuo.

III. Metodologia

Este artigo integra uma pesquisa científica em desenvolvimento e representa uma etapa dentro dela. Para a sua condução e obtenção de resultados consistentes, propõe-se a adoção de um percurso metodológico estruturado em etapas sequenciais. Nesse contexto, será utilizado o ciclo PDCA (*Plan, Do, Check, Act*), uma ferramenta da gestão da qualidade que visa à promoção da melhoria contínua em processos organizacionais. Dessa forma, a construção das referidas etapas relaciona a melhoria contínua para solucionar um problema enfrentado por uma distribuidora brasileira de energia. A figura 3 expõe as etapas da pesquisa enquadradas em um ciclo PDCA e a discussão desse procedimento metodológico será realizado na sequência.

Fig. 3. Metodologia estruturada em um ciclo PDCA



Fonte: Autores (2025).

O ciclo de Deming, também conhecido como ciclo PDCA, é uma abordagem metódica usada para adquirir informações úteis e compreensão para melhorar consistentemente um produto, processo ou serviço, que foi originalmente usado como uma ferramenta para controle de qualidade do produto [19,20]. Além disso, a base dessa abordagem está relacionada ao processo de aprendizagem das organizações por meio da aquisição de conhecimento e melhores práticas [21]. Dessa forma, os procedimentos metodológicos da pesquisa estão estruturados nas quatro etapas do ciclo do PDCA, as quais são detalhadas abaixo conforme [22].

Plan: O problema ou questão no processo é definido para definir uma meta ou propósito e formular um plano para resolvê-lo [24]. A fase de planejamento estabelece a base para as próximas etapas do ciclo [23]. No cenário dessa pesquisa, a

fase "*Plan*" compreende a identificação do problema enfrentado pelas distribuidoras de energia elétrica, o qual se deseja solucionar nessa pesquisa. Compreende também a construção do referencial teórico, servindo como base para o entendimento completo do tema a ser desenvolvido e seus principais elementos constituintes. Em adição, nessa etapa a classificação da situação do problema enfrentado pela distribuidora de energia elétrico e sua natureza será realizado através do modelo *cynefin*. O modelo *cynefin* ajuda a solucionar problemas ao classificar a situação em diferentes domínios –claro, complicado, complexo, caótico e desordenado– e recomendar abordagens específicas para cada contexto. Essa categorização permite escolher estratégias apropriadas, aumentando as chances de encontrar soluções eficazes e adaptadas à natureza do problema. Esse modelo servirá como base para estruturar as estratégias do desenvolvimento das seguintes fases da pesquisa, promovendo soluções mais eficazes, auxiliando no entendimento do problema para a construção mais assertiva das seguintes fazes do ciclo PDCA.

Do: Nessa fase, a organização implementa os componentes do plano, como desenvolver e produzir um produto ou executar um processo específico. Para o contexto dessa pesquisa, a fase "Do" será executar um processo específico, através da análise das normativas nacionais e internacionais para a segurança do trabalho com risco de arco elétrico, a fim de estruturar um embasamento de suas diretrizes e principais orientações acerca do tema em questão. Posteriormente, será realizado um benchmarking com as principais distribuidoras brasileiras de energia elétrica com a intenção de verificar quais são as principais práticas de segurança dos trabalhadores executadas por dessas distribuidoras.

Check: Durante essa etapa, os resultados das ações tomadas são monitorados e avaliados. Essa avaliação ajuda a identificar sinais de progresso e sucesso, bem como quaisquer problemas ou áreas de melhoria que possam ter surgido. Nesse contexto, a aplicação dessa fase nessa pesquisa se dará através de um diagnóstico, através de uma matriz SWOT, tendo como base os resultados obtidos na fase anterior "Do". Isso permitirá um entendimento robusto do atual cenário brasileiro sobre as práticas de gestão da segurança do trabalho com risco de arco elétrico, identificando possíveis gargalos, pontos de melhoria e soluções a serem aprimoradas nesse cenário.

Act: Nesta fase, aprendizado e o conhecimento adquiridos ao longo de todo o processo do ciclo é integrado. Isso pode envolver refinar a meta, modificar métodos, reformular teorias ou até mesmo estender o ciclo de aprendizado e melhoria para uma escala maior. Para essa etapa, a pesquisa irá contribuir com a segurança do trabalho através da construção de uma matriz de risco, onde os principais riscos intrínsecos ao arco elétrico serão classificados de acordo com a sua probabilidade de ocorrência e impacto potencial. Para a efetiva finalização dessa etapa do ciclo PDCA, essa proposta final será documentada e apresentada à distribuidora de energia para sua análise e implementação.

O ciclo PDCA enfatiza que o processo de aprendizagem e melhoria é contínuo [25]. Uma vez concluída a etapa "*Act*", a organização inicia o ciclo novamente a partir da etapa "*Plan*", com base no conhecimento e nas experiências adquiridas nas iterações anteriores [26]. Essa abordagem permite aprendizagem organizacional, levando a um ciclo infinito de melhoria contínua. Ao seguir esse processo sistemático, as organizações podem efetivamente reunir conhecimento, adaptar suas estratégias e tomar decisões informadas para melhorar seus produtos, processos ou serviços ao longo do tempo [27]. Como resultados parciais do projeto, são apresentadas e discutidas as etapas "*Plan*" e "*Do*" do ciclo PDCA.

Para o cumprimento das etapas "*Plan*" e "*Do*", tema focal desse artigo, foi realizada uma Revisão Sistemática de Literatura (RSL) e pesquisas na literatura cinza como coleta de dados de artigos relevantes para o âmbito dessa pesquisa. O protocolo de RSL compreendeu à exploração de estudos científicos sobre arco elétrico ao redor do mundo, buscando responder a seguinte questão de pesquisa: De que forma as normas regulamentadoras de segurança para arco elétrico conduzem a gestão das distribuidoras de energia para garantir a segurança dos colaboradores? Pra isso, duas bases de artigos científicos foram selecionadas: SCOPUS e Web of Science. É importante destacar que a base de dados IEEE Xplore não foi utilizada nesta RSL, uma vez que os artigos dessa base também estão presentes na Scopus, o que contribui para a redução do número de artigos duplicados. Além disso, a IEEE Xplore possui um foco predominantemente técnico, voltado para a área de eletricidade, o que não se alinha ao principal objetivo desta RSL, que é explorar temas relacionados à gestão. As leituras iniciais permitiram selecionar as palavras-chave que resultaram na seguinte frase de pesquisa: TITLE-ABS-KEY ((“*Arc Flash*” OR “*Electric Arc*”) AND (“*Business*” OR "*Standard* OR “*Utilities*”) AND (“*Safety*”)). A estratégia de busca empregada nas bases de dados compreendeu os metadados “Título”, “Resumo” e “Palavras-chave”, com a restrição de tipo de documento, o qual foi selecionado apenas artigos; bem como o filtro de tempo, restringindo aos últimos dez anos e apenas publicações em inglês. A frase de pesquisa submetida resultou em 244 títulos, destes foram removidos os duplicados. Assim, foi aplicado um filtro, o qual consistiu na leitura dos títulos, resumos e palavras-chave de todos os artigos para separar os que tinham potencial para apresentar o tema de arco elétrico sob o ponto de vista de distribuidoras de energia elétrica, para isso, respondeu-se às seguintes questões de filtragem: O artigo aborda o tema arco elétrico? (sim/não); O artigo a segurança do trabalho com risco de arco elétrico em distribuidoras de energia? (sim/não). Se pelo menos uma das respostas a essas questões foi "Não", o artigo foi excluído da amostra. Nesse processo, 89 artigos foram removidos, resultando em 98 artigos aptos para serem lidos na segunda filtragem de leitura. Deste modo, a segunda filtragem foi realizada, onde inclui-se a leitura da introdução dos artigos oriundos do filtro. Nesse processo, 33 artigos foram removidos resultando em 65 artigos. A terceira filtragem foi realizada com esses 65 artigos, onde foi analisado o desenvolvimento e conclusão desses artigos, nesse processo foram excluídos 12 artigos. Por fim, 53 artigos resultantes dos filtros de leitura foram aptos a extrair as informações relevantes para essa pesquisa.

A união da RSL com pesquisa na literatura cinza constitui uma revisão integrativa. A literatura cinza, como normas técnicas e publicações de órgãos reguladores, fornece uma base sólida de regulamentações e exemplos de implementação que podem complementar os achados da RSL. Isso assegura que a pesquisa não só esteja alinhada com a literatura científica, mas também com as práticas e exigências do setor, resultando em um trabalho mais robusto e aplicável. A importância da revisão integrativa reside em sua capacidade de proporcionar uma compreensão mais completa e

aprofundada do tema pesquisado. Normalmente, a revisão integrativa é a mais ampla abordagem metodológica referente às revisões, permitindo a inclusão de estudos experimentais e não-experimentais para a compreensão completa do fenômeno analisado [28].

IV. Resultados parciais

Os resultados desse artigo serão divididos em duas subseções: etapa "*Plan*", a qual busca classificar a situação da segurança do trabalho com risco de arco elétrico nas distribuidoras de energia conforme a sua natureza e criticidade através do modelo *cynefin*; e etapa "*Do*", a qual tem como objetivo analisar as principais normativas para arcos elétricos.

A. Etapa "Plan" – Classificação da situação da segurança do trabalho com risco de arco elétrico

A classificação dos aspectos relacionados à segurança do trabalho com risco de arco elétrico em domínios do modelo *cynefin*– simples, complicado, complexo e caótico – garante a compreensão das abordagens necessárias para a gestão do risco de arco elétrico pelas distribuidoras de energia, considerando a natureza e a criticidade dos perigos associados. Cada domínio oferece uma perspectiva sobre como lidar com os riscos e as situações de perigo, permitindo uma gestão orientada às necessidades da segurança do trabalho.

O domínio simples é caracterizado por situações em que as causas e efeitos são claros e previsíveis, permitindo a aplicação de soluções diretas e estabelecidas. No contexto da segurança do trabalho com risco de arco elétrico, isso se refere a procedimentos normatizados e treinamentos técnicos que abordam os riscos de forma sistemática e com base em normas regulamentadoras. Exemplos incluem a utilização adequada de equipamentos de proteção individual (EPIs), através da implementação de procedimentos operacionais padrão (POPs) para operações de manutenção em ambientes controlados. A gestão da segurança do trabalho com risco de arco elétrico nesse domínio é eficiente porque as ações podem ser planejadas e executadas com base em diretrizes claras e predefinidas, minimizando o risco de acidentes em atividades rotineiras e situações previsíveis.

No domínio complicado, a situação exige um maior nível de especialização e análise para entender as interações entre diferentes fatores e tomar decisões. Embora os riscos associados ao arco elétrico ainda possam ser compreendidos, eles envolvem variáveis que exigem soluções técnicas mais avançadas. Por exemplo, o planejamento de cenários para prever diferentes condições de operação, como falhas em equipamentos de proteção ou mudanças nas condições ambientais, entra nesse domínio. Técnicas como análise de falhas, inteligência de negócios e o pensamento sistêmico são fundamentais para mitigar riscos. A segurança no trabalho em situações que envolvem risco de arco elétrico neste domínio, exige maior conhecimento técnico e capacidade de analisar dados para prever possíveis falhas.

O domínio complexo, por sua vez, envolve situações em que as interações entre os fatores são dinâmicas e imprevisíveis, tornando as soluções difíceis de antecipar. A ocorrência de um arco elétrico pode ser categorizada neste domínio, pois, embora as causas e efeitos já sejam conhecidas, a manifestação do risco é frequentemente imprevisível. Nesse contexto, o modelo de decisão "sondar, sentir e responder" se aplica, pois é necessário monitorar constantemente as condições de operação, avaliar os sinais de risco em tempo real e ajustar as respostas conforme necessário, tornando complexa a garantia da segurança do trabalho. A interação de equipes multidisciplinares, como engenheiros, técnicos e operadores, em ambientes dinâmicos, como linhas de transmissão de energia ou subestações, é um exemplo de situação complexa. Os riscos de arco elétrico em tais contextos podem ser mitigados com uma abordagem adaptativa, onde as decisões são baseadas em observações contínuas e flexibilidade para ajustar os procedimentos conforme o contexto operacional, visando tornar o trabalho mais seguro.

Já o domínio caótico é caracterizado por situações de extrema urgência, onde eventos críticos e inesperados, como um arco elétrico que resulta em um acidente grave, exigem respostas imediatas para evitar danos maiores. Nesse estado, as causas e efeitos são tão imprevisíveis que a única ação possível é a intervenção rápida para restaurar a ordem e minimizar as consequências. Na ocorrência de um arco elétrico, isso pode envolver a evacuação imediata da área de risco, a ativação de sistemas de proteção e a aplicação de procedimentos de emergência para controlar o fogo ou a explosão resultante. Para que se tenha alguma segurança no trabalho com risco de arco elétrico nesse domínio, é necessário equipes altamente treinadas para reagir rapidamente emergências e um sistema de monitoramento que permita a detecção e resposta rápidas a incidentes.

Dessa forma, é evidenciado que a segurança do trabalho com risco de arco elétrico é uma situação complexa para as distribuidoras de energia. Destarte, essa pesquisa busca orientar as distribuidoras de energia a transitar de um estado complexo para um estado simples, em que as melhores práticas de engenharia são implementadas. Assim, os esforços da pesquisa devem convergir para o alcance de um estado simples dentro do modelo *cynefin*, evitando que a segurança do trabalho com risco de arco elétrico se torne caótica ou desordenada.

B. Etapa "Do" – Análise das normas regulamentadoras de segurança do trabalho com risco de arco elétrico

A conscientização moderna sobre os riscos no local de trabalho criou uma série de padrões de segurança e melhores práticas agora aceitos e implementados no projeto e construção de muitos tipos de instalações industriais e comerciais [29]. Ao padronizar as medidas de segurança, as normas regulamentadoras asseguram que todas as empresas do setor adotem um nível mínimo de proteção, reduzindo significativamente a incidência de acidentes graves e fatais[30]. Além disso, promovem uma cultura de prevenção e conscientização entre os trabalhadores, incentivando a adesão às melhores práticas de segurança e a realização de treinamentos contínuos. A conformidade com essas normativas também facilita a fiscalização e o cumprimento das regulamentações vigentes, garantindo que as empresas sejam responsabilizadas por qualquer descumprimento [3].

O tema arco elétrico tem sido estudado nos últimos 40 anos, especialmente nos EUA, por organizações como a *Occupational Safety and Health Administration* (OSHA), o *Institute of Electrical and Electronics Engineers* (IEEE) ou a *National Fire Protection Association* (NFPA). Essas organizações desenvolveram métodos de eficácia comprovada [32], a fim de atingir um nível suficientemente alto de segurança individual e coletiva para não colocar em risco os trabalhadores expostos a sistemas elétricos energizados. Na

Europa, a especificação alemã DGUV-I 203–078 classificada na norma alemã BGI/GUV-I 5188-E é considerada uma referência dentro da União Europeia, embora IEEE Std. 1584 de 2018 e NFPA 70E tenham se tornado as verdadeiras referências internacionais para estudos de arco elétrico.

Em 1995, a NFPA 70E [31] foi publicada, estabelecendo um marco na regulamentação dos perigos do arco elétrico. A NFPA 70E fornece diretrizes para a segurança elétrica no local de trabalho, focando na prevenção de ferimentos relacionados a choques elétricos e explosões de arco. A norma define práticas seguras, como o uso de Equipamentos de Proteção Individual (EPIs) e a delimitação de zonas de risco em torno de equipamentos elétricos. Com a adoção da NFPA 70E, as indústrias ganharam ferramentas para mitigar os riscos, marcando o início da formalização de práticas de segurança no ambiente elétrico. As normas NFPA 70E e OSHA 1910 são amplamente referenciadas em estudos e trabalhos acadêmicos [33,34], sendo aplicadas na engenharia e servindo de base para o desenvolvimento de normas de segurança em outros países, como a NBR 16384 [35] no Brasil.

Em 2002, foi publicada a IEEE Std 1584-2002, um guia que tem como objetivo prover modelos matemáticos aplicáveis na determinação da distância segura de exposição ao arco elétrico e da energia incidente [36]. A primeira versão do guia foi publicada em 2002, consolidando-se como o principal documento técnico para a estimativa de energia incidente. Desde então, recebeu atualizações em 2004 e 2011, culminando na publicação de uma segunda versão em 2018. Esse padrão consolidou uma metodologia para calcular a energia incidente, auxiliando engenheiros e profissionais de segurança a avaliar com precisão os perigos associados a diferentes cenários de arco elétrico. A IEEE 1584 introduziu métodos que variam com base em fatores como a tensão do sistema, a corrente de curto-circuito e o tempo de clareamento do arco, oferecendo uma ferramenta essencial para calcular zonas de proteção e selecionar EPIs.

A norma EN 50110-1, da união Europeia, divide o trabalho em três procedimentos diferentes, muito semelhantes à NFPA 70E: trabalho em estado desenergizado (ou trabalho em estado morto); trabalho energizado; e trabalho nas proximidades de partes. O trabalho em estado desenergizado é o procedimento básico mais optado. No trabalho morto, a desenergização é básica para criar uma condição de trabalho eletricamente segura energizadas [37]. A norma europeia exige que seja realizado um teste de tensão, mas não exige a verificação da funcionalidade do instrumento antes e depois do uso. Ambas as normas, europeia e norte-americana, exigem uma inspeção visual dos instrumentos. Esse teste apresenta o risco de arco elétrico, sendo que, sua execução incorreta pode causar um arco elétrico em fases subsequentes.

Atualmente, a gestão de segurança ocupacional aplicada em atividades envolvendo eletricidade no Brasil está principalmente embasada na Norma Regulamentadora (NR) 10 [38], criada pela Portaria 3.214/78 do Ministério do Trabalho e Emprego e atualizada pela última vez em 2019. Essa norma visa a segurança em instalações e serviços em eletricidade e dispõem sobre medidas de controle individual e coletiva, segurança em instalações elétricas energizadas, trabalhos envolvendo alta tensão e situações de emergência (BRASIL, 2019). Entretanto, essa norma não trata de diretrizes para os perigos advindos especificamente do arco elétrico. Em contrapartida, a NBR 16384 [35] , elaborada pela Associação Brasileira de Normas Técnicas (ABNT), aborda questões de segurança em eletricidade, incluindo diretrizes relativas ao arco elétrico, como a definição de zonas de risco e recomendações sobre vestimentas e equipamentos de proteção. Diferentemente das Normas Regulamentadoras (NRs), entretanto, as Normas Brasileiras (NBRs) têm caráter voluntário, a menos que sejam referenciadas em regulamentações específicas ou contratos.

Assim sendo, a segurança do trabalho em atividades com risco de arco elétrico em distribuidoras de energia requer conhecimento profundo dos requisitos, procedimentos e responsabilidades de segurança elétrica das normas internacionais como a IEEE e NFPA 70E [39]. Ainda, as normas regulamentadoras internacionais podem servir como guia para a estruturação e melhoria das normas regulamentadoras brasileiras.

Normas de segurança como a NFPA-70E visam reduzir condições perigosas, mas reconhecem que atingir risco zero é improvável. O trabalho desenergizado é a prática mais comum nas atividades de manutenção e operação de instalações elétricas no Brasil, por proporcionar maior segurança aos trabalhadores. No entanto, a interrupção do fornecimento de energia pode gerar prejuízos significativos para as distribuidoras, especialmente quando realizada sem aviso prévio. A energia elétrica é uma infraestrutura essencial para o funcionamento de diversos setores da sociedade, como hospitais, universidades, indústrias e serviços de segurança pública. Assim, a desenergização requer um planejamento criterioso, que nem sempre é viável diante da alta demanda operacional diária. Nesse cenário, torna-se fundamental o desenvolvimento de soluções que mantenham os padrões de segurança, ao mesmo tempo em que reduzam os impactos para as distribuidoras, consumidores e, principalmente, para os profissionais que atuam diretamente nas redes elétricas.

V. Conclusão

Com base nos objetivos e fundamentações teóricas apresentados, a presente pesquisa destaca-se por analisar a situação da segurança do trabalho frente ao risco de arco elétrico em distribuidoras de energia, considerando a natureza do risco e as regulamentações envolvidas. A utilização do modelo *cynefin* na etapa de planejamento permitiu uma classificação precisa dos contextos enfrentados pelas distribuidoras de energia, possibilitando uma leitura sistêmica da complexidade do problema e, com isso, o direcionamento adequado das ações de gestão a serem tomadas nas próximas etapas do ciclo PDCA. Tal estruturação favorece a identificação de soluções mais assertivas e a prevenção do estado de desordem, especialmente crítico em um tema sensível como a segurança do trabalho.

A análise das normas técnicas nacionais e internacionais realizada na fase inicial da etapa “Do” proporcionou um panorama sobre as diretrizes vigentes para mitigação de riscos decorrentes do arco elétrico. Essa investigação normativa fundamenta tecnicamente o desenvolvimento de mecanismos de gestão mais eficazes, reforçando a importância da conformidade legal e da adoção de boas práticas já consolidadas no setor elétrico global. Ao alinhar teoria, legislação e prática, a pesquisa avança na construção de uma base sólida para a elaboração das próximas etapas do ciclo PDCA, contribuindo diretamente para a institucionalização de uma cultura organizacional voltada à segurança e à melhoria contínua.

Como conclusão parcial, observa-se que as etapas "*Plan*" e "*Do*" já revelam o potencial do ciclo PDCA como ferramenta estruturante para transformar desafios complexos em ações gerenciáveis e efetivas dentro das distribuidoras de energia elétrica. A integração entre o pensamento sistêmico do modelo *cynefin* e o pragmatismo do ciclo PDCA demonstra ser uma estratégia promissora para o desenvolvimento de soluções práticas e sustentáveis. Espera-se que, com o avanço da pesquisa e a finalização das etapas subsequentes, seja possível consolidar um modelo replicável que contribua significativamente para a segurança do trabalho no setor elétrico brasileiro.

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Safety considerations for electric vehicles in residential condominiums.

Estellito Rangel Junior
Consultant
Rio de Janeiro, Brasil
estellito.consultor@gmail.com

Abstract* — *As a basic characteristic, electric vehicles (EVs) are powered by batteries that can be recharged even at conventional outlets. However, since there is a concentration of buildings in urban centers and EVs will be parked in common areas, the provision of charging points brings some challenges, not only in relation to the capacity of the electrical grid to meet the new demand, but also to the risks of explosions and "spontaneous" fires caused by the EVs' Li-ion batteries. This article questions the statistics about the possibility of fires in EVs, presents firefighters' concerns, debates initiatives by regulatory agencies and makes recommendations aiming to reduce the impacts of EVs on Brasilian condominiums built at a time when only combustion-powered cars existed.

Keywords* — *electric vehicle, lithium-ion batteries, explosions, safety, standards, fires, regulations

I. Introduction

The electric car market in Brasil has shown significant growth in recent years. In 2024, the sector recorded an 89% increase in sales compared to the previous year, reaching a total of 177,358 electrified vehicles, including hybrids and pure electrics [1]. This growth is driven by several factors, in particular the touted savings in battery charging, compared to the cost of filling the tank with gasoline.

Electric cars, despite their advantages, face several challenges to their widespread adoption in society. Among the main obstacles are the lack of charging infrastructure, high initial cost, limited autonomy, concerns about batteries (cost, fire and explosion risks, disposal), regulatory and public policies.

Although electric cars emit fewer greenhouse gases during use, the production of batteries and the extraction of the materials used in their manufacture have a significant environmental impact.

With the increase in sales, the interest of electric vehicles' (EV) owners in having a charging point in their space is emerging, which impacts technical and legal issues.

II. EVs' Fire Statistics

News about fires and explosions in EVs has been frequent. However, "statistics" have been disseminated on social media indicating that "*EVs have a lower fire rate than combustion vehicles (ICV)*" , pointing values as "11 times lower" (US) [2], "29 times lower" (Sweden) [3], and even "80 times lower" (Australia) [4].

It is important to analyze such data in order to verify if a consistent procedure was used to elaborate these statistics. Table I reproduces the numbers of fires by type of vehicle, reported by the site AutoinsuranceEz [2].

Table I: Fires by vehicle type

Fuel type	Fires per 100k sales	Total fires
Hybrid	3,474.5	16,071
Gasoline	1,529.9	199,533
Electric	25.1	52

AutoinsuranceEZ is not an insurance company, just an online comparison site, and informed that the Table I numbers were obtained from the National Transportation Safety Board (NTSB) database. Since 1967, the NTSB has investigated accidents, crashes, and other events in the aviation, highway, marine, pipeline, and railroad transportation modes, as well as those related to the transportation of hazardous materials, but, NTSB does not compare the quantity of fires related with the fuel type of cars involved in fires. Due to the possible complexity of highway crashes and the extensive nature of the investigation process, a highway safety investigation often requires 12 to 24 months to complete.

In fact, the NTSB made a data report on the prevalence of EV battery fires, compiling data from: the National Highway Traffic Safety Administration (NHTSA)'s Fatal Accident Reporting System (FARS); the NHTSA Complaint Database and Manufacturer Communication Database; the Highway

Loss Data Institute (HLDI) Database; the US Fire Administration (USFA) National Fire Incident Reporting System (NFIRS); the National Fire Protection Association (NFPA) Survey; and the Towing Traffic Incident Reporting System (TTIRS) [5].

The NHTSA's Fatal Accident Reporting System (FARS) published a report with the 2013-2017 fatal injuries suffered in motor vehicle traffic crashes in the US by fuel type and battery type [6]. The data come primarily from police accident reports filled out by local law enforcement officers. NHTSA FARS analysts verify and supplement the data from the police reports.

Those data are shown in Table II, where, overall, 3.16% of vehicles in fatal crashes experienced a fire. The fuel type associated with the highest incidence of fire was diesel (4.68%). This difference might be partly attributable to the fact that diesel fuel use is more common among large trucks, which in addition to being bigger and older, have a higher chance of causing fatalities in collisions. Gasoline fueled vehicles (also including older vehicles), in second, electric-and-gasoline vehicles, and EV (which are generally less than 12 years old), had fire rates of 3.22%, 1.36%, and 1.96%, respectively [6].

Comparing these data to the number of registered vehicles on the road in 2017, the fatal crash rate would be - diesel: $347/10^5$; gasoline: $75/10^5$ registered vehicles, what is expected, as the number of diesel and gasoline vehicles on the road doesn't change very much year-over-year. The rate for EVs would be $13.5/10^5$ registered vehicles, but this number is misleading, as Internal Combustion Vehicles (ICVs) have been running for decades, with a homogeneous sample during the 5 years; however, as in 2013 there were only 100k EVs registered in US, and in 2017 there were approximately 377k EVs. So, the sample did not remain homogeneous during the period, and as consequence, such comparison is invalidated.

TABLE II: VEHICLES INVOLVED IN FATAL HIGHWAY CRASHES IN THE US BETWEEN 2013-2017 THAT EXPERIENCED FIRES BY FUEL TYPE (NHTSA/FARS)

Fuel Type	All Model Years			Model Year 2013 and Later		
	Fire	Total	Percent	Fire	Total	Percent
Compressed Natural Gas	4	153	2.61%	4	86	4.65%
Convertible	1	134	0.75%	0	7	0.00%
Diesel	1,318	28,155	4.68%	311	6,439	4.83%
Electric	1	51	1.96%	1	41	2.44%
Electric-and-Diesel Hybrid	0	6	0.00%	0	4	0.00%
Electric-and-Gasoline Hybrid	24	1,765	1.36%	12	543	2.21%
Flexible	422	14,146	2.98%	104	3,798	2.74%
Gasoline	5,508	171,220	3.22%	644	20,315	3.17%
Hydrogen Fuel Cell	0	1	0.00%	0	1	0.00%
Propane	0	5	0.00%	0	4	0.00%
Unknown	0	26	0.00%	0	14	0.00%
No VIN Decode Value	661	35,384	1.87%	178	10,413	1.71%
Total	7,939	251,046	3.16%	1,259	41,665	3.02%

A closer look into Table I reveals that their data were taken from Table II, but, with some distortions:

a) In Table II, the numbers shown are not for fires, but are the total number of vehicles involved in fatal collisions on US roads between 2013 and 2017 that resulted in fires. So, fires that occurred in parked EVs, in charging EVs, or in EVs traveling on the road, are not included. As long as everybody made it out, the fire is not counted, and this results in a major under representation of vehicle fires across all fuel types;

b) In Table I, vehicles types data taken from FARS were regrouped into only new three categories. In the new "gasoline" category, are included: compressed natural gas, gasoline, diesel, and propane vehicles; in the new "hybrid" category are included: flexible fuel vehicles, electric-and-diesel hybrids, electric-and-gasoline hybrids, and "convertible" vehicles (those that have been adapted to run on a different fuel than the original one); and in the new "electric" category are: EVs and those powered by hydrogen fuel cells;

c) In Table I, the "number of fires per 100 thousand vehicles sold" leads to a misleading comparison, as the sample of fires should be related to a specific batch of manufactured vehicles. Mixing events that occurred with vehicles of different ages with new vehicle sales does not make sense;

d) In Table I, it seems that AutoInsuranceEZ linked the Bureau of Transportation Statistics HEV, PHEV and BEV 2018's sales numbers [7], to define its number of "Fires per 100k sales". As example, dividing the "Total fires" of EVs (52) by the BEV 2018's sales figures in Table III (207,062), it results in 25,11 that is the number of "Fires per 100k sales" in Table I. So, not only AutoInsuranceEZ misinterpreted FARS data, but also created a completely meaningless ratio, using not every vehicle on the road, not even the total sales over a five-year (period that the "statistics" was based on), but only over one year EVs' sales, as shown in Table III.

Additionally, it is important to note some caveats on Table II:

- the FARS database does not provide enough information to know whether the source of the fire was in the fuel system;
- it is likely that the age range for conventionally fueled vehicles (diesel or gasoline), was much greater than that for alternatively fueled vehicles (hybrid or electric); and
- because of the small number of electric-and-gasoline hybrid (1,765) and EV (51) in the population (0.72% overall), fire prevalence estimates for this group are less likely to be reliable.

TABLE III: 2018 US ELECTRIC VEHICLE SALES

Vehicle type	Quantity
Plug-in Hybrid Electric Vehicle (PHEV)	123,883
Hybrid Electric Vehicle (HEV)	338,083
Battery Electric Vehicle (BEV)	207,062

a.

It is not surprising that vehicles that are at least 10 years old are at greater risk of a fire started by a mechanical or electrical failure or malfunction [8]. It is also important to note that today's vehicles are older than in the past. In 1990, the average household vehicle was 7.7 years old, compared to 10.3 years old in 2022. Highway vehicle fires were more likely to begin due to collisions than any other specific item [9].

It should also be noted in Table II that 14.1% of vehicles involved in fatal fire collisions in the US did not have their fuel type identified, as shown by adding the lines: Unknown + No VIN (Vehicle Identification Number) Decode Value. Therefore, it arises a question on how accurate these numbers are.

The NTSB report [5] presented the following facts:

a) The FARS database has no information about the sources of fires;

b)The NTSA database is not a representative sample of events and relies completely on self-report from consumers and manufacturers;

c) The HLDI database provides no information about causes or sources of the fire;

d) The USFA NFIRS database is not clear on determining the fuel type and battery type for the vehicles listed in the NFIRS;

e) The NFPA database does not collect detailed information about fire causes;

f) The TTIRS database does not include vehicle data, except for its size.

The NTSB report [5] concluded that "*Consequently, although it appears that EV have a higher noncrash fire claim frequency, severity, and losses than all passenger cars, we cannot conclude that the differences were related to the fuel sources without additional information*".

Developing a statistical database isn't limited to simply counting the number of fires. The fire that occurred in the car rental parking lot near Humberto Delgado Airport in Lisbon [10], was originated from a Tesla and destroyed more than 200 cars. And the one that occurred on the same month, in an underground parking lot in Seoul, Korea, which originated from a Mercedes EQE, destroyed 140 cars and caused smoke poisoning in 23 people [11]. So, two EV caused fires in 340 others, the vast majority of which were ICV. Were these cases simply included in the statistics about ICVs fires?

Other comparisons on EVs and ICVs fires, based on "number of vehicles sold" were done in other countries, like Sweden [3] and Australia [4], but they had similar flaws. Considering their elementary datasets, limitations in the scope, quality of the data, and the way the cases' selection was made and analyzed, their results do not constitute reliable statistics to point out whether ICVs are more prone to fire than EVs. [12]

III. Types of Chargers

Electric cars can be recharged using alternating current (AC) or direct current (DC) chargers, also referred to as "slow" or "fast" charging, respectively [13].

DC chargers are devices designed for fast charging on highways and at gas stations, completing the charge in less than one hour. The DC charger supplies power directly to the vehicle's battery, and therefore needs to match the power supplied by the AC grid with that used by the battery (DC). This charger is not for residential or condominium use, and is recommended in cases where vehicles run day and night and have little time to recharge.

AC chargers are designed to connect the charging module installed in EV to the conventional electrical grid. They operate at 220V or 380V, single-phase or three-phase, at currents ranging from 6A to 32A, delivering up to 22kW of power to the car [14]. In this type of charging, the compatibility of the grid energy with the EV's battery is carried out by the charging module located inside the EV itself.

There are portable models, for use in occasional or emergency situations, and the wall model, for continuous use. They can be connected via the internet to the manufacturer's system that coordinates and manages the recharge.

Portable chargers must be plugged into adequate electrical outlets. In turn, fixed chargers of 11,000W and 22,000W must be connected to networks with a three-phase voltage of 380V. A single or three-phase 220V network can power chargers of up to 7,000W. If the EV can remain in the parking space for 6 to 8 hours per day, the 7,000W charger will meet its daily charging needs.

Chargers up to 16A can be connected to standard 20A residential outlets; those with 32A must be connected to 32A industrial sockets, and the power supply branch must meet the requirements of NBR 5410 [15] and NBR 17019 [16].

Beating the five-minute barrier charging would be a huge leap forward for an EV industry that acknowledges 'range anxiety' is the biggest deterrent to people switching from petrol to electric, and technology that charges as fast as it takes to fill a fuel tank is the key to unlocking new customer demographics globally. On this way, the chinese battery maker CATL made an announcement showing an EV charging from 5% to 80% in just 15 minutes at temperatures of -10 ºC [17]. But, in practice, achieving these charging times outside the testing labs will require high investments in expanding the utilities' distribution networks, with new transformers, substations, etc. [18]

Just one 60kWh battery would require a charger capable of supplying 720kW of power to charge it in just five minutes. Therefore, more energy will be needed the more cars are charged simultaneously. As a result, the faster the charge, the greater the stress on the battery, reducing its service life [19]. And the cost of replacing an EV battery can be as much as US$ 15,000.

IV. Condominium Bylaws

Condominiums have their internal bylaws (which establish the rules for the use of the properties by residents), and in older ones, it was not foreseen the parking of EV, or charging points.

The new condominiums already have parking spaces for EVs, but situations vary from a situation where all parking spaces have EV charging points, to spaces where the parking spaces are not clearly defined, which require the issuing of guidelines for use the chargers at certain times, according to a sharing scheme, that is, after a vehicle has been charged, it must leave the space so that the next vehicle can park and start its charging. In this modality, the utilization rate is generally low, because people start to prefer charging points outside the condominium, rather than waiting in line for their turn.

Regarding the electricity bill, the most common configuration is one consisting of chargers that allow the user to pay in advance with their credit card, having defined the amount of energy that will be purchased for each recharge. The charger's power supply branch must be exclusive, from the condominium's main electrical panel, with an dedicated wattmeter installed by the local utility company. [20]

Chargers should not be connected to the individual wattmeters of the condominium units, as this usually will require replacing them and reclassify the unit in a higher billing band [21].

The condominium bylaws usually establish mandatory insurance against fires, and some insurers may place restrictions on compensation for damages caused by EV fires,

especially in cases where the condominium has no resources to effectively fight such fires, like a fire brigade. [22]

V. FIREFIGHTERS' CONCERNS

Firefighting resources for Li-ion batteries are still limited, because all the elements needed to fuel the fire are already present inside the battery. Therefore, traditional smothering and cooling techniques are ineffective to stop fire in Li-ion batteries, what presents other particular risks [23], as:

Release of gases (off-gassing): When heated, the electrolyte in the battery cells vaporize, forming a flammable cloud. The makeup of this cloud, its toxicity and flammability, depend on a range of factors including the specific battery chemistry, form, state of charge and total Ah. In an EV Li-ion battery fire, a variety of toxic and flammable gases are released;

Directional flames: EV battery packs are often located under the floor of the vehicle. As gasses are vented from damaged battery cells, they can create directional 'jet like' flames issuing from underneath the vehicle and venting to either side. These flames are at a similar heat to those from an ICV (800-1000°C), but can burn for longer;

Vapour cloud explosion: If the HV battery enters thermal runaway and begins off gassing in a confined space with limited ventilation (such as basement or multi-storey car parks), where gases are unable to escape, they can build up and may explode if the cloud comes into contact with an ignition source;

Debris projectiles: All vehicle fires will produce some debris and projectiles; however, EV fires may pose an additional risk as gasses vent from the HV battery, which may cause some additional debris as thermal runaway starts;

Secondary ignition: EV battery fires take longer to extinguish and may reignite either on scene, during transport or at the storage facility. On scene, EVs should be monitored for at least 60 minutes once the fire is suppressed. Recovery drivers should be briefed, and the vehicle should be loaded onto a flatbed where possible. Once in storage, monitoring for heat, vapour and flames should continue. The EV should be stored away from structures and vehicles if possible;

It is worth noting that fires occur in batteries with several cells, each of which can catch fire at a different time. Products that promise to extinguish fires in EV, such as "fire extinguishing blankets" and special extinguishers, are already being announced, and the characteristics of these two products are shown below.

A. Fire blankets

The media usually has advertized them as "fire extinguishing blankets", but the publication of DIN SPEC 91489 [24] established the correct terminology for them: "fire limitation blankets". The DIN SPEC 91489 issued requirements for the manufacture and use of the "fire limitation blankets", and, among them, are:

- the minimum thermal resistance must meet the DIN EN 13501-1 [25] B classification;
- It must have protection against electric shock due to electrostatic discharges;
- It must be resistant to chemicals;
- It must be handled by at least two trained first responders, using personal protective equipment and breathing apparatus.

Although DIN SPEC 91489 is considered an important milestone for the commercialization of fire limiting blankets, more recent studies have shown that their use leads to explosion risks, due to the flammable gases that are trapped under them during a fire in Li-ion batteries. Since the Li-ion battery releases flammable gases, the fire will be a source of ignition of them, causing an explosion [26].

The gases released by a Li-ion battery in thermal runaway are: Hydrogen (H_2), Carbon monoxide (CO), Carbon dioxide (CO_2), Methane (CH_4), Ethylene (C_2H_4), Hydrofluoric acid (HF), and other volatile organic compounds (VOC) as: Ethylene carbonate and Dimethyl carbonate. These gases, especially HF and CO, can be extremely hazardous to human health, and the resulting smoke can make it difficult to see and access the fire site

The risk of explosion, as well as the intense flames released when EV batteries catch fire, make placing blankets over burning EVs an unsafe activity for firefighters, even when wearing special clothing.

The possibility of installing a system that automatically throws a fire limiting blanket over the parked burning car is an option, which would act in less time than the arrival of the fire brigade.

B. Fire extinguishers

There are some new fire extinguishers being announced as suitable for Li-ion battery fires, which are predominantly water-based (83%) with an Aqueous Vermiculite Dispersion (AVD) component (17%). The action principle is to use water for effective cooling and AVD to encapsulate and isolate the cells.

Standard fire extinguishers such as water, foam, wet chemicals, powder, and CO_2 are likewise not suitable for extinguishing fires caused by Li-ion batteries. Although they may momentarily control the flames, there's a significant chance of re-ignition due to the liberation of flammable gases under a thermal runaway. It is important to say that the Li-ion fire extinguishers are not suitable for extinguishing fires caused by flammable gases (class C), flammable liquids (class B), or cooking-related fires (class F). Additionally, they are not available for use in EV fires, but only in fires involving devices with small Li-ion batteries.

The São Paulo Fire Department (CBPMSP), in order to research the safest methods to contain EV fires, erected a laboratory for testing EV fires at the Fire Department's Higher Education School in Franco da Rocha, SP. [27] The facility has automatic sprinklers, smoke detectors and gas extraction devices, as well as a thermographic camera that detects temperature, smoke and carbon monoxide.

Tests have already been carried out there on HEV and ICV to analyze their behavior on fire. One of them, with an EV equipped with its 83 kWh battery at 98% charge, was forced to ignite, and after 7 minutes (the average response time of the CBPMSP) they began fighting the fire. It is worth to say that the fire in Li-ion batteries is not extinguished by water. Water is important to cool the surroundings, until the flammable material inside the Li-ion battery is extiguished. In this test,

3,500 liters of water were used, which was considered the common means of fighting fires, used by all fire departments.

The current edition of NFPA 88A [28] requires automatic sprinklers in enclosed and open parking structures.

VI. Requirements on EV Charging Safety

Concerned about the various cases of fires in EV, especially those occurring in parking lots, some entities have already issued guidelines in order to improve safety and reduce the number of new fire cases, as shown below:

- The European Parking Association has developed a guidance document [29] for fire safety focusing on EV charger installations, where among the recommendations are: install automatic fire detection and alarm system; provide automatic isolation of power supply linked to detection system / suppression system / automatic de-energization of connection cables, and provide appropriate structural fire resistance within the car park;

- The Municipal Code of San Francisco [30] requires new buildings - residential and commercial - to have 10% of parking spaces "turnkey ready" for EV charger installation. Regarding fire fighting requirements, EV charging zones in new garages must use EH2 sprinklers (0.40 gpm/ft²), extending coverage 3 ft beyond each EV space. And existing garages adding EV chargers likewise must upgrade to EH2 density and area requirements - though smaller zones (< 2,500 ft²) only need the 3 ft extension, not the full 15 ft of NFPA 88A;

- The Seoul Metropolitan Government [31] implemented a policy to limit charging to 80% State of Charge (SoC) at EV public fast-chargers, what will reduce peak battery stress and the probability of thermal-runaway [32]. SoC represents the amount of energy stored in a battery relative to its total capacity, expressed as a percentage.

- The CBPMSP proposed in a public consultation new regulations for parking of EVs [33], which caused such a stir because they made some requirements difficult to be adopted by existing parkings, such a 5m distance between EV charging points in open areas, as shown in Fig. 1.

Such distance could be drastically reduced when using sprinklers and fire resistant walls to avoid the fire from spreading to the building or near cars, a situation that occurs in underground car parking [34] as shown in Fig. 2.

Another firefighters' concern is the enormous water consumption to contain EV fires, something that is also taken into account by the CBPMSP to define the contingent for each occurrence. Even after the fire is controlled, there is still a risk of reignition in the battery, hence the need to take the damaged EV to an open area where a new fire will not bring new risks.

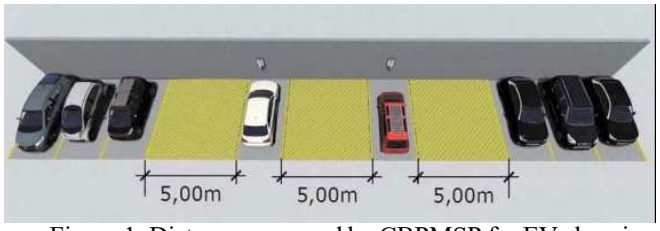

Figure 1: Distance proposed by CBPMSP for EV charging points in open areas.

It is important to emphasize that EV manufacturers have set charging limits up to 80% [35], due to the accelerated growth of dendrites that occurs from this level of charge, as well as to reduce the energy released in the event of a fire, which is directly proportional to the battery SoC [32].

That public consultation of CBPMSP resulted in a Directive [36] that will serve as a basis for the development of requirements by fire departments in other Brasilian states for occupancies designated as garages and locations with Electric Vehicle Charging Points (SAVE).

The distance between EV charging points was abandoned, but the new requirements depend on the type of the location, which were classified in four groups:

1- Locations with SAVE;

2- Garages in outdoor areas with SAVE;

3- New buildings with installations approval required (garages and occupations with garages);

4- Existing buildings with installations approval required (garages and occupations with garages with SAVE).

Each group has specific requirements, such as:

- Use only charging modes 3 and 4 (the safest), as per NBR IEC 61851-1 [13];
- Manual shutdown switch at least 5 meters from each charging point;
- Identified circuit breaker for each charging point;
- Minimum 5-meter distance in garages with a single escape route;
- Installation of automatic sprinklers;
- Fire detection system;
- Risk management.

Additionally, it is worth to highlight that the UK's PAS 63100 [37] recommends that Battery Energy Storage Systems (BESS) need to keep their SoC below 80% for indoor and 90% for outdoor systems. BESS is a stationary energy storage system using battery technology. The majority are built with Li-ion technologies, but other battery technology can be also used. The PAS 63100 was issued after more than 30 BESS fire incidents, what posed concerns and doubts towards the safety of Li-ion BESS [38].

Figure 2: EV charging point isolated and provided with sprinklers, proposed by CBPMSP for underground parking.

VII. The Search for Explosionproof Batteries

After hundreds of fires and explosions involving EVs' batteries, manufacturers recognized the dangers of li-ion batteries and began investing in research to find ways for consumers to regain confidence in the safety of EVs. Two manufacturers have announced solutions for this purpose.

A. The GB 38031 standard

The battery manufacturer CATL (Contemporary Amperex Technology Co., Limited) announced its "Qilin", the third generation of the cell-to-pack (CTP) technology. It offers a volume utilization rate of 72% and their LFP (lithium iron phosphate) versions reach an energy density of 160 Wh/kg. As it was certified under the requirements of the Chinese standard GB 38031 (set to take effect on July 1, 2026), it is considered a "no fire, no explosion" battery [39].

The GB 38031 [40] establishes as requirements that the battery cells must not catch fire or explode in the tests defined therein: overdischarge, overcharge, external short-circuit test, heating test, temperature cycle test, fast charge cycle and extrusion test. And battery packs shall not have leakage, fire or explosion in the following: vibration test, simulated collision test, extrusion test, damp heat cycle test, water immersion test, external fire test, temperature shock test, salt spray test, and thermal diffusion analysis.

Qilin has a cooling system designed to prevent heat transfer between cells, reducing the risk of thermal runaway.

But, it is not correct to call it as an "explosionproof battery", because such certification does not mean that the battery will never explode, but that a brand new one did not explode during those specified tests. Although GB 38031 is considered the most though standard for EV batteries, until now there is no standard that guarantees the non-formation of dendrites throughout the battery's life, which is the main cause of short circuits and subsequent thermal runaway in li-ion batteries. [23]

B. The solid state electrolyte battery

The use of a solid electrolyte is a new technology that promises greater safety in EVs, by eliminating the flammable liquid electrolyte currently used in EVs' batteries.

The Chinese car manufacturer BYD announced the production of its first solid-state cells with 20 Ah and 60 Ah on its pilot production line in 2024 [41]. BYD is focussing on sulphide electrolytes in the development of solid-state cells, but there are other technology paths for solid-state cells as oxides and polymers.

While in traditional Li-ion batteries the electrolyte is a flammable liquid, solid-state cells are formed of: a cathode, which can be made with the same compounds as a Li-ion battery (eg. LFP, NMC, LMO, etc); a separator, generally ceramic or solid polymer, which also works as the electrolyte (it becomes the medium through which the ions move and also has electric insulating properties, acting as a mechanical separator between the anode and cathode); and an anode made of lithium metal.

Another advantage of solid-state electrolyte in terms of safety is the greater resistance to dendrites, or the sharp, uneven build-up of lithium that forms during movement from the cathode to the anode. In fact, lithium does not move evenly and tends to group together and form points which, like real pins, grow and pierce the separator. However, due to its thickness, solid separators are more resistant to piercing from dendrites and therefore, avoid possible short circuits and the gradual deterioration of the cell.

What is certain is that true solid-state batteries for automotive use are still in the experimental phase, and the costs are high. But if major EV makers are investing in this direction, they have sufficient evidence to believe that current batteries are unsafe and that the cost of new ones could be reduced with mass production.

VIII. Conclusions

Li-ion batteries are preferred for EVs because they offer advantages such as greater charge density per volume and decreased prices due to mass production. However, concerns have been raised due to the increasing number of fires involving EVs being recharged or even cruising on the road, as firefighters still lack the tools to extinguish them due to the high energy released.

The statistics spreaded in social media, pointing that EVs are less proned to fires than ICV were made without the necessary mathematical care, and are not a reliable predictor of future events. To reliably assess the fire risks of EVs, it is necessary to consider in detail: the situations and causes of fires (while recharging, while parked, while driving, collisions, etc.), the ages and types of vehicles, and the battery technologies involved in fires and explosions.

Considering the distortions found on manipulating the data, where older ICVs fire cases (mixing events with cars and trucks), were compared with newer EVs that catched fire only when involved in collisions (excluding the cases of fires when charging), it is incorrect to claim that EVs are safer than ICVs. The media should avoid repeating such comparison without questioning the source of the information and its accuracy. It's easy to twist numbers when no one checks the math. Society needs honest comparisons, especially when life-altering decisions depend on them.

Since traditional fire suppression approaches are not as effective on EV fires as they are on ICV fires, the cost of equipping buildings with measures to fight EV fires is high, what has caused conflicts in condominiums, as EV owners wish charging points in their parking spaces, being unaware of the complexity involved, not only with regard to the availability of the electricity provider, but also with regard to the requirements of the local Fire Department.

The lack of any requirements in fire codes for active protection systems in open parking structures, and trends of larger vehicle widths and tighter parking spaces in garages suggest that large, devastating fires in these structures could become increasingly common. [42]

Hyundai and Kia EV manufacturers already recognized the risks of Li-ion batteries [43], and to minimize damage after incidents, the firms introduced the EV Fire Safety Program, including EV Safety Checkups offered free for 10 years, and also providing up to US$ 75 million in compensation beyond insurance coverage including third-party damages.

Therefore, civil society should demand batteries that are as efficient as Li-ion ones, but without the dangerous effects of thermal runaway [44], which would bring peace of mind not only to EVs' owners, but also to all the people that live in condominiums.

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Arc Flash Risk Exposure Analysis in Electric Power Distribution Utility – Low-Voltage Energy Meters

line 1: 1st Aguinaldo Bizzo de Almeida
line 2: *DPST*
line 3: *BT Ensaios Elétricos*
line 4: Agudos, Brasil
line 5: email bizzo@dpst.com.br

line 1: 4th Diego Bruo Tognon
line 2: DPST
line 3: BT Ensaios elétricos
line 4: Agudos, Brasil
line 5: email diego@dpst.com.br

***Abstract*— Present the results of the analysis of exposure to arc flash risk in the maintenance process of electric power distribution networks, typical of the EPS – Electric Power System, specifically in activities carried out on low-voltage electricity meters.**

Keywords—electric arc, risk analysis, EPS

I. INTRODUCTION

The assessment of arc flash risk exposure for professionals performing operation and maintenance activities in electrical installations of power distribution utilities requires a specific risk analysis, considering the particularities of the various electrical scenarios within this typical segment of the EPS – Electric Power System. In this context, several activities are carried out on Low Voltage distribution networks, specifically on LV electricity meters, where, on a daily basis, Authorized professionals are intrinsically exposed to the electrical risk factor, with the possibility of arc flash occurrence.

For the proper assessment of arc flash risk in activities performed on LV electricity meters, it is necessary to consider specific factors of the locations where these activities are carried out, especially the level of incident energy and the control measures adopted by the Organizations, in accordance with the premises established in NR10 and NR1, particularly the hierarchy of control measures, namely: Elimination of the Hazard, adoption of Collective Protection Measures, Administrative and Organizational Measures, and Individual Protection Measures.

II. SCOPE AND CONTEXTUALIZATION

Exposure to arc flash risk is an intrinsic condition for Authorized professionals who perform activities on LV – low-voltage electricity meters, where serious accidents may occur, as shown in Figure 1 – Activity on a single-phase meter in a service entrance standard with an external metering box, where the potential for harm due to possible arc flash exposure is minimized.

Therefore, it is necessary that the risk analysis of these activities be carried out properly, under penalty of "trivializing" the real assessment of the risk level in the various existing scenarios.

This work presents a specific risk analysis under real working conditions in the electric power distribution segment, focusing on activities performed on low-voltage electricity meters, considering the technical and legal requirements and criteria established in NR10 – Safety in Electrical Installations and Services and NR1 – Occupational Risk Management.

Numerous factors must be considered for an effective risk analysis in these activities, among which we highlight: the level of incident energy, the constructive characteristics of electrical installations, work methods and procedures, control measures, emergencies, communication, and the qualification and training of authorized professionals.

Fig. 1 – Activity on a single-phase meter in a service entrance standard with an external

The content is based on real scenarios and data used in specific work carried out in power distribution utilities in different states of Brazil, presenting actual results of incident energy calculation and risk analysis in typical installations, on a sample basis, considering factors intrinsic to the constructive characteristics of different locations, as well as the work methods and procedures adopted by professionals.

The Arc Flash Risk Exposure Analysis addressed in this work distinctly covers two (2) "types" of processes:

a) Calculation of the incident energy level; and

b) Risk analysis.

III. STUDY OF INCIDENT ENERGY FOR ELECTRIC POWER SYSTEMS – EPS– OSHA© 1910-269 & NESC© C2 2023

Using as a reference the values of the symmetrical phase-to-ground short-circuit currents provided, the calculation of the incident energy resulting from the formation of an electric arc will be carried out in accordance with IEEE© 1584-2011, NFPA© 70E - 2021, and NESC© C2 – 2023 standards, see Figure 2 - Table Extracted from OSHA© 1910-269.

The Arc Flash Risk Assessment calculation will be based on the following conditions:

- Power and short-circuit current value at each point of the installation;
- Symmetrical phase-to-ground short-circuit current;
- Calculated value of arc short-circuit current;
- Type of activity;
- Protection operation time;
- Shape factor;
- Equipment type;
- Working distance.

The calculation of the incident energy value is in accordance with IEEE© 1584-2011, NFPA© 70E - 2021, and NESC© C2 – 2023 standards, as applicable, see Figure 2 - Table Extracted from OSHA© 1910-269.

	600 V and Less			601 V to 15 kV			More than 15 kV		
	1Ø	3Øa	3Øb	1Ø	3Øa	3Øb	1Ø	3Øa	3Øb
NFPA 70E-2012 Annex D (Lee equation)	Y-C	Y	N	Y-C	Y-C	N	N3	N3	N3
Doughty, Neal, and Floyd	Y-C	Y	Y	N	N	N	N	N	N
IEEE Std. 1584b-2011	Y	Y	Y	Y	Y	Y	N	N	N
ARCPRO	Y	N	N	Y	N	N	Y	Y4	Y4

Fig. 2 – Table extracted from OSHA© 1910-269

IV. METHODOLOGY FOR INCIDENT ENERGY CALCULATION

According to ANSI© C2 – 2023, the ARCPRO© software methodology will be used for incident energy calculation.

ARCPRO© METHODOLOGY

This type of model considers the energy produced by the single-phase short-circuit current, part of which is converted to generate an electric arc.

Permitted values for calculation using ArcPro©:

- Currents from 0.2 kA to 100 kA
- Duration from 0.05 cycles to ∞ cycles
- Arc lengths from 1 inch to ∞ inches
- Working distances from 0.04 inches to 400 inches from the arc

The following limits for calculation are guaranteed and validated by testing:

- Currents from 3.5 kA to 21.5 kA
- Duration from 4 cycles to 30 cycles
- Arc lengths from 1 inch to 12 inches
- Distances from 8 inches to 24 inches from the arc

When the value between current, voltage, and arc length is incompatible, the software terminates its execution. The information above was extracted from the manufacturer's manual of the ArcPro© program.

V. RESPONSE TIME OF PROTECTIVE EQUIPMENT

As a general guideline for protection operating times, specifically for incident energy calculations, the same values from Table 1 below, extracted from IEEE© 1584:2011, will be considered.

Table 1. Operating times of components

Equipment	Cycles	Time [ms]
LV Circuit breaker	1,5	25
LV Circuit breaker w/ relay	3,0	50
MV Circuit breaker ≤ 35 kV	5,0	80
HV Circuit breaker	8,0	130

For fuse links, the operating time will be calculated based on the maximum I^2t, respecting the following limits:

- Minimum time of 10 ms;
- Minimum energy of 0.25 cal/cm².
- Time determined by I^2t @ 20 In.
- Arc current value greater than 20 times the fuse's nominal current for melting.

For microprocessor-based relays, in addition to the protection curve time, the breaker opening time plus relay latency time will be added.

For medium-voltage circuit breakers, an opening time of 3 to 5 cycles (50 to 80 ms) is considered, while for high-voltage circuit breakers 5 to 8 cycles (80 to 130 ms) are considered.

- Relay latency: 30 ms
- Physical contact switching time: 20 ms

For electromechanical relays, a response inertia of approximately 80 ms plus 20 ms of contact switching time will be considered.

VI. MINIMUM APPROACH DISTANCE (MAD)

The minimum approach distance for work is understood as the distance required for the worker to move, including handling equipment or tools, without the risk of initiating an electric arc relative to their body (see Figure 2 – MAD).

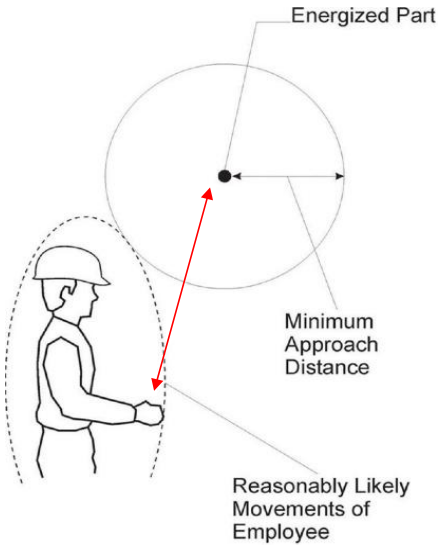

Fig. 2 – MAD (Minimun Approach Distance)

MAD is composed of two components:

- Electrical MAD
- Ergonomic factors

MAD = Electrical MAD + Ergonomic Factor

VII. Reference Documents

For the preparation of the incident energy study, documentation provided by the Organizations was used, referring to single-phase and three-phase circuits of various power transformers installed in electrical distribution networks.

VIII. Types of Work

Work on energized electrical equipment in compartments

- Activity characterized by segregated and energized equipment. Typically electrical panels with compartment violation and possible access to energized parts.

Work on energized electrical equipment outdoors

- Activities performed on non-compartmentalized equipment installed outdoors. Energized parts are exposed, and electric shock protection is ensured by keeping them out of normal reach.

Live-line work at a distance

- Work performed on live lines using appropriate tools while keeping the worker outside the minimum approach distance (MAD).

Live-line work at potential

- Live-line work with equipotential bonding between the worker and the equipment. The worker must maintain at least the MAD from other energized conductors or the ground reference potential.

Remote work in the free and/or controlled zone

Work performed in the free or controlled zone (in terms of electric shock according to NR-10), but with the possibility of arc flash risk. Examples: remote switching, inspection, and verification with energized parts out of reach.

For each type of equipment, the activities performed as well as the calculation methodology applied were established, as follows:

Table 2. Methodology used for each equipment

	Outdoors energized equipment	Live-line contact work	Methodology
Activities on energized LV meter	√	√	ANSI C2/ OSHA 1910
Live-line LV contact work	√	√	ANSI C2/ OSHA 1910

In Figure 3. Replacement of a two-phase meter, an example of the sampling applied is presented.

Fig. 3 – Replacement of two-phased meter

IX. General Considerations for Incident Energy Calculations

For incident energy calculations at different points, the following premises were adopted (Table 3), according to OSHA© 1910-269 for physical working distances based on activity type:

Table 3. Working distances

Voltage class	Working distance (m)
Energized LV meter replacement	0,40*
LV Live-line work at contact	0,40*

* Value for live-line contact work per OSHA© 1910 – 269

For incident energy calculations, must be utilized: the phisical distance minus 2 times de arc distance.

$$D_{CALC} = MAD - 2.ARC_{DISTANCE}$$

$$D_{CALC} = 40 - 2\,.\,3{,}2 = 33{,}60$$

Adopted 33 cm as calculation distance for this example.

Various medium-voltage feeder branches with different configurations were analyzed, and short-circuit values were obtained from the documents provided. In most cases, the available current in the primary network is less than 1 kA of short-circuit current, a condition that results in a lower reflected fault current and increases the operating time of the protection system.

X. TRANSFORMER PROTECTION SYSTEM

The protection of distribution transformers is normally carried out with fuse links in the primary. Thus, a secondary phase-to-ground short-circuit must be interrupted by the primary fuse through the reflected current, depending on the transformer's connection group.

Accordingly, a single-phase short-circuit in the secondary is reflected as a two-phase short-circuit at 58% in the primary.

In circuits with single-phase transformers, the short-circuit current on the secondary side is directly reflected to the primary side through the transformation ratio.

Based on the data provided by the Organization, the reflected currents for each type of transformer are presented in Tables 3 and 4.

Table 4. Single-phase transformers at 13.8 kV

transformers	Impedance	Voltage		Reflected S.C.	S.C.	Device
		Primary	Secondary	Primary Symmetrical	Secondary Symmetrical	Protection
	[%]	[kV]	[kV]	[A]	[A]	Fuse
10 KVA	2,50%	13,8/√3	0,44	36,85	667	2H
15 KVA	2,50%	13,8/√3	0,44	43,96	796	3H
25 KVA	2,50%	13,8/√3	0,44	76,63	1387	5H
37,5 KVA	2,50%	13,8/√3	0,44	90,98	1648	6K
50 KVA	3,00%	13,8/√3	0,44	97,60	1767	8K

Table 5. Three-phase transformers at 13.8 kV

transformers	Impedance	Voltage		Reflected S.C.	S.C.	Device
		Primary	Secondary	Primary Symmetrical	Secondary Symmetrical	Primary
	[%]	[kV]	[kV]	[A]	[A]	Fuse
15 KVA	3,50%	13,8	0,38	9,09	570	1H
30 KVA	3,50%	13,8	0,38	17,99	1126	2H
45 KVA	3,50%	13,8	0,38	25,98	1627	3H
75 KVA	3,50%	13,8	0,38	38,96	2439	5H
112,5 kVA	3,50%	13,8	0,38	53,85	3372	6K
150 KVA	3,50%	13,8	0,38	59,52	3721	6K
225 KVA	4,50%	13,8	0,38	81,14	5080	10K
300 KVA	4,50%	13,8	0,38	83,83	5249	15K
500 KVA	4,50%	13,8	0,38	122,48	7669	25K

XI. RESULTS OBTAINED WITH THE PROVIDED VALUES

The incident energy value was calculated for various power ratings of single-phase and three-phase transformers.

For contextualization and exemplification, Figure 5 – Incident energy calculation – LV energy meter, and Figure 6 – Incident energy calculation – LV secondary electrical network, present sample results for transformers rated 13.8/√3 – 0.44 kV – 45 kVA.

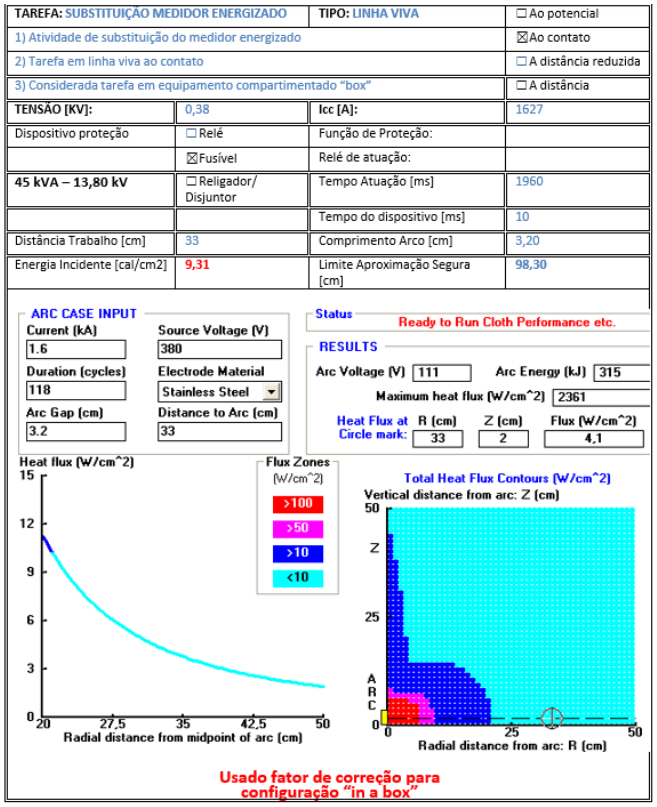

Fig.5 Incident energy calculation – LV energy meter

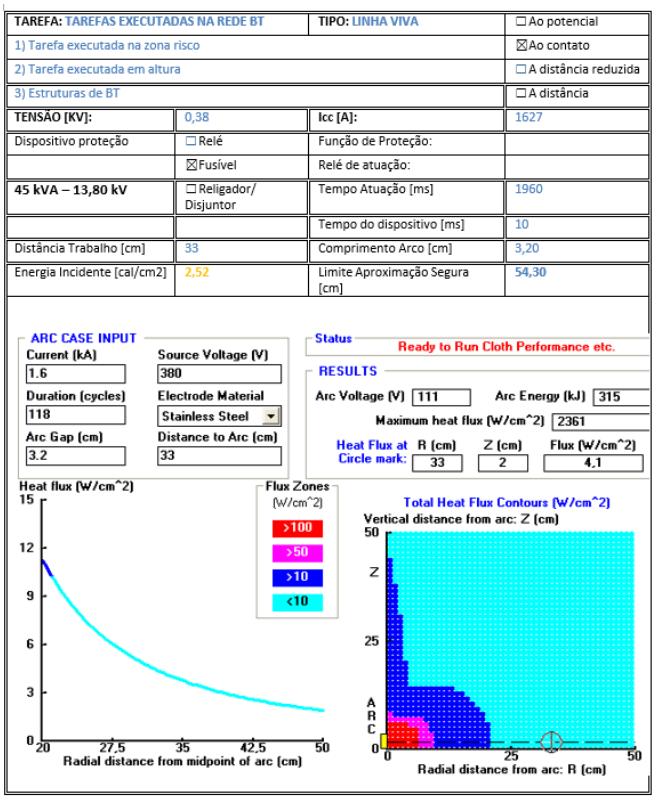

Fig.6 Incident energy calculation – LV Secondary electrical network

XII. CONSIDERATIONS

For low-voltage activities, the incident energy calculation method applied was in accordance with OSHA© 1910.269 using the ArcPro© software, along with adjustment factors for the "in a box" configuration, applicable to meter replacement tasks or any other work carried out in confined environments. For other activities, the "open" condition was considered.

For the calculated points, the incident energy was obtained using the phase-to-ground short-circuit value and the operating time provided by the fuse curves.

From the graph, the cold-melting time for a phase-to-ground short-circuit in the secondary (reflected in the primary) was extracted in order to obtain the incident energy.

To provide a safety margin for the executed calculations, an arc length greater than 10 kV/in was established, in accordance with OSHA© 1910-269.

For the calculation of the new arc length, a switching overvoltage factor of 3.0 pu was adopted, as shown in Table 6.

Table 6. Arc length according to IEEE© 516:2019

AC line-to-line voltage	T for live work
At and below 362 kV	3,0 pu
363 to 550 kV	2,4 pu
551 to 800 kV	2,0 pu

For the activities, the smallest working distance for determining the energy levels was considered, such as work on energized low-voltage circuits, with a typical working distance of 40 cm, in accordance with OSHA© 1910-269.

In the case of live-line contact work, the incident energy calculation used the working distance minus twice the arc length (0.33 cm).

Incident energies were calculated for two types of activities, with results presented in Figure 7 – 13.8 kV Single-Phase Transformers and Figure 8 – 13.8 kV Three-Phase Transformers:

- Live-line activities under the enclosed configuration ("box");
- Live-line activities under the open-air configuration ("open").

Transformador	Un[kV]	Icc [kA]	Device	Ei [cal/cm2] box	Ei [cal/cm2] open
10 kVA – 2,5%	0,44	0,67	FUSE 2H	0,86	0,57
15 kVA – 2,5%	0,44	0,79	FUSE 3H	0,79	0,53
25 kVA – 2,5%	0,44	1,39	FUSE 5H	0,48	0,32
37,5 kVA – 2,5%	0,44	1,65	FUSE 6K	0,35	0,23
50 kVA – 3,0%	0,44	1,77	FUSE 8K	0,49	0,33

Figure 7. 13.8 kV Single-phase transformers

Transformador	Un[kV]	Icc [kA]	Device	Ei [cal/cm2] box	Ei [cal/cm2] open
15 kVA – 3,5%	0,38	0,57	FUSE 1H	3,91	1,22
30 kVA – 3,5%	0,38	1,13	FUSE 2H	6,94	1,68
45 kVA – 3,5%	0,38	1,63	FUSE 3H	9,31	2,52
75 kVA – 3,5%	0,38	2,44	FUSE 5H	7,11	2,44
112,5 kVA – 3,5%	0,38	3,37	FUSE 6K	3,49	1,51
150 kVA – 3,5%	0,38	3,72	FUSE 6K	2,84	1,25
225 kVA – 4,5%	0,38	5,08	FUSE 10K	4,94	2,58
300 kVA – 4,5%	0,38	5,25	FUSE 15K	12,34	6,61
500 kVA – 4,5%	0,38	7,67	FUSE 25K	19,68	13,03

Figure 8. 13.8 kV Three-phase transformers

XIII. RISK ANALYSIS

The Arc Flash Exposure Risk Analysis in this study complies with the provisions of NR10 – Safety in Electrical Installations and Services and NR1 – Occupational Risk Management.

It is a global evaluation of electrical scenarios and activities performed by professionals from different Organizations, in which a sampling assessment was conducted of activities carried out in diverse scenarios and locations. These samples reflect real working conditions regarding generic parameters in activities involving LV (low-voltage) energy meters from these Organizations.

It is important to emphasize that, in addition to the assessment of arc flash risk (the main focus of this study), professionals are also inherently exposed to the risk of electric shock by direct contact, for which specific control measures must be adopted.

The assessment of exposure to hazards with arc flash risk must consider parameters specific to the working reality of professionals exposed to the Hazard of Electricity and the consequent exposure to arc flash risk. Several factors must be addressed to ensure an adequate risk analysis, including:

- Incident energy level and Safe Approach Limit;

- Construction characteristics of electrical installations;
- Incident energy level and Safe Approach Limit (reiterated);
- Competence of Persons (Qualified/Authorized – BA) versus control measures;
- Work Methods and Procedures;
- Additional Risks (External Hazards);
- Prohibitive Conditions;
- Collective, Administrative, and Organizational Control Measures;
- Professional Qualification and Training;
- Emergency Procedures;
- Communication;
- Others.

XIV. General Requirements for LV Energy Meters

There are numerous models of LV energy meters, especially with the development of new technologies, including those related to solar energy.

For the purpose of contextualization and to limit the scope of this study, some basic premises will be considered, which, regardless of the meter type, must be evaluated in a risk analysis.

Thus, it is necessary to identify the different types of meters for a stratified evaluation in each Organization.

LV energy meters essentially consist of "input and output terminals" where the low-voltage conductors are installed. Under normal operating conditions, the terminal compartment is segregated by an enclosure that prevents accidental access to live parts.

Figure 9 – Terminals of LV Energy Meters shows the construction features of LV energy meters, highlighting the terminals after the enclosures have been removed. In the example, an LV energy meter is being installed in a residence with a specific entry standard, where the conductors are of the "extra-flexible cable" type. This pattern is not the most common, since installations with rigid cables are predominant.

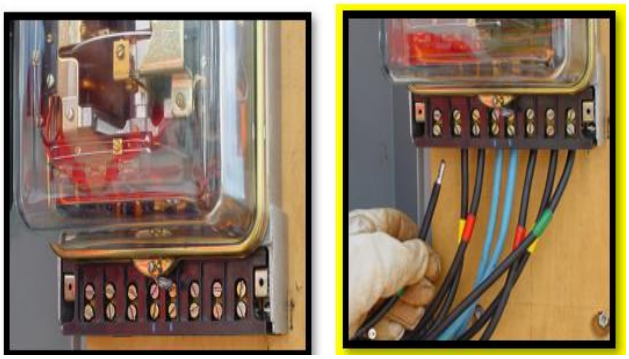

Figure 9- terminals of LV energy meters.

The example above serves to confirm the different construction conditions. Considering the risk of arc flash occurrence, in this type of installation there are factors that increase the probability of arc flash events during activities performed with energized circuits, due to the characteristics of the extra-flexible cable, where the correct soldering (tin welding) procedure is essential.

Energy meters can be single-phase, two-phase, or three-phase, and this condition is intrinsic to the correct assessment of exposure risk both to electric shock by direct contact and to arc flash. In two-phase or three-phase meters, there is the possibility of phase-to-phase short-circuits and a higher probability of arc flash events, since multiple energized conductors are handled simultaneously.

Note: For activities in de-energized electrical circuits, the exposure to the risk of electric shock by direct contact and to arc flash does not initially occur, except for activities performed in "proximity" as defined in NR10.

XV. Field Evaluations

Field inspections were carried out in a customized manner, monitoring activities under real and/or simulated conditions, observing the actual working environment of professionals performing tasks on LV (low-voltage) energy meters.

In general, the following activities were evaluated:

LV meters installed in rural areas with single-phase transformers;

LV meters installed in urban areas with three-phase transformers, including residential applications and grouped metering in buildings, as well as meters in entry standards with indirect metering, among others.

Note: Other specific scenarios, such as activities involving LV meters in underground networks, are not included in this document. However, it is essential to emphasize that such scenarios require specific criteria for incident energy calculation and risk analysis of activities.

Activities on LV Energy Meters – Single-Phase Transformers

Performing activities on low-voltage energy meters is a common condition. In rural areas, single-phase transformers predominate, and metering boxes are typically installed in open areas.

Authorized Professionals routinely carry out service disconnection and reconnection due to non-payment, by removing the conductors from the output terminals of the meters.

Occasionally, activities require the removal of LV energy meters themselves, where the input conductors to the meters are also disconnected. These conductors remain energized, and after removal, the energized ends are insulated using a specific protective cap.

These activities, with few exceptions, are performed with the circuit energized.

Use of PPE – Personal Protective Equipment

Personal Protective Equipment (PPE) is used for protection against the risk of electric shock by direct contact, consisting of LV insulating rubber gloves (class 00 or 0) and Arc-Rated (AR) Risk Category 2 garments (as designated by the Organization) with a minimum ATPV of 8 cal/cm²,

including AR shirt and trousers, which are also used as the standard uniform.

Specific PPE for face protection against arc flash hazards is only used during meter removal activities. This equipment consists of a helmet with an Arc-Rated face shield – Risk Category 2 – with a minimum ATPV of cal/cm², as shown in Figure 10 – PPE for Arc Flash Protection.

Fig. 10 – PPE for arc flash protection

The activity is performed with the low-voltage energized circuit (127 volts), where in certain situations it is necessary to handle the phase conductor for removal/reconnection at the meter terminal.

After removal of the meter, the phase conductor's energized end is insulated with a specific insulating device (protective cap).

Considering the single-phase transformer of 13.8 kV and 50 kVA that feeds this meter, the incident energy at the meter is 0.49 cal/cm².

This incident energy value is below 1.2 cal/cm², the reference threshold in NFPA 70E for the mandatory use of PPE against arc flash hazards, as well as below 2 cal/cm², the reference threshold in OSHA© 1910 for the mandatory use of arc flash PPE.

Thus, the PPE used by Authorized Professionals in the execution of this activity, in this specific electrical scenario (single-phase 13.8 kV / 50 kVA transformers), is deemed adequate. In other words, the AR clothing and Face Shield with a minimum ATPV of 8 cal/cm², together with insulating rubber gloves overlaid with leather gloves, allow for the characterization of a controlled risk.

Additionally, it is necessary to consider the risk of electric shock by direct contact, an intrinsic condition due to handling of the energized phase conductor. In this specific electrical scenario—single-phase meter in an open location with adequate space for professional positioning and movement—the existing control measure, based on the professional's qualification, training, and skill, along with the use of LV insulating rubber gloves, can be accepted as a sufficient control measure for the characterization of controlled risk.

Activities on LV Energy Meters – Three-Phase Transformers

Performing activities on low-voltage energy meters is a common condition. In urban areas, three-phase transformers predominate, with metering boxes typically installed in closed locations, such as residential buildings or commercial and industrial facilities.

Most activities are carried out at ground level on the LV energy meter, with the circuit energized—specifically service disconnection due to non-payment. When necessary to remove the meter, the power conductors are cut either at the consumer unit's entry point or at the LV overhead distribution network, with the professional positioned at an elevated level using extendable insulating ladders or aerial lifts. This same condition applies to new installations, where the installation of energy meters involves conductor handling in a de-energized state.

The service disconnection due to non-payment can generally be carried out in different ways:

"Symbolic disconnection", where the professional switches off the customer's installation circuit breaker and installs a mechanical lockout device or a signaling label;

"Meter disconnection", involving removal of the electrical conductors from the output terminals of the utility's energy meter;

Power supply disconnection at the service entry conductors or the LV secondary network, i.e., without direct intervention at the meters.

For activities performed at elevated positions, whether at the service entry standard or the LV distribution networks, PPE is used to protect against the risk of electric shock by direct contact. These include LV insulating rubber gloves, as well as collective protective equipment such as sleeves or insulating blankets, class 0 – 1 kV.

Professionals also wear AR Risk Category 2 garments (as designated by the Organization) with a minimum ATPV of 8 cal/cm², including AR shirt and trousers, which are also used as the standard uniform.

For face protection, it has been observed that in some Organizations, professionals only use safety glasses and Class B helmets. In other Organizations, however, the use of an AR Face Shield is a mandatory requirement (see Figure 11 – PPE in Meter with Three-Phase Transformer).

Fig. 11 – PPE in meter with three-phase transformer.

It is observed that for activities carried out at ground level on energy meters, in general, the use of PPE for arc flash protection is subject to the assessment of Authorized Professionals.

As a matter of common practice, especially in activities of "service disconnection due to non-payment", when a "symbolic disconnection" is performed—i.e., only by witching off the consumer's main circuit breakers—LV insulating rubber gloves as well as PPE for face protection against arc flash are not used.

Instead, professionals typically use safety glasses, a Class B helmet, and general-purpose work gloves (see Figure 12 – "Symbolic Disconnection").

Fig. 12 –"Symbolic Disconnection"

In general, when it becomes necessary to perform a service disconnection due to non-payment at the meter terminals—that is, when the enclosure (cover) providing access to the terminals is removed—after the removal of this enclosure, professionals wear LV insulating rubber gloves to carry out the actual "power cut", by removing the conductor (in single-phase meters) or conductors (in two-phase or three-phase meters) from the output terminals of the LV meters, using insulated hand tools.

PPE for face protection against arc flash is not used in these situations. Instead, professionals use safety glasses and a Class B helmet.

Occasionally, activities require the complete removal of LV energy meters, where the input conductors at the meter terminals are also disconnected. These conductors remain energized, and after removal, their energized ends are insulated with a specific protective cap.

In general, the use of AR Risk Category 2 garments (as commonly designated by the Organizations) is standardized and applied continuously for all Authorized Professionals.

In some Organizations, the use of PPE for face protection against arc flash (AR balaclava and AR face shield), along with LV insulating rubber gloves, is mandatory for any intervention in energy meters with energized electrical circuits.

Critical electrical scenarios, common across all Organizations, include activities on energy meters in "grouped metering" installations, including in residential and commercial buildings, as well as activities on meters in standards with indirect metering using CTs – Current Transformers (see Figure 13 – External Grouped Metering – Housing Complex and Figure 14 – Commercial Service Entrance – Indirect Metering).

Fig. 13 – External grouped metering – housing complex

Fig. 14 – Commercial service entrance – indirect metering

The service disconnection due to non-payment is performed through the "disconnection at the meter", which involves removing the electrical conductors from the output terminals of the utility's LV energy meter.

For the "disconnection at the meter", professionals use LV insulating rubber gloves and PPE for face protection against arc flash—specifically, a Risk Category 2 helmet with face shield.

In cases where meter removal is necessary, the energized conductors at the input terminals of the meters are also disconnected, and the energized ends are insulated with protective devices.

According to the Incident Energy Study, in this scenario the incident energy value was 9.31 cal/cm² for 45 kVA transformers (see Figure 8 above), in a closed location. In customer service entry circuits, the calculated incident energy value was 2.52 cal/cm², in an open location.

It should be considered an intrinsic condition that professionals must work in a crouched position due to the height of the energy meters installed in this type of electrical setup.

It was observed that in certain locations with service entrance standards for residential complexes, as well as in

indirect metering standards, after opening the metering box door, there are LV electrical circuits without segregation and with Protection Degree below IP2X. In other words, accidental access is possible within the limits established in NR10 as ZC – 70 cm and ZR – 20 cm. This same condition also occurs inherently when the terminal covers of the meters are removed.

It was also observed that some LV circuit breakers feeding customer installations do not have IP2X protection degree, where even in "symbolic disconnection" activities due to non-payment, accidental access to energized live parts is possible.

There are typical scenarios in which energy meters are installed in metering boxes mounted on poles. In such situations, the risk of electric shock by direct contact—and especially by indirect contact—is increased. Figure 15 – External Grouped Metering Installed on Pole illustrates this condition, in which activities on LV energy meters require a specific risk analysis regarding exposure to electrical hazards and risks. The arc flash risk in this type of scenario requires a dedicated evaluation, where "additional risks" as prescribed in NR10 must necessarily be considered, especially work at height and emergency procedures.

Fig. 15 – External grouped metering installed on pole

XVI. Technical Report

The activities carried out by Authorized Professionals in electricity distribution utilities, specifically in low-voltage energy meters, are routinely performed with energized electrical circuits. Consequently, professionals are inherently exposed to the Electricity Risk Factor, particularly the risks of electric shock and arc flash.

For the calculation of incident energy levels and the respective risk analysis, activities on meters were characterized as Work on energized electrical equipment in compartments, typically electrical panels with compartmentalization violations and the possibility of access to energized parts.

Most electrical installations lack automatic switching devices in the secondary network, a factor that is decisive in the calculation of incident energy. However, it was observed that in specific situations LV circuit breakers are installed either at the secondary transformer outputs of distribution networks or inside the metering boxes at the input conductors of the meters, significantly reducing the calculated incident energy levels.

Due to the absence of automatic switching devices upstream of LV meters in distribution networks, the incident energy level is directly related to the power and type of transformers, particularly the characteristics of fuse links. This condition contributes to the "uncertainty" in ensuring the maintenance of the initially calculated risk level, since the actual calculated value depends on the guarantee that the fuse link "will not be altered"—a condition that inherently depends on human action.

Transformers with high power ratings (above 300 kVA), which are common today, presented extremely high incident energy values, exceeding 15 cal/cm² in certain locations and service entrance standards, specifically for activities in LV energy meters, due to the absence of secondary network protection devices.

It was also observed that there are different interpretations and operational procedures between Organizations and professionals. As a result, risk analyses are often conducted subjectively, based on what is called Deductive Risk Analysis, which assumes that Authorized Professionals "know the risk." Consequently, Administrative and Organizational Measures are considered sufficient to protect against electrical hazards, particularly arc flash—a view that does not reflect the reality observed.

Existing procedures in most Organizations allow activities on LV energy meters to be performed with energized circuits, including the removal of conductors from the input terminals of meters. From a probability perspective, this condition is intrinsically characterized as arc flash risk, since different electrical scenarios exist depending on the physical space of each installation and the types of meters used—especially in two-phase and three-phase meters. Moreover, activities are often carried out in common areas, where the presence of BA1 – Ordinary Persons may occur.

XVII. Conclusion

Exposure to arc flash risk is an intrinsic condition in activities involving low-voltage energy meters.

Considering the "severity of damage" criterion established in NR1 – Occupational Risk Management for risk level evaluation, there are scenarios where professionals, due to construction characteristics, must work in restricted physical spaces and in a crouched position. These ergonomic factors aggravate the potential exposure to arc flash, even with incident energy values below 8 cal/cm². In some cases, incident energy values exceed 12 cal/cm².

Incident energy must be calculated for all existing electrical scenarios, along with the respective Safe Approach Limit (LAS), to define the mandatory PPE for activities involving LV energy meters in both closed and open environments.

Activities in common areas must include control measures to account for the potential exposure of BA1 – Ordinary Persons to arc flash events.

It is essential to highlight that incident energy calculation is a fundamental step for effective risk analysis of activities. However, by itself it is not sufficient for defining the specific PPE to be used in activities involving LV energy meters. A stratified risk analysis must be developed, reflecting real working conditions and considering the various factors of each work environment.

It must be emphasized that incident energy levels are a dynamic condition, subject to alteration due to human factors, which may modify the actual exposure level of professionals to arc flash risk and, consequently, the effectiveness of PPE used. This is particularly critical in activities with LV energy meters, given the need for effective assurance that the primary network fuse links are maintained under the same conditions used in incident energy calculations.

Therefore, Organizations must prioritize the construction of safe electrical installations, adopting collective control measures with design requirements that follow the hierarchy of control measures prescribed in NR10 and NR1. Today, new technologies are available that enable such a paradigm shift, particularly concerning incident energy reduction.

As for the use of PPE as a control measure, this is an intrinsic and applicable requirement in activities involving LV energy meters, where professionals are inherently exposed to electric shock and arc flash risks. Thus, they must mandatorily use specific and adequate PPE.

Specifically for arc flash protection, any professional performing interventions in LV energy meters, positioned within the Safe Approach Limit (LAS), must use PPE specifically designed for arc flash protection according to the calculated incident energy level. This includes, beyond AR clothing, the mandatory use of PPE for face protection.

It is essential to emphasize that the incident energy level in LV energy meters is primarily determined by the characteristics of the primary network fuse links, since, with few exceptions, there are no automatic switching devices in the LV secondary networks or in the circuits upstream of the energy meter. This condition requires continuous monitoring of the practices adopted by professionals in distribution utilities to ensure that fuse links are maintained as originally used in the incident energy calculations. Otherwise, the actual characterized risk level may change—especially when the control measure relies solely on the use of PPE.

Operational procedures prevailing in most Organizations—except in a few cases—intrinsically increase exposure to possible arc flash occurrences, particularly during the removal of energy meters involving handling of energized input conductors.

It is necessary to reassess these work procedures, which are currently based on Administrative and Organizational control measures, and which rely on humans to ensure effective risk control. Continuous training of professionals is therefore an intrinsic requirement for the actual effectiveness of the adopted procedures.

Evidence shows a lack of awareness among some professionals regarding the real arc flash risk exposure. Furthermore, NR10 training courses currently provided are inadequate and insufficient as effective control measures.

It is therefore necessary that operational training courses, and especially NR10 courses, be customized to reflect real working conditions in activities involving LV energy meters, and that they be taught by professionals with proven proficiency in this field.

Finally, it is critical that Organizations shift the paradigm: the design of electrical installations must prioritize collective control measures with engineering requirements that minimize professional exposure to the Hazard of Electricity, and consequently to arc flash risk.

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A Transformação da NR-10: Rumo A Um Modelo De Gestão Integrada Do Risco Elétrico No Brasil

Glauber Maurin
Eletro Alta Engenharia
Ribeirão Preto SP, Brasil
maurin@eletroalta.com.br

Resumo - A segurança elétrica no trabalho no Brasil é regida pela NR-10. Embora a revisão de 2004 tenha sido um marco, os indicadores permanecem desfavoráveis: entre 2013 e 2024, as mortes por choque elétrico cresceram mais de 28%, frente a um aumento populacional de 5,8%, evidenciando a limitação de um modelo prescritivo e centrado em documentação. Este artigo apresenta um diagnóstico crítico das fragilidades estruturais da NR-10 e uma comparação com referenciais internacionais (OSHA/NFPA 70E, EN 50110, CSA Z462), apoiada em estatísticas nacionais e em duas décadas de inspeções industriais. Propõe-se a transição para um Sistema de Gestão do Risco Elétrico (SGRE) alinhado à NR-1 (GRO/PGR) e à ISO 45001, com quatro eixos: (i) PIE digital integrado ao eSocial para fiscalização preditiva orientada por dados; (ii) programas corporativos obrigatórios — PTE, LOTO e análise de arco elétrico; (iii) eliminação da categoria "capacitado", reconhecendo apenas qualificado e habilitado, com autorização vinculada à competência comprovada; e (iv) força vinculante às normas ABNT NBR, admitindo normas internacionais mais protetivas. Conclui-se que a modernização proposta migra da conformidade formal para a gestão por resultados, com potencial de reduzir substancialmente os acidentes elétricos ocupacionais no país.

Palavras-chave - NR-10; segurança elétrica; gestão de riscos; SGRE; PIE digital; eSocial; LOTO; PTE; arco elétrico (arc-flash); ISO 45001; ISO/IEC 17024; ABNT NBR; conformidade; governança; fiscalização preditiva.

I. INTRODUÇÃO

A segurança elétrica no ambiente de trabalho é um pilar fundamental para a integridade física dos trabalhadores e a sustentabilidade das operações industriais. No Brasil, a Norma Regulamentadora nº 10 (NR-10) [4] é o principal instrumento legal que rege os requisitos e condições mínimas para a segurança em instalações e serviços com eletricidade. Embora a NR-10, revisada em 2004, tenha sido um marco para a segurança elétrica, o setor elétrico brasileiro passou por transformações profundas impulsionadas pela inovação tecnológica, sua efetividade é questionável, passadas duas décadas. Entre 2013 e 2024, as mortes por choque elétrico cresceram mais de **28%**, [1]. enquanto a população aumentou apenas **5,8%** [2], com a taxa de fatalidades passando de 3,05 para 3,57 por milhão [1], [2] — sinal inequívoco de modelo estático com baixa efetividade.

Fig. 1. - Choque elétrico – série histórica (2013 – 2024). Fonte: Abracopel

A. *Histórico, Avanços e Fragilidades*

A revisão da NR-10 em 2004 [4] trouxe avanços inegáveis, introduzindo ferramentas importantes como o Prontuário das Instalações Elétricas (PIE) e a obrigatoriedade de treinamentos, o que incorporou a segurança elétrica ao cotidiano das operações industriais. Contudo, essa estrutura, que mistura requisitos de gestão com um núcleo prescritivo de detalhes técnicos, gerou uma fragilidade intrínseca. Faltou uma arquitetura de gestão dinâmica que assegurasse atualização contínua, auditorias e aprendizado organizacional [17].

B. *O Paradoxo da Defasagem*

Duas décadas após sua revisão, a NR-10 evidencia uma defasagem preocupante. Enquanto o cenário global testemunhou uma revolução tecnológica com a proliferação de sistemas fotovoltaicos, baterias de armazenamento (BESS), usinas eólicas, veículos elétricos e digitalização em larga escala, a NR-10 permaneceu estática, preservando um modelo de meios em vez de resultados. Em contraste, referências internacionais como a OSHA (29 CFR 1910) [13] e NFPA 70E® [11] nos EUA, a EN 50110 [12] na Europa e a CSA Z462 [14] no Canadá, avançaram significativamente, incorporando metodologias modernas de gestão de risco

elétrico. O resultado é um paradoxo regulatório: o Brasil possui normas técnicas atualizadas (NBR 16384, NBR 17227, NBR 5419), mas a NR-10 não lhes confere força normativa suficiente, limitando a aplicação efetiva e verificável.

Este artigo propõe uma mudança de paradigma: adotar uma gestão dinâmica e sistêmica do risco elétricos alinhada à NR-1 (GRO/PGR) [5] e às melhores práticas internacionais. Experiências de outros países demonstram que a combinação de gestão de riscos, certificação profissional e fiscalização baseada em dados reduz fatalidades em mais de **70%** [20]. Para o Brasil, recomenda-se: (i) digitalizar o Programa de Gestão do Risco Elétrico (PGRE) e integrá-lo ao eSocial com responsabilidade técnica pela implantação, gestão e resultado; (ii) exigir maior qualificação profissional; e (iii) conferir maior força jurídica às normas técnicas da ABNT, aceitando referências internacionais mais protetivas. Menos papel, mais desempenho: gestão dinâmica, resultados mensuráveis.

II. Essência do Problema: Sintomas e Evidências das Falhas na NR-10

O aumento consistente de acidentes elétricos nas últimas duas décadas, registrado pelos anuários da Abracopel e estatísticas do Ministério Público do Trabalho (MPT) [1], [3], evidencia que a NR-10 [4] falha não por omissão textual, mas por **não conseguir transformar requisitos em gestão eficaz.** A norma prescreve o "**como fazer**", mas não assegura que o feito seja dinâmico, auditável e retroalimentado, resultando em formalismo normativo com baixo impacto real na redução de acidentes. **Formalismo normativo não salva vidas; governança por resultados, sim.**

Nossa experiência de mais de 20 anos em inspeções industriais e a literatura especializada confirmam deficiências estruturais e problemas crônicos na aplicação da NR-10, que persistem e colocam vidas em risco [18]. Estes achados, que caracterizam o Paradoxo Brasileiro, reforçam a percepção de que a norma, em seu formato atual, produz burocracia técnica, sem a efetividade esperada na prevenção de acidentes.

A. Principais Falhas e Achados Crônicos

Ao permanecer em modelo estático, a NR-10 gera papel e não gestão de risco mensurável nem segurança real [17]. O caminho não é ampliar listas de requisitos, mas adotar um paradigma de gestão integrada.

Entre as falhas mais recorrentes, destacam-se:

- **PIE Desatualizado e Ineficaz**: O Prontuário das Instalações Elétricas (PIE), concebido como memória técnica dinâmica em 2004, encontra-se frequentemente desatualizado. Relatórios de SPDA [9], ensaios de isolação e registros de manutenção não são sistematicamente incorporados ou revisados. Esquemas unifilares permanecem inacessíveis aos eletricistas no momento da intervenção, aumentando o risco de seccionamento incorreto e falhas de bloqueio e na grande maioria o Cronograma de Adequações com status em branco!
- **Procedimentos no Papel, sem Treinamento Real**: Empresas possuem procedimentos e instruções elaborados principalmente para auditorias externas, sem internalização pelos eletricistas. Treinamentos de integração são genéricos, receituário repetido e superficiais, não abordando riscos elétricos específicos do local de trabalho, o que cria uma falsa sensação de conformidade.
- **APR e PTE Genéricas**: Análises Preliminares de Risco (APR) e Permissões de Trabalho (PTE) são frequentemente padronizadas e copiadas, sem considerar as especificidades do local, como fronteiras de zona de risco, energias armazenadas ou fontes reversas.
- **Ausência de LOTO Estruturado**: Um dos maiores déficits é a falta de programas corporativos robustos de Lockout–Tagout (LOTO), sem requisitos claros para inventário de fontes de energia, responsabilidades definidas ou auditorias. Muitas instalações não estão "*LOTO-ready*", levando à improvisação [13].
- **Formação Baseada em Certificados**: A NR-10 [4], ao vincular a "**autorização**" a certificados de treinamentos formais sem exigir competência acreditada **[15]**, abriu espaço para um mercado de certificados sem avaliação prática ou aprendizado real. A falta de mão de obra qualificada leva ao improviso.
- **Instalações Inadequadas e Conflito Prescritivo**: A condição das instalações elétricas reflete o fracasso do modelo atual, com soluções superficiais (proteções de policarbonato, etiquetas de advertência) que criam uma aparência de conformidade sem eliminar riscos estruturais, como seletividade deficiente, SPDA [9] precário e painéis obsoletos. Máquinas e equipamentos ainda possuem comandos acima de 50V [8].
- **Qualidade dos Materiais Elétricos**: Um fator externo preocupante é a qualidade dos materiais elétricos no mercado brasileiro, com cerca de **74%** dos fios e cabos elétricos comercializados sendo irregulares e contendo menos cobre do que o especificado, o que aumenta o risco de superaquecimento e incêndios. Produtos importados da China sem certificação aprovação normativa [22].
- **Subnotificação de Incidentes**: A ausência de uma cultura de retroalimentação e aprendizado organizacional impede a melhoria contínua, fazendo com que erros se repitam. Registros do MPT indicam acidentes elétricos persistentemente entre as principais causas de mortes ocupacionais. **[3]**.

As estatísticas reforçam que essas falhas não são incidentes isolados, mas a expressão de um modelo normativo equivocado que gera burocracia, e não segurança.

III. Referenciais Internacionais e Governança

A análise comparativa de referenciais internacionais é essencial para compreender como diferentes países estruturam a segurança elétrica ocupacional [18],[19]. Enquanto o Brasil mantém um modelo prescritivo estático desde 2004, países líderes evoluíram para sistemas baseados em gestão, com ciclos regulares de revisão, reporte compulsório de acidentes e programas corporativos auditáveis.

A. Abordagens de Segurança Elétrica em Países Líderes

- **Estados Unidos** – OSHA (29 CFR 1910) [13] e NFPA 70E®: A OSHA exige locais de trabalho livres de perigos reconhecidos e referência normas técnicas de consenso como a NFPA 70E® [11], revisada a cada três anos. Seus elementos-chave incluem programas

corporativos de LOTO [13] (29 CFR 1910.147), estudos de energia incidente (Arc Flash) com atualização periódica (NFPA 70E, Art. 130.5), treinamentos baseados em desempenho e a definição de "pessoa qualificada" com comprovação prática de competência. Resultados da ESFI (2021) mostram uma redução superior a 70% nas fatalidades ocupacionais por choque elétrico entre 1992 e 2020 [20].

- **Reino Unido** – HSWA (1974), EAWR e RIDDOR [21] (2013): O HSWA impõe proteção "tanto quanto razoavelmente praticável". A técnica é delegada ao HSE (Health and Safety Executive), que publica códigos de prática (ACoP) com força quase legal. O RIDDOR [21] torna obrigatório o reporte de fatalidades, lesões graves e quase-acidentes, e o HSE publica análises anuais, fechando o ciclo PDCA. O HSE reporta que choques elétricos representam menos de 2% das fatalidades ocupacionais.
- **União Europeia** – EN 50110-1: Esta norma define papéis formais de responsabilidade (responsável pela instalação, pela operação, pessoa autorizada) e estabelece distâncias numéricas de segurança para cada nível de tensão, integrando-se com normas IEC específicas. Países como Alemanha e França registram menos de 30 mortes elétricas anuais.
- **Canadá** – CSA Z462 [14]: Baseada na NFPA 70E [11], a CSA Z462 integra a segurança elétrica a um sistema de gestão ocupacional mais amplo (CSA Z1000). Exige estudos de arco, etiquetagem, LOTO [13] e reciclagem baseada em desempenho. Relatórios da ESA Ontario indicam menos de 40 mortes anuais.
- **Japão e Suécia**: Relatórios indicam que choques elétricos representam menos de 1% dos acidentes fatais, destacando a importância da cultura e governança.

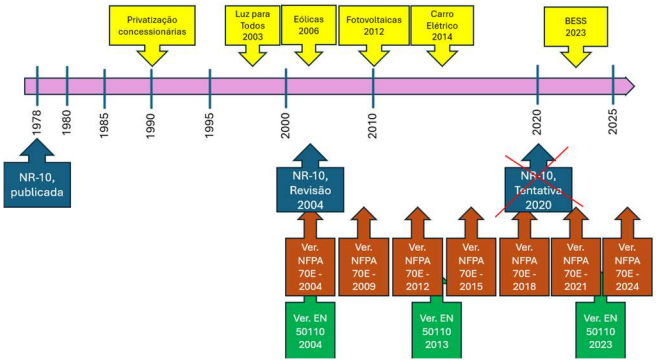

Fig. 2. Linha do Tempo Evolução das Normas Internacionais.

B. *Síntese Comparativa de Governança e Processos de Revisão*

A síntese dessas práticas internacionais demonstra que nenhum país líder mantém um modelo prescritivo estático. Todos utilizam normas de gestão obrigatórias, delegam os aspectos técnicos a organismos especializados (como NFPA, CSA, CENELEC, IEC), possuem programas corporativos auditáveis (LOTO, Arc Flash, PIE digital), exigem reporte compulsório de acidentes e quase-acidentes e qualificam profissionais com base em competência prática e certificações reconhecidas. A persistência dos acidentes elétricos no Brasil decorre de uma falha estrutural: a NR-10/2004 define requisitos mínimos e depende de gestão dinâmica e atualização contínua para ser efetiva, mas essa governança não se consolidou.

O processo de revisão no Brasil é lento e pouco técnico, centrado em negociações tripartites, sem resposta compatível com a velocidade tecnológica. Essa estrutura privilegia negociação política e consenso social, mas frequentemente carece de profundidade técnica e agilidade frente à inovação tecnológica [23]. Em contraste, normas como a NFPA 70E [11] e a CSA Z462 [14] seguem ciclos fixos de três anos; a EN 50110-1 adota ciclos de cinco a sete anos, garantindo alinhamento rápido com o estado da arte. A experiência internacional demonstra que uma segurança eficaz se apoia em normas finalísticas, responsabilidade legal clara, indicadores de desempenho e aprendizado organizacional (investigação e reporte).

C. *Conexão com a Realidade Brasileira*

O Brasil permanece focado em "**meios**" (checklists e modelos prontos) e não em "**resultados**". A NR-1 já migrou para a lógica de gestão (GRO/PGR) [5]; a convergência da NR-10 é tecnicamente viável e juridicamente compatível. A prioridade é gestão: papéis, responsabilidades, evidências, indicadores, auditorias e integração PIE-digital/eSocial. **Insistir em listas prescritivas sem prova de eficácia é um risco.**

IV. Proposta de Adequação da NR-10

A proposta de adequação da NR-10 [4] visa transformá-la de uma norma prescritiva em um modelo de gestão integrada do risco elétrico (SGRE), alinhado à NR-1 (GRO/PGR) [5] e às melhores práticas internacionais de sistemas de gestão de segurança e saúde ocupacional, como a ISO 45001[16]. O objetivo é assegurar uma gestão proativa, auditável e continuamente aprimorada da segurança elétrica no Brasil. De modelo estático a abordagem sistêmica: segurança que se verifica em campo.

10.1 OBJETIVO E CAMPO DE APLICAÇÃO

10.1.1 Objetivo

Esta NR estabelece requisitos e condições mínimas de segurança e saúde para quem interage em instalações elétricas e serviços com eletricidade. Visa implementar medidas de controle e sistemas preventivos para eliminar perigos e controlar riscos, em todo o ciclo de vida: projeto, construção, montagem, operação, manutenção, desativação e desmonte.

10.1.2 Campo de aplicação

Aplica-se à geração, transmissão, distribuição, consumo **e armazenamento de energia** elétrica. Abrange trabalhos nas proximidades de instalações elétricas, elétricos ou não.

10.1.3 Integração com a NR-01 (GRO/PGR)

A aplicação desta NR é integrada e obrigatória com a NR-01. O Sistema de Gestão do Risco Elétrico (SGRE) é parte do PGR. A NR-10 é o pilar jurídico da gestão do risco elétrico, articulando inventário de perigos, avaliação de riscos e plano de ação.

10.2 COMPETÊNCIA, QUALIFICAÇÃO E AUTORIZAÇÃO

10.2.1 Requisitos gerais:

10.2.1.1 **BA1 (pessoa comum**) – não trabalha com eletricidade: executa apenas operações de ligar/desligar em baixa tensão por interfaces usuais e protegidas (botoeiras, IHM, comandos selados), sem abrir invólucros, sem exposição a partes vivas; atua somente em zona livre.

10.2.1.2 **BA4 (pessoa instruída**): treinada para reconhecer perigos e manter distância; atua exclusivamente em instalações desenergizadas ou zona livre; vedado medir/testar tensão ou intervir em zona de controle/risco. Quando designada como acompanhante-socorrista, deve possuir treinamento em primeiros socorros e plano de emergência aplicável.

10.2.1.3 **BA5 (pessoa qualificada)** - profissional com diploma de curso de formação elétrica reconhecido pelo MEC (técnico ou superior), com carga mínima de 750 horas-aula e registro do curso no cadastro e-MEC; submetido a avaliação prática e entrevista técnica internas. Pode atuar, mediante autorização formal, em zona de controle e zona de risco, observadas as demais exigências desta NR (incluindo PTE, LOTO e EPC/EPI conforme estudo).

10.2.1.4 **Profissional habilitado**: profissional com registro ativo em CREA/CRT, quando exigido por lei; habilitação não substitui a competência operacional (BA5) para atuação em zonas de controle/risco; quando ambos forem exigíveis, o atendimento é cumulativo.

10.2.1.5 **Trabalhador autorizado**: pessoa BA1/BA4/BA5, designada formalmente pelo empregador ou RT.

10.2.2 Formação e evidências mínimas (BA5)

a) Diploma de curso reconhecido pelo MEC (e-MEC),

b) Histórico ou ementa que comprove a carga horária elétrica com mínimo de 750 horas-aula em conteúdos de eletrotécnica/eletricidade (ex.: fundamentos elétricos, máquinas/equipamentos, proteção, instalação, segurança elétrica).

c) Avaliação prática e entrevista técnica documentadas pela organização pré-autorização.

d) Treinamento de Reciclagem e revalidação da autorização conforme políticas do SGRE (recomendado ciclo trienal ou diante de mudanças relevantes).

10.2.3 Limites por zona e tipo de tarefa:

a) BA1: zona livre; vedado acesso a zona de controle/risco; vedado abrir painéis, medir/testar ou intervir em circuitos.

b) BA4: zona livre e instalações desenergizadas com prova de ausência de tensão (seccionamento, impedimento de reenergização, verificação, aterramento, proteção adjacente); vedado atuar em zona de controle/risco.

c) BA5: zona de controle e zona de risco, mediante autorização; trabalho energizado e proximidade somente com PTE, APR elétrica, LOTO, estudos (curto-circuito/coordenação e energia incidente) e EPC/EPI compatíveis.

10.2.4 Escopo e validade da autorização: Autorização é pessoal, intransferível e limitada ao escopo definido com a atividade, local e instalação, zona e prazo definidos.

10.2.5 Atualização, reciclagem e avaliação prática:

a) Autorização e treinamentos devem ser renovados em no mínimo de 3 (três) anos.

b) A reciclagem será antecipada sempre que ocorrer mudança de empregador ou mudança de função, bem como em alterações tecnológicas, de processo, método ou instalação que impactem o risco.

c) Revisão de procedimento: treinamento formal no posto de trabalho (OJT – On-the-Job Training) a cada nova versão, com registro de: data, versão do procedimento, conteúdo ministrado, instrutor responsável, participantes e avaliação de proficiência. Deve-se repetir os treinamentos de procedimentos sempre que algum desvio, incidente ou acidente for identificado.

d) A autorização exige avaliação prática independente e entrevista técnica pré-liberação; sua manutenção fica condicionada à proficiência demonstrada nas reciclagens e nos treinamentos OJT.

e) Todos os registros (renovações, reciclagens, OJT, avaliações e decisões de autorização) devem ser arquivados no PIE: atualização, certificados e avaliação prática

10.2.6 Matriz de autorização por zona e tarefa

A organização deve manter matriz de autorização que identifique, por pessoa, as tarefas e a zona (livre, controle, risco) para as quais está autorizada, com o respectivo lastro de habilitação/autorização.

10.2.7 Contratantes e contratadas

Firmar acordo formal de interface, registrado no PIE, assegurando equivalência de requisitos de segurança. A autorização de trabalhadores terceirizados deve ser emitida por profissional habilitado responsável pela contratada, com anuência formal da contratante. A autorização formalizada pelo RT contratada com devida ART, validando as exigências de formação e competência do item 10.2.2, sem prejuízo dos requisitos legais de habilitação e dos controles operacionais aplicáveis.

10.2.8 Harmonização regulatória

Quando a atividade exigir habilitação legal (CREA/CRT), a autorização somente será emitida com a habilitação vigente. A competência operacional seguirá o 10.2.2 (formação reconhecida pelo MEC com $\geqslant$ 750 horas-aula, avaliação prática e entrevista técnica). A competência operacional será comprovada exclusivamente pelos requisitos do 10.2.3, vedada a exigência de certificações acreditadas não disponíveis para o escopo. Todas as evidências devem constar no PIE.

10.3 SISTEMA DE GESTÃO DO RISCO ELÉTRICO (SGRE)

10.3.1 Estabelecimento do SGRE

A organização deve estabelecer, documentar e implementar o SGRE como parte do PGR. O SGRE deve ser proativo, auditável e de melhoria contínua.

10.3.2 Trabalho desenergizado como regra geral

O trabalho deve ser realizado, como regra, em condição desenergizada. O estabelecimento da condição segura inclui: seccionamento, impedimento de reenergização, verificação de ausência de tensão, aterramento e proteção contra partes adjacentes energizadas.

10.3.3 Exceções ao trabalho desenergizado

Trabalho energizado somente quando:

a) tecnicamente inviável desenergizar; ou

b) a desenergização introduzir riscos adicionais inaceitáveis.

Nesses casos, é obrigatória Permissão de Trabalho Energizado (PTE), com justificativa técnica e análise de risco específica.

10.3.4 Hierarquia de controles

1) Eliminação;

2) Substituição;

3) Controles de Engenharia (EPC);

4) Medidas Administrativas; 5) EPI.

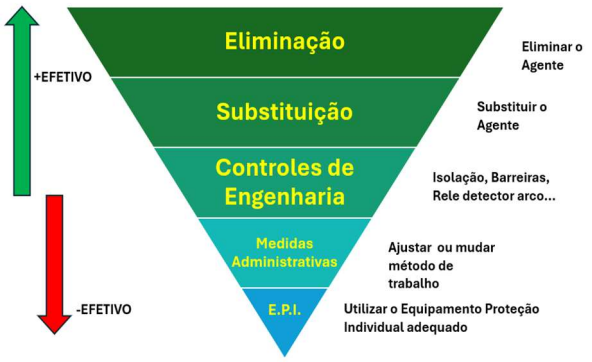

Fig. 3. Hierarquia de Controle do Risco

10.3.5 Metas e indicadores

O SGRE deve possuir metas e indicadores mensuráveis de eficácia e eficiência.

10.3.6 Investigação e melhoria contínua

Todos os incidentes, inclusive sem afastamento, devem ser registrados, investigados e analisados. Devem ser especificadas as causas e as medidas adotadas para evitar a reincidência. Resultados alimentam o SGRE.

10.3.7 Auditorias e revisão pela alta direção

Devem ocorrer auditorias periódicas do SGRE, com relatório e plano de ação. A alta direção deve realizar revisão anual, deliberar recursos e metas, e registrar as decisões em ata no PIE.

10.4 DOCUMENTAÇÃO E PRONTUÁRIO (PIE)

10.4.1 Organização e formato

O PIE deve ser constituído, organizado e atualizado pelo empregador ou RT, em formato físico, digital ou híbrido, garantindo integridade, rastreabilidade e disponibilidade.

10.4.2 Acesso e custódia

O PIE permanece sob custódia do Responsável Técnico (RT). O acesso é:

a) seletivo a trabalhadores autorizados, limitado ao necessário à tarefa;

b) integral à fiscalização;

c) restrito a certificados pessoais e dados sensíveis, conforme lei.

10.4.2.1 Estruturas com múltiplos RTs

Quando houver mais de um RT, a empresa deve designar um RT Coordenador (RTC) para a custódia central do PIE e definir RTs Delegados por área ou instalação. O Plano de Custódia e Acesso ao PIE deve:

I) indicar papéis (RTC, Delegados, Gestor documental);

II) definir matriz de acesso por papel/função;

III) prever substituições e continuidade operacional.

10.4.2.2 Controle de acesso e registros

A fim de garantir a proteção de dados pessoais (LGPD), os documentos do PIE com informações pessoais terão acesso restrito ao Responsável Técnico (RT), gestores designados e auditorias, ficando aos demais usuários apenas o acesso às informações estritamente necessárias à execução de suas tarefas.

10.4.3 Conteúdo mínimo

a) Procedimentos e instruções técnicas e administrativas implantados e medidas de controle.

b) Inspeções e medições de SPDA e aterramentos, quando aplicável.

c) Especificações de EPC, EPI e ferramental.

d) Registros de qualificação, habilitação, autorizações e treinamentos.

e) Resultados de testes de isolação de EPC/EPI, ferramentas e dispositivos.

f) Certificações de equipamentos e materiais elétricos em áreas classificadas.

g) Relatórios técnicos de inspeções com não conformidades e plano de adequação (periodicidade máxima: 3 anos).

h) Diagramas unifilares e projetos as built atualizados, incluindo aterramento, dispositivos de proteção, cabos e indicação do nível de energia incidente.

i) Estudos de curto-circuito, coordenação/seletividade e energia incidente (Arc Flash) e especificação de vestimentas e EPI adequados.

j) Inventário de energias perigosas, pontos de inserção de LOTO e especificação dos dispositivos de bloqueio/etiquetagem.

k) Atas e deliberações da alta direção sobre o SGRE (análise crítica, decisões e acompanhamento).

l) ART/CRT/TRT para projetos, documentos técnicos do PIE e serviços elétricos, com comprovante de pagamento.

10.4.4 Prazo de atualização

Atualizar o PIE em até 30 dias úteis após evento ou modificação relevante.

10.4.5 Condição impeditiva (GIR)

Caracteriza GIR executar serviços sem diagramas atualizados ou sem identificações, sem procedimento ou

desatualizado e informações essenciais à comunicação segura (etiquetas de circuito, mapa de painéis, lista de cargas, registros de inspeção), quando necessários à tarefa.

10.5 PROGRAMAS CORPORATIVOS OBRIGATÓRIOS

10.5.1 PTE — Permissão de Trabalho Energizado

É proibida intervenção energizada sem PTE formal prévia. A PTE deve conter: justificativa técnica, APR específica de perigos elétricos, teste de comunicação (10.7.3), matriz de autorização (10.2.5) e **checklist** de condição desenergizada quando aplicável. PTEs devem ser auditadas com periodicidade definida no SGRE. Aprovador responsável técnico pela atividade.

10.5.2 LOTO — Bloqueio e Etiquetagem

Implementar programa corporativo de LOTO com inventário de pontos de energia, procedimentos por sistema e auditoria amostral trimestral e anual completa.

10.6 MEDIDAS DE PREVENÇÃO ESPECÍFICAS

10.6.1 Proteção coletiva (EPC)

a) Choque elétrico: isolação de partes vivas, barreiras/invólucros, colocação fora do alcance, limitação de tensão e seccionamento automático conforme normas técnicas.

b) Arco elétrico: componentes resistentes a arcos, abertura sob carga, chave de aterramento resistente a curto-circuito, intertravamentos, fechaduras com chaves não intercambiáveis, limitadores de corrente, tempos de interrupção curtos e operação a distância segura conforme LAS definido pelo estudo de energia incidente (IEEE 1584/NFPA 70E).

c) Explosão: prevenção de ignição e uso de equipamentos avaliados no SBAC ou ATEX. Controlar eletricidade estática com dispositivos de descarga.

d) Sobretensões e descargas atmosféricas: conforme normas técnicas oficiais.

10.6.2 Proteção individual (EPI)

a) Adotar EPIs específicos e adequados, com base em análise de risco.

b) EPI é estritamente pessoal. É vedado o compartilhamento.

c) Vestimentas devem considerar condutibilidade, inflamabilidade e campos EM. A especificação deve considerar os efeitos térmicos do arco e do fogo repentino, segundo Anexo IV e os estudos de energia incidente.

d) É vedado o uso de adornos pessoais durante trabalhos energizados ou em proximidade.

Nota: É possível o empréstimo controlado de itens não ajustáveis e não íntimos apenas em emergência, com higienização/ensaio (evita travar a operação em contingência).

10.6.3 Comandos em tensão segura

Máquinas e equipamentos devem possuir comandos em extrabaixa tensão (<50 Vca ou <130 Vcc, ou SELV/PELV conforme norma técnica).

10.6.4 Plano de Manutenção Elétrica (PME) — requisitos mínimos (novo)

O PME deve conter, no mínimo:

I) cadastro de ativos e criticidade;

II) periodicidades e escopo de inspeções/ensaios (incluindo proteções e intertravamentos);

III) SPDA e aterramentos conforme normas técnicas;

IV) termografia de painéis e conexões críticas;

V) critérios de aceitação/rejeição;

VI) responsáveis, prazos e registros de execução.

10.7 TRABALHOS ENERGIZADOS E PROXIMIDADE

10.7.1 Requisitos de pessoal

Serviços com exposição ⩾ 50 Vca ou ⩾ 130 Vcc somente por profissionais que atendam aos requisitos do item 10.2.

10.7.2 Trabalho em equipe (SEP e MT)

Serviços > 1000 Vca e 1500 Vcc, trabalhos em proximidade e serviços no SEP não podem ser executados individualmente.

Nota: exceção para manobras remotas/telecomando fora de zona de risco.

10.7.3 Comunicação

Em MT, SEP e proximidade, a equipe deve dispor de comunicação permanente com redundância de canal de comunicação (ex.: rádio full-duplex com repetidor, telefonia ou satélite). A empresa deve testar a comunicação antes do início do serviço e registrar o teste na PTE.

10.7.4 Religamento automático

Serviços dentro da zona de risco exigem desativação/bloqueio de dispositivos de religamento automático, com sinalização inequívoca.

10.7.5 Check-in/Check-out operacional

Serviços em MT, SEP e proximidade devem adotar check-in no início e check-out ao término, com registro do canal de comunicação e do responsável de operação.

10.8 MONITORAMENTO, AUDITORIAS E MELHORIA

10.8.1 Indicadores mínimos obrigatórios

a) % de documentos do PIE atualizados (eficiência).

b) Número e gravidade de não conformidades (eficácia).

c) % de cumprimento do cronograma de adequações (eficiência).

d) Taxa de notificação de incidentes, quase-acidentes e acidentes (eficácia).

e) % de estudos de energia incidente e etiquetagem atualizados (⩽ 5 anos ou após modificações) (eficácia).

f) % de LOTO auditado e deficiências por auditoria (eficiência).

g) % de metas do SGRE/PGR cumpridas (eficácia global).

10.8.2 Auditorias internas

Auditar o SGRE em ciclos definidos pela organização, nunca superiores a 12 meses. Abranger documentação, práticas, LOTO e estudos de risco.

10.8.3 Revisão pela alta direção (ajustado)

A revisão anual deve analisar os indicadores do 10.8.1, deliberar recursos e prioridades e determinar prazos e responsáveis. Registrar ata no PIE.

10.9 RESPONSABILIDADES

10.9.1 Empregador

Implementar o SGRE. Prover recursos. Manter o PIE atualizado. Garantir auditorias. Assegurar que apenas profissionais qualificados e autorizados atuem em zonas de controle e de risco.

10.9.2 Responsável Técnico (RT)

Aprovar procedimentos e PTE. Custodiar o PIE. Validar estudos, especificar medidas de controle. Garantir conformidade técnica.

10.9.3 Gestor do SGRE

Coordenar indicadores. Consolidar relatórios de desempenho. Supervisionar auditorias internas e externas.

10.9.4 SESMT

Apoiar tecnicamente a execução. Verificar medidas de prevenção. Não substitui o RT. Integrar-se ao RT em reciclagens, indicadores e auditorias.

10.9.5 Supervisores

Assegurar equipes competentes e autorizadas. Verificar validade de certificações e autorizações.

10.9.6 Trabalhadores

Cumprir procedimentos. Usar corretamente EPC/EPI. Respeitar limites de autorização. Reportar incidentes e não conformidades.

10.9.7 Contratantes e contratadas

Firmar acordo formal de interface, registrado no PIE, assegurando equivalência de requisitos. A contratada emite a autorização por profissional habilitado, com anuência formal da contratante.

10.10 GRAVE E IMINENTE RISCO (GIR)

10.10.1 Situações de GIR (embargo/interdição)

a) Inexistência de PTE ou LOTO aplicável, ou trabalho energizado sem PTE/EPI especificado.

b) Não observância da sequência de desenergização/reenergização prevista nesta NR.

c) Atividade por trabalhador em desacordo com os requisitos do item 10.2.

d) Execução individual de serviços vedados pelo item 10.7.2.

e) Ausência de ensaios e testes de isolação de EPI/EPC, ferramentas e dispositivos.

f) Ausência do Plano de Manutenção Elétrica (PME) ou não execução comprovada do PME com índice de cumprimento inferior a 75% no último semestre para itens de segurança crítica (proteções, SPDA, aterramentos, intertravamentos). (substitui a alínea original)

g) Ausência do estudo de energia incidente do arco elétrico.

10.11 DISPOSIÇÕES FINAIS

10.11.1 Direito de recusa

O trabalhador deve interromper a tarefa diante de risco grave e iminente e comunicar de imediato ao superior, que adotará as medidas cabíveis.

10.11.2 Fiscalização

O descumprimento desta NR sujeita a organização às providências da NR-03.

10.12 DISPOSIÇÕES TRANSITÓRIAS

10.12.1 A empresa terá até 6 meses para adequar competência/autorização (Cap. 10.2).

10.12.2 Adoção do PME (10.6.4) em até 12 meses.

10.12.3 Implementação do Plano de Custódia e Acesso ao PIE (10.4.2.1) em até 6 meses.

10.12.4 As exigências de comunicação permanente (10.7.3) e check-in/check-out (10.7.5) entram em vigor em 90 dias.

V. Discussões

A NR-10/2004 [4], embora tenha representado um marco regulatório, não acompanhou as transformações tecnológicas e organizacionais das últimas duas décadas. Normas centradas em meios tendem a produzir formalismo normativo, não resultados operacionais, sem assegurar eficácia real na gestão de riscos. Isso se reflete nos dados de acidentes elétricos, que cresceram significativamente. O problema não é a ausência de regras, mas a falha de essência de um modelo que produz papel, mas não gestão dinâmica com retroalimentação.

A. O Paradoxo Brasileiro e a Força Jurídica das Normas Técnicas

O Brasil dispõe de um acervo robusto de normas técnicas atualizadas, como: NBR 16384:2022 [6] – Gestão de Riscos Elétricos; NBR 17227:2023 – Arc Flash [7]; NBR 5419:2015 – SPDA [9]; NBR IEC 60079 sobre Áreas Classificadas.

Apesar disso, a NR-10/2004, em seu item 10.1.2, ainda emprega a redação:

"... trabalhos realizados nas suas proximidades, observando-se as normas técnicas oficiais estabelecidas pelos órgãos competentes e, na ausência ou omissão destas, as normas internacionais cabíveis."

O problema reside no termo "**observando-se**", que sugere mera recomendação. Para garantir segurança efetiva, a redação deveria impor caráter obrigatório, substituindo por:

"Todas as instalações e serviços em eletricidade devem obedecer obrigatoriamente às normas da ABNT."

E, de forma complementar:

"Na ausência de norma brasileira, ou quando houver norma internacional reconhecida que proporcione maior nível de proteção ao trabalhador, admite-se a sua aplicação (IEC, NFPA, IEEE, EN, entre outras)."

Neste cenário, o Responsável Técnico (RT) teria o dever de justificar a escolha normativa e registrar formalmente no PIE digital a norma adotada em cada caso.

Atualmente, a NR-10 não confere às normas técnicas força vinculante suficiente. Assim, o país permanece em uma contradição: possui conhecimento técnico disponível para reduzir acidentes, mas carece de instrumento jurídico que obrigue sua aplicação.

Em contraste, Estados Unidos, Reino Unido e Canadá integram normas técnicas de consenso ao arcabouço legal, estabelecendo o dever de resultado. Isso significa que a conformidade material, ancorada em desempenho seguro comprovado.

Portanto, uma nova NR-10 deve:

- Conferir primazia às NBRs da ABNT;
- Permitir a adoção de normas internacionais (IEC, NFPA, IEEE, EN) quando estas forem mais protetivas;
- Exigir do RT o registro formal no PIE digital da norma aplicada, assegurando rastreabilidade e responsabilidade técnica.

Essa diretriz está em convergência com a *New Approach Directive* da União Europeia e com a prática da OSHA (EUA) [13], que reconhece normas de consenso como prova de conformidade técnica e jurídica.

B. Implicações Práticas da NR-10 de Gestão Integrada

A adoção de uma NR-10 de gestão integrada implica em mudanças significativas:

- **Cultura organizacional**: Deslocar o foco do cumprimento formal para a gestão efetiva de riscos.
- **Fiscalização**: Avaliar não apenas documentos, mas a eficácia de programas e indicadores.
- **Sanções**: Ausência de PGRE, LOTO, PTE ou PIE atualizado deve configurar Grave e Iminente Risco (GIR), com interdição imediata.
- **Competência profissional**: Certificações acreditadas idealmente pela ISO/IEC 17024 [15] devem substituir capacitações meramente formais.

A NR-10 prescritiva está esgotada! O Brasil precisa migrar para um modelo de gestão integrada, vinculado ao PGR, com PIE digital vivo, indicadores auditáveis, reporte compulsório e sanções efetivas. Persistir no modelo atual significa converter riscos em estatísticas; adotar a gestão significa transformar eletricidade em energia segura para trabalhadores e sociedade.

Fig. 4. Eletricista Autorizado com EPI, Loto, Verificando ausencia de tensão.

VI. Referenciais Internacionais: Rumo a uma Norma Global de Segurança Elétrica

Dados internacionais confirmam a eficácia de modelos baseados em gestão. Nos Estados Unidos (OSHA + NFPA 70E), houve redução superior a 70% nas fatalidades elétricas ocupacionais entre 1992 e 2020, atribuída a programas de LOTO [13], estudos de energia incidente e treinamentos por competência. No Reino Unido (HSWA + RIDDOR [21]), choques elétricos representam menos de 2% das fatalidades ocupacionais, sustentado por reporte compulsório de incidentes. A União Europeia (EN 50110-1) [12] define papéis formais de responsabilidade, e países como Alemanha e França registram menos de 30 mortes elétricas anuais. No Canadá (CSA Z462) [14], a integração à CSA Z1000 garante a inserção da segurança elétrica na gestão ocupacional, resultando em menos de 40 mortes anuais. O denominador comum é inequívoco: dever de resultado, gestão corporativa auditável e reporte legal compulsório.

Em 2020, um novo comitê de projeto (PC 128) foi aceito na Comissão Eletrotécnica Internacional (IEC) para elaborar uma norma global de segurança para trabalhos elétricos. Em setembro de 2022, foi decidido que o trabalho da IEC PC 128 será baseado na norma europeia EN 50110 [12].

Os elementos-chave da EN 50110 [12] que a tornam uma base sólida incluem:

- Definição de papéis formais de responsabilidade (responsável pela instalação, responsável pela operação, pessoa autorizada).
- Distâncias numéricas de segurança para cada nível de tensão.
- Integração com normas IEC específicas.
- Foco na prevenção de arco elétrico, priorizando medidas passivas e exigindo análise de perigo de arc flash e uso de EPI em trabalhos energizados.

O objetivo inicial da IEC PC 128 é elaborar uma pré-norma ou especificação técnica (TS) que amplie a EN 50110 [12] ao incorporar boas práticas de outros países membros da IEC, garantindo que o documento não entre em conflito com as legislações nacionais existentes. Isso indica uma busca por convergência, aproveitando o que há de mais eficaz em diferentes sistemas regulatórios. Nesse processo, outras normas de segurança elétrica amplamente reconhecidas, como

a NFPA 70E dos Estados Unidos e a CSA Z462 [14] do Canadá, servem como referenciais complementares de "boas práticas".

Os princípios comuns para a segurança global, que ressaltam a necessidade da transformação da NR-10, incluem:

- Modelos baseados em gestão, não prescritivos, adaptáveis à evolução tecnológica.
- Delegação de aspectos técnicos a organismos especializados ágeis.
- Programas corporativos robustos e auditáveis (LOTO, Arc Flash, PIE digital).
- Reporte compulsório de acidentes e quase-acidentes, gerando aprendizado contínuo.
- Qualificação profissional por competência acreditada**[15]**, baseada em experiência comprovada e certificações reconhecidas.
- Ciclos regulares de revisão para rápido alinhamento com o estado da arte.

Esses princípios reforçam que a solução para os desafios da segurança elétrica no Brasil não está em adicionar mais prescrições à NR-10, mas em redefini-la como uma norma de gestão integrada, que estabeleça papéis, responsabilidades, indicadores e governança, delegando os métodos técnicos às normas da ABNT, IEC e NFPA.

VII. Governança e Fiscalização: O Papel Transformador do e-Social

A governança brasileira, baseada no tripartismo da CTPP, garante representatividade, mas carece de capacidade técnica especializada, sendo ineficiente para setores de alta complexidade técnica. Enquanto OSHA, HSE e CSA revisam normas em ciclos regulares de 3–5 anos, a NR-10 permanece há mais de 20 anos sem atualização substancial, gerando um processo de revisão lento e pouco técnico.

A. O Desafio da Fiscalização Tradicional no Brasil

Os métodos tradicionais de fiscalização da NR-10 no Brasil são predominantemente reativos, fragmentados e presenciais, com foco na verificação documental. Isso limita a cobertura e a eficácia, gerando uma "falsa sensação de conformidade" e baixa preditividade devido à ausência de registro sistemático de incidentes e quase-acidentes.

B. Proposta de Integração da NR-10 ao eSocial

A integração da NR-10 ao eSocial é vista como uma revolução na fiscalização, permitindo migrar de um modelo reativo e burocrático para um sistema proativo, transparente e orientado por evidências. Empresas de alto risco seriam obrigadas a registrar no eSocial, em formato padronizado:

- Acidentes, incidentes e quase-acidentes elétricos, com análise de causas, ações corretivas e prazos de execução.
- Cronograma de Adequações do PGRE, atualizado a cada 90 dias, com status (planejado, em andamento, concluído).
- Indicadores de eficiência e eficácia: % de adequações concluídas no prazo, % de auditorias internas realizadas, taxa de acidentes por milhão de horas-homens, entre outros.
- Evidências digitais: ARTs, laudos, relatórios técnicos e registros de treinamentos anexados ao PIE digital.

Com a estruturação desses dados no eSocial, a Auditoria Fiscal do Trabalho poderá migrar para uma fiscalização proativa e preditiva, utilizando ferramentas de big data e inteligência artificial para detecção de padrões e priorização de riscos reais. Dados, auditorias e aprendizado: o tripé da redução sustentada de acidentes.

C. Implicações Jurídicas e Sanções no Novo Modelo

A integração digital ao eSocial reforça a responsabilização jurídica, tornando as sanções mais diretas e eficazes:

- Multa automática por falta de reporte de acidentes/incidentes.
- Grave e Iminente Risco (GIR) e interdição imediata em caso de não atualização do cronograma de adequações no eSocial, ou realização de intervenções sem esquemas elétricos atualizados/acessíveis, inexistência de PTE/LOTO, equipe sem autorização válida expirada.
- Responsabilização criminal por ocultação deliberada de eventos.

Essa mudança consolida o PGRE como programa vivo, auditável e eficaz, com potencial de reduzir significativamente os acidentes elétricos no país.

VIII. Conclusões e Recomendações Finais

A análise integral deste trabalho conduz a uma constatação inequívoca: o modelo estático, baseado em listas, se esgotou [17]. A norma, concebida para um Brasil de duas décadas atrás, não acompanhou a velocidade da inovação tecnológica nem o dinamismo da gestão moderna de riscos. O "**paradoxo brasileiro**" é que, embora tenhamos normas técnicas avançadas, a NR-10 atual não lhes confere força vinculante, impedindo sua plena aplicação.

A. Pilares da Transformação

O novo modelo deve:

- Definir objetivos e exigir resultados.
- Delegar os métodos técnicos às normas da ABNT/IEC/NFPA, revisadas em ciclos regulares de 3 a 5 anos.
- Integrar-se aos sistemas digitais de fiscalização e indicadores de desempenho.

Os pilares dessa transformação são:

- **Tecnologia**: A integração ao eSocial representa uma revolução na fiscalização, permitindo auditoria baseada em dados e priorização de riscos reais em detrimento da mera verificação documental.
- **Competência**: Eliminamos a figura do “capacitado” e adotamos BA1/BA4/BA5. A **autorização** passa a exigir formação reconhecida pelo MEC (mínimo 750 horas-aula em conteúdos de eletricidade, com validação no e-MEC) e comprovação prática por prova/avaliação em campo e entrevista técnica conduzidas pelo empregador/RT, com reciclagem

periódica e matriz de autorização por zona/tarefa — competência lastreada em evidências verificáveis.

- **Migrar para gestão dinâmica e abordagem sistêmica** é reconhecer o gap estrutural e colocar vidas no centro.

B. Recomendações Finais para a Modernização da NR-10

Com base na análise das melhores práticas internacionais e nas fragilidades do modelo brasileiro, as recomendações finais para a modernização da NR-10 e a redução sustentável dos acidentes elétricos são:

1) Revisão do Artigo da NR-10:

- Migrar para a Gestão: Reescrever a NR-10 para que ela seja uma norma de gestão de riscos elétricos, alinhada aos princípios da NR-01 (GRO/PGR) [5].
- Delegar a Técnica: Referenciar explicitamente as normas técnicas da ABNT (NBR 16384, 17227, 5410 [6] [7] [8], etc.) e aceitar normas internacionais de consenso (NFPA 70E®, IEC), estabelecendo a primazia da norma mais protetiva ao trabalhador.
- Aprimorar a Qualificação: Eliminar a figura do "profissional capacitado" para trabalhos em zona de controle/risco, reconhecendo apenas o BA5 qualificado (formação) e o habilitado (CREA), e vinculando a autorização à competência comprovada.

2) Implementação de Programas-Chave:

- PGRE Digital: Tornar obrigatória a implementação do Programa de Gestão de Risco Elétrico (PGRE), com registros digitais, inventário de riscos e um cronograma de adequações auditável via eSocial [5].
- LOTO Corporativo: Instituir programa robusto de bloqueio e etiquetagem, com procedimentos específicos por máquina/equipamento e auditoria anual certificada.
- Análise de Arco Elétrico: Exigir estudos de energia incidente e etiquetagem de Arc Flash em painéis elétricos, baseados em normas nacionais e internacionais.
- Cultura de Competência: Exigir a certificação de profissionais elétricos por organismos acreditados (ISO/IEC 17024), eliminando a prática de treinamentos apenas para "cumprir formalidade".
- Reporte Compulsório: Criar obrigatoriedade de notificação de choques, arcos, incidentes e quase-acidentes no eSocial, com análise de causa e plano de ação.

3) Roteiro de Transição:

- **Grupo de Trabalho**: Criar um grupo de trabalho focado na modernização da NR-10, com ampla participação de especialistas técnicos da ABNT, institutos de engenharia e setor privado, além da representação tripartite.
- **Período de Transição**: Estabelecer um período de transição de 36 meses para a implementação das novas exigências de gestão, com foco inicial nos setores de alto risco.
- **Comunicação**: Lançar uma campanha nacional para educar e conscientizar empresas e trabalhadores sobre a mudança de paradigma, da "norma de listas" para a "norma de gestão".

A adoção dessas recomendações não apenas colocará o Brasil na vanguarda da segurança elétrica, mas, mais importante, salvará vidas, tornando o trabalho com eletricidade mais seguro e eficaz para todos.

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Irregularidades em instalações elétricas residenciais observadas em perícias no Maranhão

Amanda de A. Serra Lima
Engenheira eletricista pelo CREA-MA
Perita judicial para o TJMA e o TJDFT
Brasília-DF, Brasil
amandalima.eng@outlook.com

***Resumo* — Este artigo apresenta a diversidade nas condições de segurança das instalações elétricas no Brasil, evidenciando situações de risco encontradas entre as mais de 100 perícias judiciais realizadas em casas na região metropolitana de São Luís - MA, principalmente em residências de baixa renda. Abordará porcentagens no uso de dispositivos de segurança contra choque elétrico e danos ao patrimônio e a percepção dos usuários a respeito dos mesmos. Além disso, abordará os desafios econômicos para adequação a uma instalação segura e as boas práticas com as quais o perito na área elétrica pode ajudar a melhorar o cenário, especialmente por meio do conteúdo de seus laudos periciais.**

Palavras-chave— segurança em residências, instalações elétricas no Nordeste, perícia judicia, dispositivos de proteção

I. Introdução

Os profissionais de engenharia elétrica possuem um papel fundamental na Segurança do Trabalho pois têm o dever contribuir com a diminuição de um dos motivos principais de acidentes, que são os relacionados à eletricidade. No âmbito jurídico, muitos engenheiros eletricistas atuam como peritos nomeados em processos judiciais relacionados à energia elétrica, nos quais são convidados a identificar problemas; e, muitas das vezes, têm contato direto com as instalações elétricas de uma das partes envolvidas, onde encontra irregularidades nem sempre conhecidas pelas pessoas em geral, por ser conhecedor das normas de eletricidade.

Nesse contexto, este artigo apresenta fotos e descrições de situações que foram encontradas em minha experiência como perita judicial na região metropolitana de São Luís, a qual é reconhecidamente uma região do Brasil com população em geral de menor poder aquisitivo. O objetivo é ilustrar, de forma concreta, para os profissionais da área, situações de insegurança, e ajudar o público não especializado, principalmente os trabalhadores, a identificar visivelmente problemas nas instalações elétricas do local onde moram ou trabalham, a fim de tomar providências a curto ou médio prazo, e evitar, assim, acidentes de origem elétrica. Também possui o objetivo de mostrar o impacto que as adequações na instalação elétrica podem trazer para o orçamento, de modo que algumas são inacessíveis para a população dessa região e de outras semelhantes.

Sobre o perfil das casas que foram visitadas nas perícias, entre 2019 e 2025, tratavam-se de residências de baixa renda ou classe média; 90% dos casos foram iniciados contra a concessionária local para contestar os valores das faturas supostamente acima do que deveriam, e seria necessário ao perito, dependendo de cada situação, fazer o levantamento de carga para simulação do consumo, verificação das instalações residenciais, análise do histórico e ensaio no medidor.

II. Aspectos destacados

A. Quadros de distribuição

O quadro de distribuição de uma residência é necessário, mesmo em residências mais pobres, a fim de centralizar os dispositivos de proteção elétrica e dividir ao menos o circuito de iluminação e o de tomadas, conforme recomendado na norma técnica ABNT NBR 5410 [1], principalmente para facilitar manutenções periódicas ou emergenciais.

No entanto, quase metade das casas que foram visitadas nas perícias não possuíam quadro de distribuição, contando somente com o disjuntor do padrão de entrada. Muitas das que possuíam, contavam somente com um disjuntor geral (Figura 1), alguns sem substituição ou manutenção há mais de 20 anos.

Entre os que possuem mais de um disjuntor, apenas em duas foi visto dispositivo de proteção contra choque elétrico (Dispositivo Diferencial Residual - DR). Já o dispositivo contra surtos e descargas atmosféricas (DPS), este não foi visto em nenhuma residência (somente em outros tipos de perícias, envolvendo cargas como elevadores e aparelhos de CFTV).

Quanto à identificação de cada disjuntor, com nome ou figura indicativa sobre o circuito a que está conectado, em menos da metade foi encontrada; ao questionar aos moradores sobre o que cada disjuntor controlava, eles não sabiam informar, o que é um perigo para a segurança em uma situação de necessidade de desligamento imediato. A Figura 2 apresenta alguns desses.

Fig. 1. Quadros de distribuição com somente um disjuntor

Fig. 2. Quadros de distribuição sem DR e sem identificação dos circuitos

B. *Aterramento das tomadas*

O fio de aterramento nas tomadas também é obrigatório em toda instalação elétrica conforme normas técnicas vigentes, conduzindo à malha de aterramento, a fim de desviar eventuais fugas de corrente de aparelhos para a terra ao invés de desviar para um possível toque humano e proteger equipamentos eletrônicos. Mais de 80% também não tinham aterramento nas tomadas, como se pode ver na Figura 3, onde as tomadas foram abertas para inspeção. Das que possuíam aterramento, a maioria se tratava de construções de políticas habitacionais (Minha Casa Minha Vida).

Fig. 3. Tomadas sem fio de aterramento (apenas fase e neutro)

C. *Uso de benjamins e extensões*

A ausência de projeto elétrico, sem a preocupação sobre a quantidade correta de pontos de tomadas e lâmpadas, e também pontos de tomada incompatíveis com o plugue do aparelho, leva a improvisos nas instalações, como uso benjamins (adaptadores em 'T'), extensões e adaptadores, os quais frequentemente não apresentam selo do INMETRO, nem abertura para pino de aterramento. Nas Figuras 4 e 5 constam algumas fotos que foram tiradas em perícias e ilustram esse tópico.

Segundo o Anuário 2025 da Abracopel (Associação Brasileira de Conscientização para os Perigos da Eletricidade) [2], das 248 mortes ocorridas em 2024 causadas por choque elétrico em residências brasileiras, 96 delas foram causadas por "conexões, extensões e instalações elétricas", fora os incêndios causados por sobrecarga ou mau-contato nesses dispositivos. Essa estatística mostra o perigo desse tipo de prática, pois as pessoas acabam tendo contato direto com dispositivos que podem ter fugas de corrente e nem sempre segue as normas sobre plugues do INMETRO [3].

Fig. 4. Uso de benjamins e adaptadores

Fig. 5. Uso de extensões

D. Instalações irregulares ou antigas

As instalações elétricas proporcionam conforto e funcionalidade no uso de aparelhos eletrodomésticos, entretanto, a forma com que é feita é por vezes negligenciada, pela falsa percepção de que já está tudo resolvido se a energia está sendo fornecida, mesmo sem o uso de eletrodutos e caixas de passagem por exemplo, como se vê nas fotos de perícias da Figura 6. Outras irregularidades e problemas muito frequentes, além dos já citados nos tópicos anteriores, são: fios desencapados, emendas sem conectores, uso de fita isolante inadequada ou mal colocada, fiação com bitola inadequada, fiação velha ou ressecada, tomadas fora do padrão, ligações irregulares (clandestinas) a partir da rede pública ou da rede de vizinho.

Muitas dessas irregularidades iniciam como improvisos e acabam se tornando definitivas. Elas levam a choques elétricos por contatos acidentais, a adaptações inseguras e a incêndios por sobrecarga de corrente na fiação.

Somente no Maranhão, houve em 2024, 14 acidentes causados por incêndios de origem elétrica, e 32 acidentes por choque elétrico (que resultaram em 24 mortes). Medidas precisam ser tomadas para que a cada ano essas estatísticas diminuam e menos vidas sejam ceifadas.

Fig. 6. Instalação exposta, sem cores corretas dos fios, ausência de caixa de passagem

A Tabela I apresenta um resumo das estatísticas apresentadas.

TABELA I. ASPECTOS OBSERVADOS NAS RESIDÊNCIAS PERICIADAS

Quadro de distribuição	40% não possuía quadro 30% possuía apenas um disjuntor Somente 2 possuíam DR
Aterramento das tomadas	80% não possuía aterramento
Uso de benjamins e extensões	90% estavam utilizando
Outras irregularidades	30% apresentavam fios fora de eletroduto

III. DESAFIOS ECONÔMICOS PARA ADEQUAÇÕES DE SEGURANÇA

As medidas de segurança que precisam ser tomadas para correção de problemas como os citados nesse artigo devem ser procedidas por um técnico em eletricidade, como a colocação de quadro de distribuição, instalação de DR e de aterramento, a inserção de novos pontos de tomada, a atualização de tomadas padrão antigo para padrão novo, ou restauração de emendas. Isso devido à necessidade de o profissional conhecer a Norma Regulamentadora 10 [4], para proteção própria e proteção da instalação.

Existe ainda o investimento necessário para o projeto elétrico a fim de evitar mal dimensionamento, além dos materiais de alvenaria para acabamentos. Dessa forma, essas medidas envolvem investimentos consideráveis que, dentro da realidade de famílias que vivem de um salário mínimo, não são possíveis de imediato.

Na necessidade de eleger uma mais urgente, pode ser priorizada a instalação do DR no quadro de distribuição (sendo instalado um caso ainda não exista, com pelo menos um disjuntor além do DR). Vale observar que a instalação de DR não dá certo se houver alguma fuga de corrente na instalação elétrica do local, de modo que esse problema deve ser investigado e corrigido de antemão.

Podemos citar também pequenos e médios investimentos e boas práticas que podem ser iniciados de imediato:

- Usar protetores de tomada, principalmente em locais com crianças, para evitar choques elétricos, e ensinar as crianças a não mexerem em tomadas;
- Usar DPS's (dispositivo de proteção contra surtos) portáteis para proteção de aparelhos como geladeiras, computadores e micro-ondas;
- Usar Equipamentos de Proteção Individual (EPIs) mínimos como óculos, botas isolantes ou caneta detectora, no contato com superfícies possivelmente energizadas;
- Manter equipamentos elétricos longe de água;
- Evitar deixar fios ao alcance de possíveis toques acidentais pois podem ter cortes imperceptíveis que podem originar choque elétrico;
- Desenergizar aparelhos em caso de manutenção;
- Evitar ao máximo uso de extensões, benjamins e adaptadores, usar o mínimo de aparelhos concomitantes.

IV. O PAPEL DO PERITO ENGENHEIRO ELETRICISTA

O perito judicial tem um papel muito claro e objetivo dentro de um processo da justiça, não podendo passar do

limite de auxiliar o juiz de forma completamente imparcial, respondendo aos quesitos dele e das partes envolvidas por meio do laudo. Entretanto, o engenheiro eletricista ora perito naquele processo é por vezes o único profissional em eletricidade confiável que os leitores terão contato por um bom tempo, de modo que, o que se fala no laudo é bastante levado em consideração.

Ciente disso, e como resultado das reflexões trazidas nesse artigo e proposta para os demais colegas de profissão, será inserido um anexo, a todos os meus laudos, de uma página (no máximo) com orientações de segurança concretas sobre eletricidade, apresentando estatísticas e informações tiradas do último anuário de acidentes de origem elétrica da Abracopel, visando conscientizar a todos que tiverem acesso ao laudo, seja magistrados, advogados, autores ou réus do processo, sobre a necessidade de cuidados com as instalações. Este material adicional deverá ser meramente informativo, sem interferir nas conclusões técnicas do laudo. Tal prática não fere a imparcialidade do laudo e irá contribuir com o papel social que o engenheiro eletricista deve assumir junto aos indivíduos que o cercam ou que têm acesso às suas produções textuais.

Ainda que, aos leitores, não seja possível pôr em prática todas as adequações, por motivos econômicos ou diversos, será possível ao menos a ampliação da consciência sobre os perigos envolvidos, deixando-os mais alertas na eminência de ocorrer algum acidente.

V. Conclusão

Diante do exposto, ficaram evidentes os problemas existentes em instalações elétricas residenciais, a partir das instalações encontradas no Maranhão, e foram esclarecidas as dificuldades para adequações de segurança, com propostas de soluções.

Ficou evidente também a necessidade do papel social do engenheiro eletricista, em especial do perito, na conscientização da população para melhoria nas mesmas, no intuito de diminuir as estatísticas de acidentes, seja no ambiente residencial ou no de trabalho.

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Eletricômetro - Ferramenta de avaliação dos riscos em subestações elétricas

Rafael Elói
Ger. Manutenção Infra Elétrica Mina
Vale S.A.
Nova Lima, Minas Gerais
rafael.eloi@vale.com

Thiago Henrique Pereira
Ger. Eng. Elétrica, Automação e Instrumentação
Vale S.A.
Nova Lima, Minas Gerais
thiago.henrique.pereira@vale.com

Helberth Gonçalves
Ger. Eng. Elétrica, Automação e Instrumentação
Vale S.A.
Contagem, Minas Gerais
helberth.goncalves@vale.com

Adilon Júnior
Ger. Serviços de Campo
SM&A Service
Contagem, Minas Gerais
adilon.junior@sma-eng.com.br

RESUMO

A norma Regulamentadora – NR 10 preconiza os requisitos e condições mínimas objetivando a implementação de medidas de controle de forma a garantir a segurança e a saúde dos trabalhadores que, direta ou indiretamente, interajam em instalações elétricas e serviços com eletricidade. Garantir que as etapas de; projetar, construir, operar e manutenir ocorra em observância as normas técnicas é uma prerrogativa importante para o processo de adequação às normas regulamentadoras, em especial à NR-10. Um sistema de gestão de segurança em eletricidade requer a implementação de um programa de avaliação periódica dos sistemas elétricos de forma a garantir atendimento à legislação. Esse trabalho tem objetivo de apresentar uma ferramenta de avaliação dos riscos das instalações elétricas da Vale, denominado de "Eletricômetro". Essa ferramenta, elaborada pelo corpo técnico da empresa, permite ranquear as instalações pelo nível de aderência aos requisitos técnicos. Essa ferramenta passou a fazer parte do programa de gerenciamento dos riscos elétricos, que permite a tomada de decisão com relação à priorização da alocação de investimentos para revitalização e adequação das instalações. Os resultados alcançados com a adoção deste modelo de gerenciamento podem contribuir na mitigação de riscos em outras empresas que buscam atingir este mesmo objetivo.

Palavras-chave — Eletricômetro, segurança, diagnóstico, checklist.

I. Introdução

Diante das revisões das normas que regem o setor elétrico com relação à saúde e segurança dos colaboradores, adequações e funcionalidades do sistema, faz-se necessário o diagnóstico elétrico das subestações que operam nas dependências da Vale no que diz respeito à Sinalização e Identificação, Segurança (Emergência), Documentação, Condições das Salas Elétricas e dos Painéis.

O objetivo deste trabalho é procurar estabelecer e elencar os itens mais críticos da instalação elétrica e consequentemente definir uma abordagem técnica para identificação das não conformidades e a proposição das soluções mínimas para sua adequação.

Este trabalho foi aplicado nas salas elétricas principais e secundárias do Complexo Paraopeba (minas de Fábrica, Viga, Mutuca, Terminal de Olhos D'Água, Jangada, Feijão) e Complexo Vargem Grande (mina do Pico, Tamanduá, Horizontes, Aboboras, Vargem Grande I, Vargem Grande II e Terminal Ferroviário de Andaime), totalizando 209 instalações diagnosticadas.

O objeto deste trabalho é uma síntese das condições atuais das salas elétricas e desenvolver uma metodologia para priorização da adequação das subestações baseado em seu percentual de atendimento avaliando o nível de risco a fim de minimizar os potenciais envolvidos.

II. Grupo Técnico

Em 2020, a equipe de Engenharia Elétrica da Vale identificou a necessidade de formar um grupo multidisciplinar para abordar o tema ''Diagnóstico de Subestações Elétrica''. Esta definição foi motivada principalmente pelo alto risco envolvido na operação e manutenção de seus sistemas elétricos e complexidade do tema.

O objetivo do grupo técnico foi padronizar a metodologia do diagnóstico de forma que sua aplicação seja viável e utilizada para priorização das revitalizações de subestações elétricas.

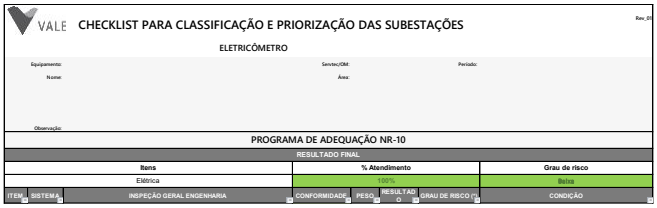
A. Metodologia de Aplicação

Para realização desse trabalho foi elaborado em conjunto ao grupo técnico um checklist para diagnosticar e classificar o nível de risco das subestações denominado "Eletricômetro".

Este checklist é baseado em requisitos de normas técnicas e padrões normativos internos Vale (PNR) tais como NR-10 (segurança em instalações e serviços em eletricidade), NR-26 (Sinalização de Segurança), NR-23 (Proteção contra Incêndios), NBR-14039 (Instalações Elétricas de Média Tensão de 1,0kV a 36,2kV), NBR-10898 (Sistema de Iluminação de Emergência), NBR-16384 (Segurança em Eletricidade), NBR-5410 (Instalações Elétricas de Baixa Tensão), NBR-5419 (Proteção contra Descargas Atmosféricas), NBR-13231 (Proteção contra Incêndios em Subestações), PNR-00051 (Sistemas Elétricos - Geral - Energia Incidente), PNR-00052 (Aterramento-PDA), PNR-00053 (Sistemas Elétricos), PNR-00069 (Requisitos de Atividades Críticas) e PNR-00080 (Sistemas de Proteção).

B. Checklist

Foram avaliados 33 requisitos subdivididos em Sinalização e Segurança (4 itens), Emergência (3 itens), Documentos (3 itens), Sistema Elétrico (8 itens), Estrutura (7 itens) e Painéis (7 itens), esses requisitos foram divididos em 4 níveis conforme apresentado a seguir. A figura 1 apresenta o cabeçalho do checklist utilizando nos levantamentos de campo.


VALE CHECKLIST PARA CLASSIFICAÇÃO E PRIORIZAÇÃO DAS SUBESTAÇÕES

ELETRICÓMETRO

PROGRAMA DE ADEQUAÇÃO NR-10

RESULTADO FINAL

Itens	% Atendimento	Grau de risco
Elétrica	100%	Baixa

ITEM	SISTEMA	INSPEÇÃO GERAL ENGENHARIA	CONFORMIDADE	PESO	RESULTADO	GRAU DE RISCO	CONDIÇÃO

Fig. 1. Checklist para classificação e priorização das subestações

Para os critérios de pesos, foram definidas as seguintes premissas:

Peso 7 - Quando dos itens não conformes possam ocasionar acidentes de **grau N1** (Fatalidades e mudanças de vida);

Peso 5 - Quando dos itens não conformes possam ocasionar acidentes de **grau N2** (Lesões registráveis com alto potencial, afastamentos, restrições);

Peso 3 - Quando dos itens não conformes possam ocasionar acidentes de **grau N3** (Primeiros socorros / dano material, quase acidente, condição insegura);

Peso 1 - Não conformidade que fere a rotina operacional e que se enquadre na classificação grau de risco "Baixa".

Para o critério do Grau de Risco foi definido conforme as seguintes premissas:

Muito alta - Quando dos itens não conformes, algum ou mais apresentam condições de risco a saúde para pessoas e vulnerabilidade das instalações. Obrigatoriamente deverá ser interditado o painel que se encontra com a condição de risco para efetuar manobras ou intervenções com o sistema energizado.

Alta - Quando dos itens não conformes, algum ou mais apresentam risco de perda operacional ou que ferem as normas técnicas e regulamentadoras.

Média - Quando dos itens não conformes, algum ou mais apresentam condições que requerem atenção e que podem evoluir ou que apresentam uma oportunidade de melhoria.

Baixa - Quando dos itens não conformes, apresentam apenas a rotina normal do ativo sem apresentar nenhum risco ao mesmo.

A figura 2 apresenta o resumo dos 33 requisitos subdivididos nos 4 níveis de classificação de risco e os respectivos critérios de grau de risco. A figura 3 representa graficamente o percentual de atendimento da subestação e indica, pelo gráfico de radar, qual dos sistemas, Segurança, Emergência, Documentos, Sistema Elétrico, Estrutura e Painéis, apresentam as piores condições.

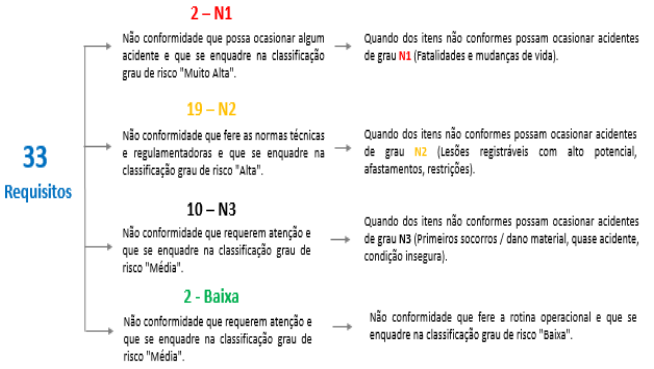


Fig. 2. Não conformidades de acordo com o Grau de Risco

SISTEMA	SOMATÓRIO DOS PESOS	SOMATÓRIO DO RESULTADO	RESULTADO	META
SINALIZAÇÃO E IDENTIFICAÇÃO	18	0	100%	90%
EMERGÊNCIA	20	0	100%	90%
DOCUMENTOS	11	0	100%	90%
SISTEMA ELÉTRICO	38	0	100%	90%
ESTRUTURA	17	0	100%	90%
PAINÉIS	37	0	100%	90%
CONFIABILIDADE	141	0	100%	Baixa

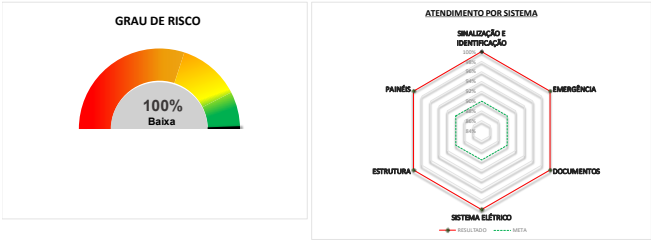


Fig. 3. Grau de Risco / Atendimento por Sistema

O Farol será representado automaticamente nas cores abaixo, Tabela I, à medida em que for alcançando seu percentual informado através do checklist.

TABELA I. FAROL PERCENTUAL DE ATENDIMENTO

Identificação	Percentual de adequação
	Entre 0 e 60%
	Entre 61 e 85%
	Entre 86 e 100%

Para as subestações que atingirem um percentual de atendimento superior ou igual a 86%, entende-se que ela atende o nível de risco mínimo para que o profissional trabalhe com segurança.

Através do diagnóstico, será sinalizado se os requisitos estão **conforme**, **não conforme** ou **não aplica**, o Nível de Risco da subestação será avaliado conforme o percentual de atendimento e o grau de risco de acordo com o

checklist e inserido na Matriz de Nível de Risco abaixo, figura 4:

Matriz Nível de Risco - Inicial		GRAU DE RISCO			
		BAIXA	MÉDIA	ALTA	MUITO ALTA
% ATENDIMENTO	0% a 60%				
	61% a 85%				
	86% a 100%				

Fig. 4. Matriz do Nível de Risco

Foi definido ainda que, para melhor aplicação e viabilidade do checklist, este não será intrusivo, ou seja, todos os itens serão inspecionados visualmente sem a necessidade de interação com os circuitos elétricos tais como abertura de painéis energizados. O objetivo do trabalho é diagnosticar sem expor o profissional ao risco.

C. Estudo de caso 01

Em posse do checklist, aplicou-se para todas as subestações do Complexo Paraopeba e Vargem Grande. Dentre as 209 subestações diagnosticadas, será apresentado dois exemplos.

Com o resultado do diagnóstico consolidado foi aplicado os critérios para definir quais as subestações prioritárias para atendimento. Será apresentado neste artigo duas subestações, onde uma delas foi necessário realizar 100% da substituição dos componentes e a outra foi possível realizar melhorias.

A primeira subestação é a 27SE02 localizada na mina da Mutuca do Complexo Paraopeba. O percentual de atendimento após o diagnóstico foi de 40% e o grau de risco classificado como muito alto.

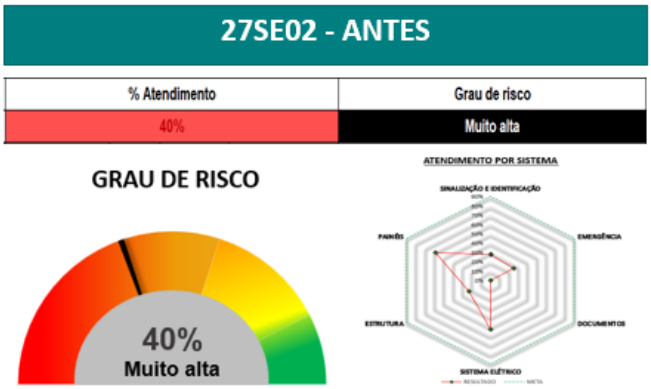


Fig. 5. Grau de Risco Antes / Atendimento 27SE02

Fig. 6. Fotos Antes -27SE02

O ponto mais crítico encontrado para essa subestação eram os constantes alagamentos nos períodos chuvosos onde as galerias de cabos e painéis elétricos ficavam submersos e eram danificados.

TABELA II. MATRIZ DO NÍVEL DE RISCO ANTES -27SE02

Matriz Nível de Risco - Inicial		GRAU DE RISCO			
		BAIXA	MÉDIA	ALTA	MUITO ALTA
% ATENDIMENTO	0% a 60%				X
	61% a 85%				
	86% a 100%				

Foi desenvolvido o projeto executivo para adequação dos itens não conforme e verificado que seria necessário realizar a revitalização completa da subestação.

Na aplicação deste projeto, viu-se a necessidade de elevar o nível da subestação para evitar novos alagamentos, optou-se por construir uma base civil para receber um eletrocentro onde este viria com grande parte dos itens do checklist adequados, entre eles a substituição dos painéis de baixa e alta tensão, instalação dos sistemas de SDAI (Sistema de detecção e alarme de incêndio), instalação do sistema de aterramento e SPDA (sistema de proteção de descarga atmosférica) além de toda documentação atualizada da subestação.

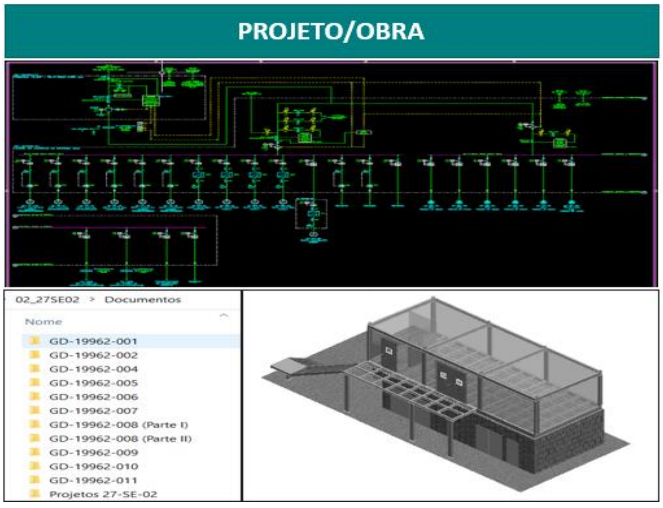


Fig. 7. Projeto executivo 27SE02

Após conclusão das obras de adequação da 27SE02, foi aplicado novamente o checklist do Eletricômetro onde obtive-se o percentual de atendimento de 98% aos requisitos, ficando com o grau de risco classificado como médio, conforme apresentado na figura 8 .

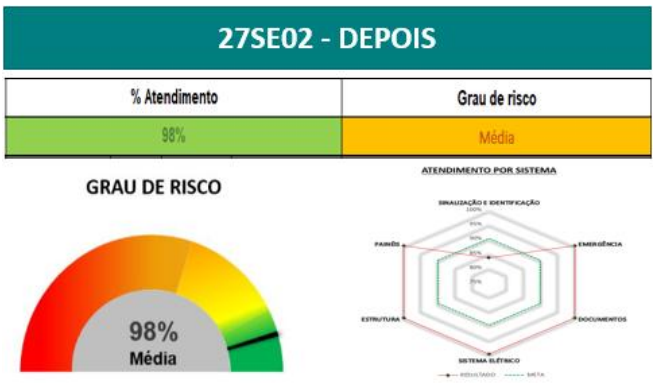


Fig. 8. Grau de Risco Depois / Atendimento – 27SE02

Fig. 9. Fotos depois da adequação - 27SE02

TABELA III. MATRIZ DO NÍVEL DE RISCO DEPOIS -27SE02

Matriz Nível de Risco - Inicial		GRAU DE RISCO			
		BAIXA	MÉDIA	ALTA	MUITO ALTA
% ATENDIMENTO	0% a 60%				
	61% a 85%				
	86% a 100%		X		

D. Estudo de caso 02

Será apresentado a subestação SE-6020-VG01, localizada na Usina de Vargem Grande II do Complexo Vargem Grande. O percentual de atendimento inicial do diagnóstico foi de 62% e o grau de risco classificado como muito alta.

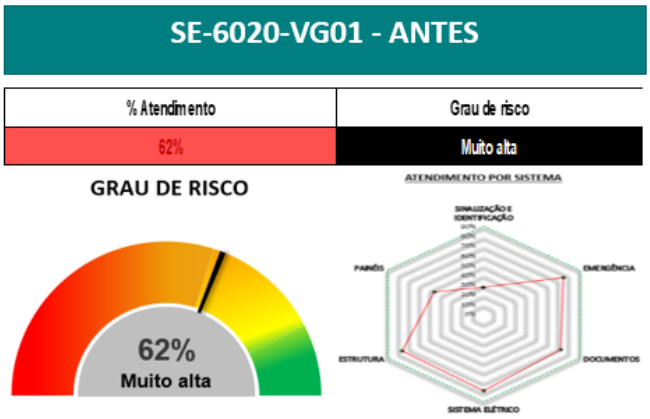


Fig. 10. Grau de Risco Antes / Atendimento – SE-6020-VG01

Fig. 11. Fotos Antes -SE-6020-VG01

TABELA IV. MATRIZ DO NÍVEL DE RISCO ANTES – SE-6020-VG01

Matriz Nível de Risco - Inicial		GRAU DE RISCO			
		BAIXA	MÉDIA	ALTA	MUITO ALTA
% ATENDIMENTO	0% a 60%				
	61% a 85%				X
	86% a 100%				

Nesta subestação foi realizado um projeto de executivo de adequação mantendo a estrutura física, porém refazendo o layout dos equipamentos em seu interior, durante o projeto foi visto a necessidade de substituição dos painéis mais críticos e manter os painéis em boas condições de operação. Com o andamento das obras de melhorias e adequações já foi possível verificar o atendimento aos itens do checklist.

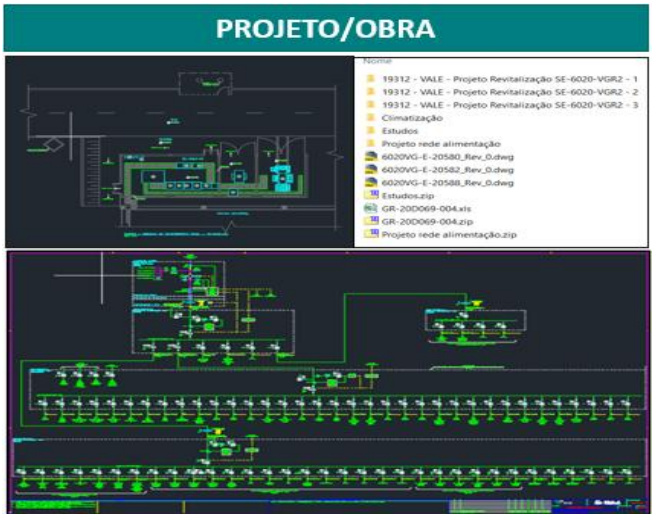


Fig. 12. Projeto executivo SE-6020-VG01

Após conclusão das obras de adequação da SE-6020-VG01 foi aplicado novamente o checklist do Eletricômetro onde obtive-se o percentual de atendimento de 99% de atendimento aos requisitos com o grau de risco classificado como baixo.

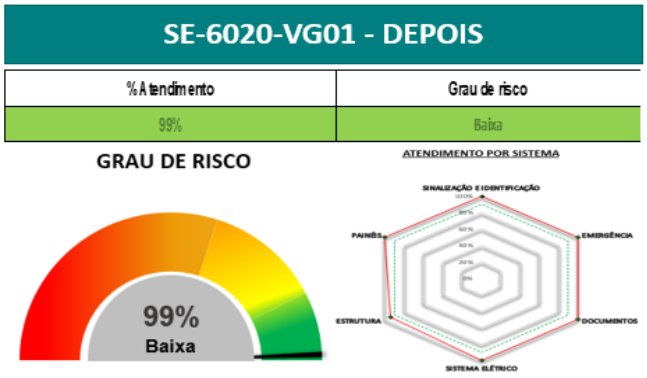


Fig. 13. Grau de Risco Depois / Atendimento

Fig. 14. Fotos depois da adequação - SE-6020-VG01

TABELA V. MATRIZ DO NÍVEL DE RISCO DEPOIS -SE-6020-VG01

Matriz Nível de Risco - Inicial		GRAU DE RISCO			
		BAIXA	MÉDIA	ALTA	MUITO ALTA
% ATENDIMENTO	0% a 60%				
	61% a 85%				
	86% a 100%	X			

III. CONCLUSÕES

Diante da necessidade de padronizar uma forma de diagnosticar as subestações elétricas, o grupo técnico elaborou um checklist denominado ‘’Eletricômetro’’ onde consolidaram os principais itens normativos de forma a quantificar e classificar o nível de risco das subestações elétricas, além de possuir uma gestão de risco como base para as adequações das instalações tornando-as mais seguras e confiáveis para as pessoas.

Foi aplicado o diagnóstico nas 209 subestações dos Complexos Paraopeba e Vargem Grande onde obtive-se uma base robusta para priorização dos investimentos plurianuais dedicada a esse programa.

Para exemplificar a aplicação do ‘’Eletricômetro’’, foi apresentado nesse artigo 2 subestações na qual o nível de risco estava classificado como muito alto e através destes diagnósticos foram priorizados e inseridos dentro do programa de revitalização para adequação dos itens não conformes, reduzindo o nível de risco para médio e baixo.

Com os riscos mapeados e classificados o trabalho permitiu uma atuação pontual em requisitos no quais foram adequados dentro da estratégia da empresa, quando identificado um risco crítico (muito alto) e não possibilita a adequação de imediato, é possível tratar risco como prevenção, realizando identificação de advertência e/ou procedimentos de trabalho.

Dessa maneira, a proposta de trabalhos futuros contempla em manter a atualização do checklist conforme normas vigentes e inclusão de itens que o grupo técnico julgar pertinente, além de realizar de forma sistemática a aplicação em campo para possuir uma base atualizada.

Esse trabalho também direciona para a elaboração de um capítulo de revitalização elétrica dentro do plano diretor dos complexos.

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Humanized Integration and Assessment of Technical Capacity as an Accident Prevention Tool

Ricardo Furlanetto
Departamento de Gestão Técnica Comercial
Celesc Distribuição S.A.
Florianópolis, Brazil
ricardof@celesc.com.br

Adison André Pscheidt
Departamento de Saúde, Segurança e Bem Estar
Celesc Distribuição S.A.
Florianópolis, Brazil
adisonap@celesc.com.br

Abstract - Safety in electrical installations is a critical factor in reducing accidents in the electrical sector. This study presents an approach based on the integration humanized and the assessment of professionals' technical capacity as fundamental elements for accident prevention. The research is based on Celesc Distribuição's experience in implementing Advanced Metering Infrastructure (AMI) in Florianópolis, which involved the installation of smart meters and remote monitoring systems.

The methodology adopted included specialized training for professionals to ensure the safe operation of new equipment, along with standardized processes for assessing technical competence. Data analysis showed that integrating humanized, combined with strict technical qualification control, significantly reduced operational risks, preventing failures and mitigating electrical incidents.

The results indicate that this approach can be replicated in other power distribution companies, contributing to the development of a stronger safety culture. It is concluded that the modernization of the electrical sector, when accompanied by professional training and continuous monitoring, is an effective path for reducing accidents and improving working conditions.

Keywords— Integration, Technical Capacity, Prevention, Safety, Qualification

I. Introduction

Energy transition and the digitalization of the electrical sector have driven the adoption of smart metering technologies as pillars for infrastructure modernization. Such systems, in addition to promoting energy security and market liberalization, enable the implementation of new tariff structures, demand response programs, and the mitigation of technical and non-technical losses [1]. CELESC, in line with this global trend, initiated a project to expand its smart metering infrastructure, aiming to optimize energy consumption management and enhance operational efficiency.

The project in Florianópolis/SC involves the installation of smart meters with remote disconnect/reconnect capabilities in 262,439 consumer units and balance meters in 5,161 distribution transformers. This initiative, aligned with the Celesc Master Plan 2025/2035 and integrated into Project 3.3.2 – AMI Project, aims to reduce non-technical losses and delinquency, optimize commercial services, and improve asset remuneration [2]. The project's complexity and scale necessitated the implementation of a robust occupational safety program, which is the central focus of this article.

The implementation phase of electrical infrastructure projects, particularly those involving the Electric Power System (EPS), is inherently associated with significant risks [3]. Proactive management of these risks, through safety and training programs, is crucial for worker protection and the achievement of project objectives. This study describes the methodologies employed to ensure compliance with regulatory standards and the effectiveness of operations, highlighting the relevance of documentary analysis, continuous training, and technical assessment as tools for accident prevention and productivity maximization.

II. Implementation Methodology and Occupational Safety Management

The project's implementation phase began after the formalization of the contract with the company Setup. The methodology of occupational safety management was divided into three main axes: documentary analysis, training,

and technical assessment. The supervision and validation of these stages were conducted by specialized teams from the Department of Technical and Commercial Management (DPGT/DVMD) and the Department of Safety, Health and Well-being (DPSS/DVST) at CELESC.

A. Documentary Analysis

Documentary analysis covered both the institutional compliance of the contracted company and the individual attitude of the workers.

A.1 Institutional Documentation

The verification of institutional documentation focused on adherence to Brazilian legal and regulatory occupational safety requirements. The analyzed documents included:

- Risk Management Program (PGR): Evaluation of the structure and scope in identifying and controlling occupational risks.
- Occupational Health Medical Control Program (PCMSO): Verification of compliance with periodic medical examinations and worker health monitoring.
- Technical Report on Environmental Conditions (LTCAT): Analysis of the identification of unhealthy and hazardous conditions and their respective control measures.
- Emergency and Contingency Plan: Evaluation of emergency response capability.
- Preliminary Risk Analysis and Safety Dialogue (APR/DDS) Model: Analysis of the methodology for risk assessment and communication before starting activities.
- Occupational Safety Manual: Compliance with internal safety guidelines and procedures.
- Operational Work Procedures (POT): Analysis of compliance with Regulatory Standard 10 (NR-10), specific to services in electrical installations.

A.2 Individual Worker Documentation

A meticulous audit of each worker's individual documentation was performed using a standardized checklist, which included:

- Employment Record Book (CTPS) registration.
- Occupational Health Certificate (ASO) indicating fitness for the function, including fitness for work at height (NR-35) when applicable.
- Personal identification documents (RG and CPF).
- Proof of schooling (completed elementary education), in accordance with Normative Instruction I1100007 – CELESC Training Policy.
- Certificates of completion for NR-10 Basic and Complementary courses.
- Certificate of completion for NR-35 (Work at Height) course.
- Certificate of completion for the Commercial Services Electrician Course, in accordance with Normative Instruction I1100007.
- Proof of formal integration with the contracted company.
- Proof of delivery of Personal Protective Equipment (PPE).
- Formal authorization for entry into risk areas (electricity), in accordance with NR-10 and NR-16.
- Proof of delivery of the Safety Service Order, in accordance with NR-1.

B. Training and Technical Assessment

CELESC's Normative Instruction nº I1100007 establishes a rigorous protocol for the training of professionals working in the EPS or performing activities at height. ASO fitness is a mandatory prerequisite for participation in any training program. The minimum requirements for the Commercial Services Electrician Course (Disconnect, Connect, and Reconnect UCs, Installer, and other commercial services of Group B) are completed elementary education, a minimum age of 18, and NR-10B, NR-10C, and NR-35 certifications. The total workload for this qualification is 176 hours, distributed as: Training Module (136h), Electrical Energy Measurement (36h), and Aerial Basket Use (4h).

Technical capacity assessment is a mandatory stage, conducted after documentary approval and before the start of operational activities. This evaluation, the responsibility of the Contract Manager, consisted of practical tests to simulate the activities to be performed. The activity release process followed these steps:

1. Documentary analysis of the contracted company.
2. Individual documentary analysis of employees.
3. Humanized Integration: Conducting integration sessions for all employees, covering the contract scope, accident statistics, preliminary risk analysis, and PPE/EPC usage. Seven humanized integrations were conducted (December 2023 - April 2025), encouraging active participation and sharing of experiences.

Fig. 1. Integration SETUP AMI 13/12/2023

Fig. 2. Integration SETUP AMI 22/12/2023

Fig. 3. Integration SETUP AMI 22/12/2023

4. Physical Inspection: On-site verification of tools, PPE, EPCs, and vehicles, using standardized checklists. Seven inspections were conducted.

Fig. 4. Inspection SETUP AMI 13/12/2023

Fig. 5. Inspection SETUP AMI 13/11/2024

Fig. 6. Inspection SETUP AMI 18/12/2024

5. Technical Capacity Assessment Test: Consisted of simulated practical activities:
   - Installation and removal of Smart Meter with panel adaptation and circuit breaker manipulation.
   - Installation and removal of Smart Communication Equipment (AP) on a pole, including the use of extension ladders and rescue simulation.
   - Installation and removal of Energy Balance Meters (MB), with aerial basket operation and rescue simulation.
   - Installation of Smart Communication Equipment on Towers, covering climbing, material hoisting techniques, and antenna installation, with rescue simulation.

Fig. 7. Technical Capacity Assessment Test 31/07/2024

Fig. 8. Technical Capacity Assessment Test 13/11/2024

Fig.9. Technical Capacity Assessment Test 02/10/2024

The technical assessment was structured in 5 stages, based on performance criteria and continuous feedback, to foster a culture of evaluation and improvement. Criteria included tool proficiency, adherence to Operational Work Procedures (POT), task completion without electrical incidents, and quality of customer communication. Formative tests with immediate feedback and remediation planning were implemented for workers who did not achieve the expected proficiency.

Upon completion of the evaluations, a technical committee provided individualized feedback to the electricians, culminating in the issuance of a fitness or unfitness report.

C. Optimization of Operational Procedures: Collective Metering Panels

The replacement of meters in collective metering panels, common in multi-family buildings, presents challenges related to thermal comfort and safety, especially in Florianópolis/SC due to climatic conditions [4]. Traditionally, this activity involved disconnecting the main circuit breaker and replacing meters with the network de-energized, but with the potential risk of accidental re-energization. NR-10, item 10.5.4, requires that such services comply with safety requirements for energized installations (item 10.6), implying the use of additional PPE, such as insulating gloves, helmet with face shield, balaclava, and flame-resistant clothing.

To optimize worker thermal comfort and ensure full compliance with NR-10 item 10.5 (Safety in De-energized Electrical Installations), a new step-by-step procedure was developed and implemented. This protocol rigorously follows the sequence of sectioning, preventing re-energization (blocking and padlock), verifying voltage absence (with a multimeter), installing temporary grounding with conductor equipotentialization, protecting energized elements in the controlled zone, and installing re-energization prevention signage. For temporary grounding, a specific 35 mm² PVPP copper cable with four claw terminals was developed, designed to equipotentialize the phases of the panel busbar and the grounding busbar (PE).

III. Results

After 15 months of contract execution, the following results were achieved:

- Integration and Training: 1 initial integration and 9 additional integrations for new teams, totaling 105 employees integrated and approved for smart meter installation activities. Additionally, 6 employees were integrated and qualified for balance meter and AP installation activities on poles, and 3 for antenna installation activities on telecommunications towers.
- Deployment Progress: Installation of 43,977 smart meters (as of 02/16/25), 36 communication equipment on poles, and 3 communication antennas on towers.
- Occupational Safety: No typical accidents (with or without injury) and no sick leaves due to occupational safety reasons recorded during the period.
- Productivity Optimization (Collective Panels): The implementation of the new procedure for collective metering panels resulted in a productivity increase of approximately 106%, rising from 17 meters/day in February 2025 to 35 meters/day in April 2025. This gain was accompanied by improved thermal comfort, increased dexterity and vision of operators, and simplification in PPE usage (dispensing with face shield and balaclava, and use of leather gloves).

IV. Discussion

The obtained results demonstrate that the adoption of a rigorous occupational safety management methodology, combined with training programs and technical assessment,

is fundamental for the success of complex projects in the electrical sector. The humanized integration of professionals and the optimization of operational procedures, such as complete de-energization in collective panels, not only ensured compliance with regulatory standards but also resulted in substantial gains in productivity and, notably, the absence of work-related accidents with injury.

The correlation between the systematic application of safety procedures and productivity improvement, observed in the case of collective metering panels, suggests that investments in safety can generate significant returns in terms of operational efficiency. The reduction in the use of more restrictive PPE, made possible by complete and safe de-energization, contributed directly to worker thermal comfort and dexterity, positively impacting task execution time.

V. Conclusion

This study reiterates the importance of an integrated and proactive approach to occupational safety in electrical infrastructure projects. CELESC's experience in implementing the smart metering project illustrates how rigorous documentary analysis, training programs, and performance-based technical assessment, complemented by optimized operational procedures and a culture of humanized integration, can mitigate risks and simultaneously boost efficiency. The absence of accidents with injury and the notable increase in productivity confirm the effectiveness of this model. Future research is suggested to explore the replicability of this methodology in different geographical contexts and types of projects in the electrical sector, as well as the quantification of direct and indirect financial impacts of accident prevention.

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Fig. 1. Integration SETUP AMI 13/12/2023

Fig. 2. Integration SETUP AMI 22/12/2023

Fig. 3. Integration SETUP AMI 22/12/2023

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Curto-Circuito Trifásico Franco em Painel de Média Tensão – Offshore, Bacia de Santos, Brasil

Drayton Roger Lebid
PETROBRAS
Santos-SP
drayton.roger@gmail.com

Carlos José da Silva Matos Pombo
PETROBRAS
Santos-SP
cjpombo@gmail.com

***Resumo*—** O presente trabalho aborda um evento ocorrido em um Painel de Média Tensão de uma unidade *offshore* da Bacia de Santos, que resultou em um curto-circuito trifásico franco, afetando pontualmente a continuidade operacional da planta. A resposta do sistema elétrico a este estresse evidenciou o desempenho satisfatório das proteções, cuja atuação rápida e em conformidade ao projeto permitiu limitar os danos à região próxima ao compartimento do componente em falha, possibilitando o restabelecimento eficiente da condição operativa, conforme constatado nas inspeções e manutenções corretivas realizadas em campo. A causa imediata do evento foi a desconexão de um componente mecânico da chave de aterramento, responsável pela articulação entre as chaves facas — que realizam a conexão à terra — e a haste de acionamento. Essa desarticulação resultou em uma indicação incorreta da posição da chave para os sistemas digitais, permitindo a liberação dos intertravamentos e a energização indevida da carga. Como consequência, desencadeou uma sequência de acionamentos das proteções em outros cubículos, incluindo a atuação do relé de arco e do limitador de corrente do *tie*. A análise das oscilografias dos relés de proteção também permitiu identificar, de forma detalhada, a contribuição dos motores de indução para o curto-circuito trifásico franco, demonstrando como a energia armazenada no fluxo magnético residual impacta a magnitude das correntes de falta. Esse fenômeno reforça a importância de sua consideração nas avaliações de proteção elétrica.

Palavras chave: chave de aterramento, curto-circuito, proteção elétrica, fixação roscada

I. INTRODUÇÃO

A confiabilidade de sistemas elétricos de média tensão é essencial para garantir a operação segura e contínua de unidades *offshore*, onde falhas podem gerar impactos significativos na produção e na segurança das instalações. Este trabalho analisa um evento crítico de curto-circuito trifásico franco ocorrido em um painel de média tensão de 13,8 kV, no qual uma falha mecânica na Chave de Aterramento (CA) resultou na indicação incorreta de sua posição. Esta falha possibilitou a energização indevida de um motor de indução de 11 MW do sistema de compressão principal em condição aterrada no painel elétrico, desencadeando a atuação de múltiplas proteções, incluindo o relé de arco e o limitador de corrente do tie, com correntes de curto-circuito atingindo picos registrados de 75 kA.

Em relação à causa imediata do evento, houve a soltura de uma porca de fixação M10 no articulador da Chave de Aterramento (CA). Como consequência, durante a manobra de abertura da CA, a chave permaneceu fisicamente fechada, enquanto seus contatos auxiliares indicavam status de aberta, concedendo permissivo de partida nos sistemas digitais. O bloco de contatos auxiliares desse sistema é posicionado na haste interna conectada ao articulador e, com a soltura da fixação, os sinais passaram a ser sinalizados sem correspondência com a posição real da chave. A Figura 1 apresenta um registro fotográfico realizado durante a inspeção interna ao Compartimento de Cabos, no dia do acidente. Em destaque na imagem: (a) a bandeirola interna, solidária ao eixo de acionamento das chaves, e (b) o pino articulador solto dentro do painel.

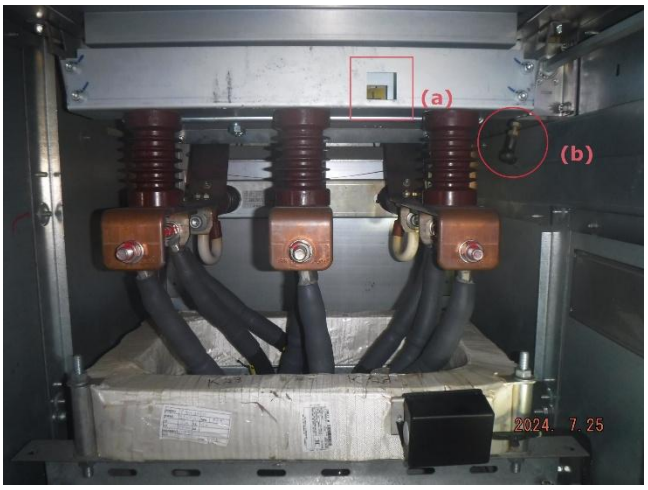

Figura 1: Pino Articulador e Bandeirola da CA

A análise das oscilografias revelou não apenas a magnitude das correntes de curto, mas também a contribuição significativa dos motores de indução que, mesmo após a interrupção da fonte de excitação, continuaram a fornecer

corrente por alguns ciclos, devido ao fluxo magnético residual. Esse comportamento destacou a necessidade de considerar as características transitórias de grandes motores nos ajustes de proteção elétrica frente a curtos-circuitos.

II. Detalhamento da Ocorrência

Nesta seção, apresentam-se as principais características técnicas do painel onde o evento ocorreu, com detalhamento do componente que falhou. Em seguida, é fornecida uma visão geral do desempenho do sistema elétrico durante o evento, destacando a atuação das proteções e a análise das oscilografias registradas nos relés.

A. Características Gerais dos Painéis

A Figura 2 apresenta alguns dados de placa do painel. Dado o estresse elétrico decorrente da falha, é importante avaliar a magnitude da corrente de curto-circuito franco atingida e o tempo de atuação das proteções, comparando-os com as seguintes características nominais do painel:

- suportabilidades, principalmente quanto as correntes de pico e de curta duração, Ip = 130 kA e Ik = 50 kA.
- classificação IAC com acessibilidade A (restrito somente a pessoal autorizado) e lados (F, L, R) com corrente e tempo de falta de 50 kA e 1 s

Parâmetro	Símbolo	Valor	Unid.
Tensão nominal	Ur	13,8	kV
Frequência nominal	fr	60	Hz
Tensão suportável nominal de impulso atmosférico	Up	95	kV
Tensão suportável nominal à frequência industrial	Ud	15	kV
Corrente nominal de regime contínuo	Ir	3150	A
Corrente suportável nominal de curta duração	Ik	50	kA
Valor de crista da corrente suportável nominal	Ip	130	kA
Duração nominal de curto-circuito	tk	1	s
Classificação de arco interno	-	IAC	-
Tipo de acessibilidade (código)	-	A (F,L,R)	-
Corrente de ensaio de arco	-	50	kA
Duração da corrente de ensaio de arco	-	1	s
Grau de proteção	-	IP 42W	-

Figura 2: Dados de Placa do Painel conforme ABNT IEC 62271-200

Vale ressaltar que Classificação IAC do Painel [1] visa oferecer um nível de proteção ensaiado às pessoas na redondeza do equipamento em condições normais de operação no caso de arco interno, pois leva em conta a sobrepressão interna que age nos fechamentos, portas, janelas de inspeção, aberturas de ventilação, etc.

Um painel com esta certificação considera os efeitos térmicos do arco, sua origem no invólucro, a expulsão de gases quentes e partículas incandescentes, mas não o dano à divisão interna e aos obturadores que não são acessíveis em condições normais de operação. Ou seja, em decorrência de um curto-franco, como o do evento, o painel precisa passar por uma inspeção criteriosa quanto à ocorrência de arco e possíveis danos internos.

B. Chave de Aterramento para Unidades Funcionais de Saída

Para unidades funcionais de saída, tem-se a instalação no Compartimento de Cabos, como item opcional, de uma CA com acionamento pela parte frontal por meio de um mecanismo de alavanca. Dentre as principais características deste sistema de aterramento, pode-se citar:

- as CAs são equipadas com mecanismos de operação de ação rápida para um fechamento em alta velocidade e são dimensionadas para a corrente nominal de curto-circuito ao serem fechadas sob carga.
- uma CA é operada manualmente para fechamento e abertura por meio de uma alavanca de operação, com a manobra realizada localmente e com a porta do compartimento de cabos fechada.
- a posição de manobra é indicada mecanicamente por uma bandeirola interna acoplada no eixo da CA e eletricamente por meio de um bloco de contatos auxiliares posicionado na lateral interna do compartimento de cabos.

Estas CAs possuem intertravamentos internos aos painéis:

- a CA não pode ser operada se a porta do compartimento de cabos estiver aberta.
- a abertura da porta inferior do compartimento de cabos só é liberada mecanicamente quando a CA estiver fechada.
- a CA só pode ser fechada quando o disjuntor estiver na posição de teste/seccionamento ou completamente fora do painel, devido ao intertravamento mecânico.
- o disjuntor só pode ser movimentado da posição de teste/seccionamento quando o disjuntor e a CA estiverem abertos. Na posição intermediaria do disjuntor, a CA fica intertravada mecanicamente.
- caso a CA esteja fechada, a parte extraível não pode ser deslocada da posição de teste/seccionamento para a posição de serviço devido a um intertravamento mecânico.

É importante destacar que o bloco de contatos auxiliares do painel em questão está acoplado à haste lateral, e não diretamente às lâminas de acionamento, conforme Figura 3. Consequentemente, quando o mecanismo está desarticulado - ou seja, com a haste lateral girando livremente - os contatos auxiliares deixam de refletir a posição real da CA.

A Figura 4 apresenta um recorte esquemático da CA modelo ST-E. A abertura desse tipo de chave ocorre pela liberação de uma mola de acionamento rápido, enquanto suas lâminas fecham o contato com movimento ascendente.

O engate com a haste de acionamento é realizado por meio de um articulador aparafusado com duas rótulas. As rótulas superiores e inferiores durante a manobra da CA sofrem esforços no sentido de apertar ou afrouxar a conexão roscada, de acordo com o seu movimento de abertura ou fechamento. Desta forma, havendo a soltura da conexão na rótula, o

mecanismo de aterramento estará desacoplado totalmente do movimento da haste de acionamento.

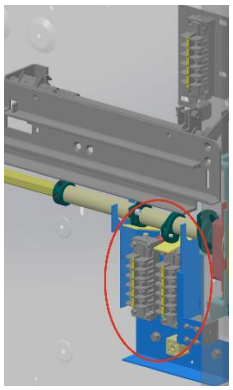

Figura 3: Bloco de Contatos Auxiliares

Figura 4: Articulador da CA

C. *Eventos e Oscilografias*

No dia do evento, durante a partida do compressor de exportação principal — que é a carga alimentada pelo cubículo que apresentou falha na articulação da CA — ocorreram os seguintes eventos no CDC principal de 13,8 kV: *trip* de dois turbogeradores, abertura do disjuntor do *tie* com atuação do limitador de corrente, sensibilização do relé de arco e desligamento de todas as cargas da semi-barra do cubículo em falha. Conforme descrito na introdução, estas atuações da proteção foram resultado do um curto-circuito trifásico franco no cubículo da carga acionada.

Nas oscilografias aquisitadas se observa o pico da corrente de curto-circuito franco atingindo o patamar de 75 kA, bem como o aterramento das três fases através dos sinais de tensão indo a zero, caracterizando um curto-circuito trifásico franco de elevada magnitude, como evidenciado pelas Figuras 5 e 6.

Em decorrência deste evento, após a investigação em campo, os danos ao painel foram considerados como marginais dado o potencial lesivo do evento, em virtude principalmente de uma eficiente detecção e contenção do nível de curto pelos elementos de proteção elétrica, em especial pelo limitador de corrente do tie, tal como previsto nos estudos elétricos do projeto da FPSO.

O limitador de corrente do tie do painel principal é um componente físico que visa limitar o nível curto na barra no cenário de máxima geração da plataforma, de maneira que não sejam ultrapassadas as suportabilidades do painel elétrico e do disjuntor. Este cenário de máxima geração acontece quando há 04 (quatro) turbogeradores de 25 MW sincronizados diretamente no painel principal de 13,8 kV. Neste cenário de máxima geração, o nível de curto simulado é de 165,9 kA de pico, acima do limite de 130 kA apresentado na Figura 2.

No entanto, como foi apresentado na Figura 5, ao abrir o tie, segregando as barras e consequentemente a geração e cargas motóricas, o nível de pico atingido foi de 75 kA, dentro das suportabilidades dos equipamentos instalados, garantindo um abertura segura do disjuntor, em virtude de uma atuação muito rápida do limitador de corrente.

A Figura 7 indica algumas variáveis lógicas e sua atuação ao longo do tempo, representando o status do disjuntor, a ativação da função de sobrecorrente instantânea e a atuação do Relé de Arco. A presença do arco foi confirmada em inspeção visual, que identificou elementos chamuscados e gotas de cobre derretido no interior do cubículo.

A Figura 8 ilustra a contribuição de um motor de indução conectado ao mesmo barramento, mas em outro cubículo, para o curto-circuito trifásico. Embora o curto-circuito remova a fonte de excitação do motor, o fluxo magnético presente no mesmo não se dissipa instantaneamente, resultando em uma contribuição significativa de corrente.

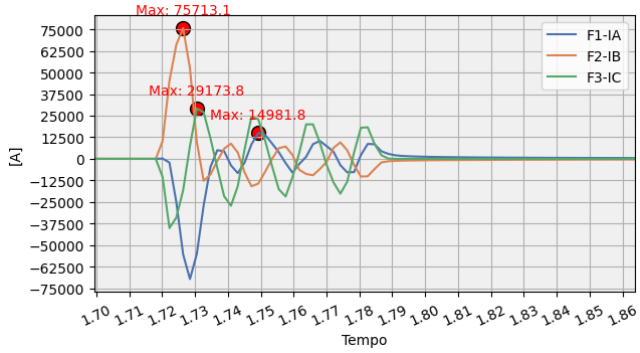

Figura 5: Corrente Registrada no Relé - Export A

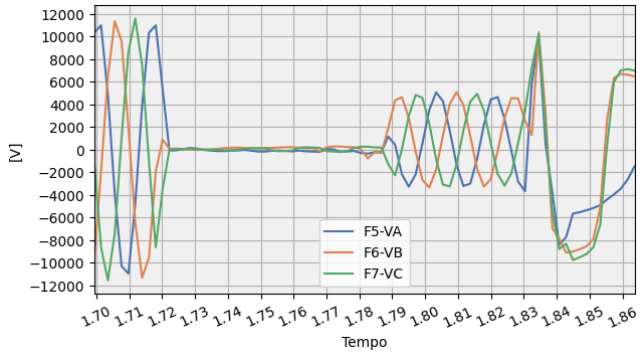

Figura 6: Tensão Registrada no Relé - Export A

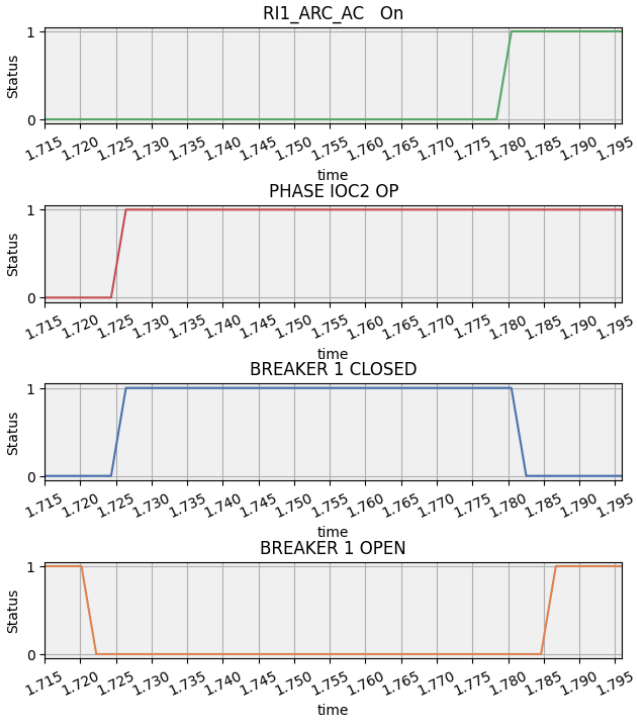

Figura 7: Status de Sinais Digitais no Relé

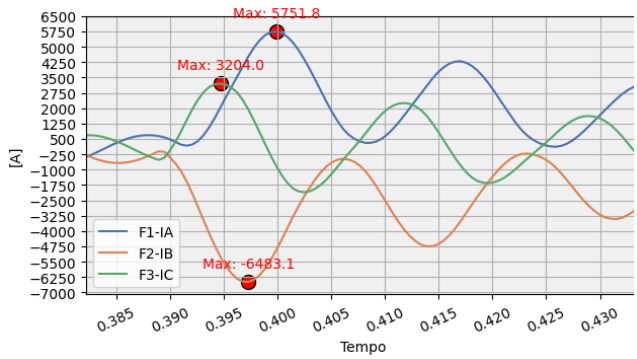

Figura 8: Corrente Registrada em Carga no Mesmo Painel - Injeção de Água

III. Desvio e Modo de Falha

A. *Desvios no CDC Principal*

No cubículo onde ocorreu a falha, durante a inspeção de campo, foram identificados os desvios decorrentes do curto:

- sinais de sublimação do cobre nas garras e facas, indicando possível formação de arco elétrico. Fenômeno também evidenciado pelas gotículas de cobre vaporizado em diversas partes da chaparia interna ao invólucro.
- campânulas da parte fixa íntegras.

Neste cubículo foram realizadas as seguintes manutenções:

- substituição das facas e garras da CA.
- substituição preventiva dos TCs, pois foram expostos a um ambiente com possível formação de arco elétrico e sinais de chamuscamento.
- instalação de um novo articulador da CA com mecanismos testados para evitar o auto afrouxamento.
- substituição da parte de potência do disjuntor, aproveitando seus internos, para testes e reparo em terra.
- substituição das ampolas do limitador de corrente

As Figuras 9 e 10 mostram o estado da CA após o evento, evidenciando as marcas de cobre derretido e carbonização. A Figura 11 e Figura 12 mostra as marcas nas câmpanulas e ambiente dos TCs (removidos e susbstituídos).

Figura 9 – CA Fechada

Figura 10 – Detalhe da Garra da CA

Figura 11 – TC retirados

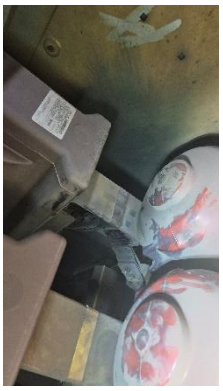

Figura 12 - Campânulas

B. *Modo de Falha*

Quanto ao cubículo em falha, anteriormente ao evento, houve um serviço de manutenção que exigiu o seccionamento e aterramento prévio. Após a execução das atividades previstas, as manobras para remoção do bloqueio e retirada do aterramento haviam sido realizadas normalmente, sem indícios de falhas no sistema. No entanto, apesar do supervisório e da bandeirola interna ao compartimento de cabos do painel indicarem que a CA estava aberta, ela permaneceu fisicamente fechada.

Na CA, o articulador é formado por dois pivôs: um inferior (conectando haste de acionamento e o articulador) e outro superior (conectando o articulador ao eixo das chaves-faca). Foi identificada, na conexão roscada da rótula superior do articulador, a ausência de mecanismos de travamento contra o auto afrouxamento da porca de fixação. Esta ausência permitiu o afrouxamento gradual da porca de fixação até a sua soltura total, rompendo assim ligação física entre a haste e o eixo de acionamento das lâminas da CA.

A Figura 13 mostra um articulador com conexão superior solta, ilustrando o modo de falha em questão. Em relação às possíveis causas, foram levantadas duas hipóteses principais:

1) carga insuficiente aplicada na montagem da porca sextavada
2) travamento de rótula devido à corrosão, resultando no afrouxamento gradual da fixação.

Figura 13 – Porca Solta

Em relação à hipótese 2, não foi verificado em campo corrosão no elemento articulador, indicado assim um problema pontual de montagem definido na hipótese 1,

associado à ausência de mecanismos contra auto afrouxamento.

No caso de fixações por parafuso, o torque é transferido ao longo do eixo do mesmo, provocando seu alongamento. Quanto maior o torque aplicado, maior o estiramento do parafuso, resultando em uma tensão de aperto maior. O atrito entre as superfícies das roscas desempenha um papel fundamental na retenção do torque, evitando sua perda.

C. *Medidas corretivas*

Juntas parafusadas podem sofrer um mecanismo de afrouxamento quando submetidas a cargas transversais, vibrações ou ciclos térmicos, o que pode levar à completa perda da pré-carga no fixador [2].

Assim, a correção implementada inclui reforços projetados para evitar a soltura gradual causada por vibrações, impactos ou variações térmicas, sendo composta pelos seguintes elementos:

- uma arruela de pressão e
- aplicação de trava-rosca.

Como parte dos desdobramentos do evento foram implementadas novas inspeções, *retrofit* da fixação para incluir mecanismos adequados contra auto afrouxamento e treinamento técnico das equipes operacionais, com foco em prevenir falhas ocultas e proteger a integridade das instalações e das pessoas.

IV. Conclusão

Um painel elétrico de média tensão é composto por diversas partes mecanicamente interconectadas, incluindo elementos móveis e componentes extraíveis, que ao longo de sua vida útil — desde a montagem em fábrica — podem apresentar problemas localizados de fixação. Esses problemas são particularmente influenciados pelas condições de armazenagem, pelos procedimentos de montagem, comissionamento e operação.

No caso analisado neste trabalho, houve uma falha na fixação aparafusada do articulador, desacoplando mecanicamente a haste de acionamento do eixo das chaves-faca. Essa desconexão levou à ocorrência de um curto-circuito trifásico franco de grande magnitude, devido a um permissivo de partida indevido nos sistemas digitais, uma vez a que o bloco de contatos auxiliares empregado nos intertravamentos lógicos estava montante do ponto de desconexão.

A segregação das barras de geração pelo limitador de corrente do *tie* e a eliminação rápida da falha por abertura do disjuntores contingenciou os danos, o que permitiu um restabelecimento ágil da condição do painel, com substituições pontuais de elementos durante a manutenção corretiva.

O detalhamento do histórico de manutenção, realizado após o evento, indicou um modo falha oculto, reforçando a importância das inspeções adequadas e da manutenção preventiva para mitigar riscos em sistemas críticos de energia.

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Vulnerability Analysis for Explosion and Fire Scenarios in Power Transformers

Edmilson José de Castro
Vale S.A.
Vitória, Brazil
edmilson.jose@vale.com

Camila Cunha Toledo Guerald
Vale S.A.
São Paulo, Brazil
camila.guerald@vale.com

Marcos Ferreira Lopes Júnior
Vale S.A.
São Paulo, Brazil
marcos.ferreira.junior@vale.com

Thallis Henrique Felipe
Vale S.A.
Vitória, Brazil
thallis.henrique.felipe@vale.com

Raphael Alasia
Vale S.A.
Vitória, Brazil
raphael.alasia@vale.com

***Abstract*— Power transformers are essential equipment in any electrical installation for the transportation or distribution of electricity, whether in systems with power plants associated with transmission systems, or in large industrial installations.**

Transformers adapt voltage levels to the different points in the system, enabling efficient and safe transportation of electricity. A feature of power transformers is the use of liquid insulating fluid, which has two main functions: to maintain the temperature at adequate levels for operation and to guarantee the electrical insulation of its components.

The point to watch out for is that this fluid has a fire point temperature that is not very high, and in the event of some failures can cause loss of tank integrity, where an explosion or fire scenario can occur. If this type of event occurs, the consequences can be catastrophic depending on the transformer's operating context.

Keywords — Transformers, Simulation, Critical Controls

I. INTRODUCTION

For the fire and explosion risk scenario of a large power transformer, a consequence analysis was carried out using software. This analysis covered the explosion and fire scenarios, occurring in an electrical substation that shares the same building with other administrative occupations. Through the results obtained from this vulnerability analysis, it will be possible to help the organization make decisions about options for improving its facilities by selecting preventive and mitigating controls effectively, contributing to risk management.

Whether or not a power transformer explodes or catches fire is not a common occurrence, but references on the subject indicate that it is not an insignificant event. Although statistics on transformer fires are not widely published, a comprehensive survey involving several countries [1] found that the average probability of serious transformer failures, which require major repairs or result in total loss, is 1% per year of service. Of these failures, approximately 10% can lead to a fire scenario.

This data can be used for a given company if it has a record of its failures classified as serious, considering that 10% of these would lead to a fire scenario, there would be an average probability of a fire of 0.1% / year. This represents an accumulated probability of 4% for an average life of 40 years for a power transformer. Therefore, although transformer fires are rare, they should not be disregarded [2].

This estimate of the probability or frequency of this event occurring could be used for risk management, but it is necessary to estimate the severity of its consequences. Severity could be defined qualitatively, but this work, using more detailed data on the operational context and the transformer itself, carried out a vulnerability analysis of the installation, defining the levels of exposure to thermal radiation and shock waves that would result from the event.

The focus of this work was to carry out a vulnerability analysis of the installation and the people exposed to this risk. However, for a better understanding, the possible fire scenarios in a large transformer will be described below.

II. TRANSFORMER FIRE SCENARIOS

This chapter will detail the possible scenarios that could be associated with an electrical transformer failure.

A. Internal arc failure and tank rupture

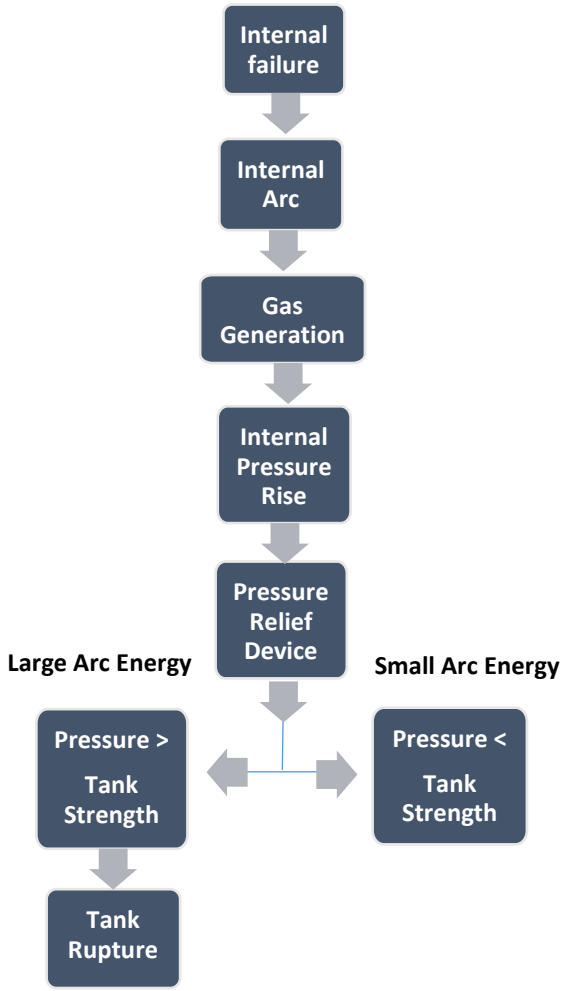
In the event of an internal failure of the transformer, there would be an arc current causing a rise in the temperature of the insulating fluid near the point of failure, generating gas and internal pressure waves which, when interacting with the welds and seals of the tank, could cause it to rupture. Without the tank rupturing, and therefore without contact with external oxygen, a fire would not start [1].

If the failed transformer is not disconnected quickly, there will be a progressive increase in the internal pressure of the tank, which could lead to its rupture, releasing this heated fluid above its fire point which, when it comes into contact with oxygen, would start a jet or pool fire, throwing fragments and

overpressure waves. The likelihood of a tank rupture occurring for an internal arc current will depend on a number of factors intrinsic to the transformer, its installation and protection systems, such as:

- The failure elimination time
- The energy released at that point in the electrical system
- The flexibility and resistance of the tank.

Figure 1



Tank rupture process due to internal failure [1]

B. Transformer bushing failure

Failures in OIP (Oil Impregnated Paper) porcelain bushings often result in an explosive failure with the breakage of the porcelain on the outer body and the displacement of the inner body in relation to the bushing's flange with the tank, expelling high-temperature oil out of the tank, which will start a fire. It is also expected that all the oil in the tank that was contained will spill out through the bushing flange, thus fueling the fire [1].

C. Failure of the cable connection box

An arc fault in the power cable connection box would lead to a very rapid rise in internal pressure, causing a catastrophic rupture of the power cable box. This rupture occurs before the electrical protection system has time to eliminate the failure. With the explosion of the box, there is a high probability that the bushings will be hit, evolving into the fire scenario initiated by a bushing failure. This scenario is very similar to arcing events in air-insulated switchgear, which are widely explored in technical literature [1].

Figure 2

Transformer explosion in a substation

III. CONSEQUENCE AND VULNERABILITY ANALYSIS

Among the possible fire scenarios presented, this work focused on internal arc failure, which could cause catastrophic rupture of the transformer tank. To manage the risk, the company's policy calls for it to be classified in its risk matrix.

In order to define the severity of the possible consequences, we considered the impact on people, both those who may be nearby for inspection and maintenance activities in the vicinity of the transformer, but also the people who work in the offices above the transformer installation site, so the vulnerability analysis carried out verified the non-tolerable risk zones for the building structure, which should remain integral allowing any evacuation of people.

The physical effects are defined according to internal procedures, which are based on recognized standards and RAGAGEPs (Recognized and Generally Accepted Good Engineering Practice) on the subject [3-6].

A. Operational context

The aim of this work is to prepare a consequence and vulnerability analyses, to support risk assessment for two transformers installed in a substation located at a Vale S.A. unit in the Port of Tubarão, located in the city of Vitória in the state of Espírito Santo. These scenarios were identified by Vale through a qualitative risk analysis, as they are installed close to places where people are constantly present.

The transformers analyzed (TF1 SAC and TF2 SAC) have 450 kVA and an oil tank with capacity of 704 liters each, and they are located in a non-structural masonry electrical substation. This substation is housed in a three-floor building with different occupancies, as shown below:

- *First floor (external area): separate cubicles where 02 transformers are installed;*
- *First floor (internal area): cable room;*
- *2nd floor: panel room;*
- *3rd floor: administrative rooms (~20 people);*

Figures 3 and 4 show the location and context described:

Figure 3

Location of the TF1 SAC and TF2 SAC transformers

Figure 4

View of the substation's transformer bays

The physicochemical characteristics of the transformer insulating fluids (TF1 SAC and TF2 SAC) were considered according to their Chemical Product Safety Data Sheet (MSDS), summarized in Table 1.

TABLE 1. PHYSICO-CHEMICAL PROPERTIES OF THE INSULATING FLUID

Type	Data
Name	Oil A
Use	Electrical insulating mineral oil
Composition	Lubricating base oil (99.7%) / 2,6-di-tert-Butyl-p-cresol (0.3%)
Flash Point	146°C
Density	0,88
Kinematic viscosity	10 mm^2 / s

The plant operates 24 hours a day, so it was decided to carry out the vulnerability analysis for both the day and night shifts. This analysis considered the specific weather conditions for each period at the site, as shown in Table 2.

The meteorological data for three years was collected from station A 612 station in the city of Vitória, Espírito Santo, which is located 7.1 km away from the area analyzed. analyzed.

TABLE 2. METEOROLOGICAL DATA

METEOROLOGICAL PARAMETERS		
Period	**Day**	**Night**
Avg. Air Temp.	27 °C	22,3 °C
Soil Temp. (day)	32,7 °C	26,2 °C
Solar radiation	379 W/m^2	11 W/m^2
Relative humidity (day)	65 %	83 %
Soil Roughness	0.25 m (Large equipment and constructions scattered)	0.25 m (Large equipment and constructions scattered)
Avg. wind speed	2,1 m/s	1,2 m/s
Pasquill Category	B	F

The purpose of the analyses is to verify the various possible effects of a given identified hazard. These effects can be:

- Fire in a pool, jet of fire or fireball;

- Explosion.

Mathematical models are inserted in software that allows calculations to be made and plot the curves for the calculated physical effects directly on a selected map. From there, it is possible to identify the areas affected, as well as defining the risks.

The scenarios analyzed, which are identified in this report as hypothesis (H) hypothesis, were broken down into two more hypotheses (H1.1 and H2.1) to evaluate Bleve's explosion exclusively using the standalone model, as shown in Table 3.

TABLE 3. ACCIDENTAL HYPOTHESIS

Identifying the Accidental Hypothesis	Accidental Hypothesis	Product
H1	Transformer explosion TF1 SAC	Transformer oil
H1.1	Explosion due to Bleve of TF1 SAC Transformer oil	Transformer oil
H2	Transformer explosion TF2 SAC	Transformer oil
H2.1	Explosion due to Bleve of TF2 SAC Transformer oil	Transformer oil

B. CONSEQUENCE ANALYSIS RESULTS

The simulation was conducted considering that the explosion occurred due to high oil temperature. According to reference [2], the explosion can result from two main hypotheses:

a) An increase in oil temperature reaching the fire point, which is higher than the flash point, due to an electric arc;

b) The formation of flammable gases, primarily hydrogen, due to oil decomposition caused by the arc, which increases

pressure and leads to the rupture of the oil tank, followed by the spontaneous ignition of H_2 upon contact with oxygen.

However, this study adopted only the first hypothesis, which is the increase in oil temperature. The are key parameters used in this simulation:

- Oil Fire Flash Point 171°C
- Vessel rupture pressure: 1.75 bar

The simulation results are presented in Table 7 for the physical effects observed across different scenarios. The results indicate the maximum range, regardless of whether it is day or night. The following effects stand out.

TABLE 7. RANGE OF EFFECTS OF ACCIDENTAL SCENARIOS

Identification of the accidental hypothesis	Accidental hypothesis	Radius of reach in meters															
		Pool fire				Cloud fire	Fireball				Cloud explosion				BLEVE explosion			
		4 kW/m²	15 kW/m²	25 kW/m²	37,5 kW/m²	LFL	4 kW/m²	15 kW/m²	25 kW/m²	37,5 kW/m²	0,21 bar	0,14 bar	0,07 bar	0,03 bar	0,21 bar	0,14 bar	0,07 bar	0,03 bar
H1_TF1 SAC	Explosion TF1 SAC	29,2	16,3	11,3	9,0	2,7	119,4	61,8	47,0	36,7	-	-	-	-	-	-	-	-
H2_TF2 SAC	Explosion TF2 SAC	29,2	16,3	11,3	9,0	2,7	119,4	61,8	47,0	36,7	-	-	-	-	-	-	-	-

- Pool fire with a maximum reach of 29.2 meters for thermal radiation of 4 kW/m²;

- Vapor cloud fire with a maximum reach at 50% of the lower flammability limit (LFL) of 2.7 meters;

- Fireball with a maximum reach of 119.4 meters for thermal radiation of 4 kW/m², making it the most significant effect among all observed.

- No pressure effects were detected, considering the adopted thresholds, in relation to vapor cloud explosion or the BLEVE that generated the fireball.

The levels of physical effects from thermal radiation and overpressure on adjacent infrastructures were assessed based on the company's standardized technical procedures. These procedures define reference values to support decision-making, identifying areas considered vulnerable. These levels are presented in Tables 8.

TABLE 8. OVERPRESSURE RANGES AND EFFECTS ON INFRASTRUCTURES

Overpressure range	Effect
30mbar ≤ P < 70mbar	Superficial damage to the structure Glass breakage, projection of unsecured components
70mbar ≤ P < 140mbar	Possible deformation of structural elements Possible projection of fragments Partial collapse of unreinforced masonry structures without windows
140mbar ≤ P < 210mbar	Possible failure of isolated structural elements Partial collapse of unreinforced masonry and concrete structure Structure cannot be repaired and must be replaced Possible serious injuries or fatalities of some occupants
P ≥ 210mbar	Complete collapse of structures Probable serious injuries or fatalities of all occupants

IV. CONCLUSION

Based on these results, the risk can be classified according to the company's risk matrix, guiding decision-making. Following a future risk analysis, preventive actions may be recommended, such as replacing oil-insulated transformers with dry-type transformers and replace OIP bushings to more modern technologies that are less susceptible to this failure mode.

Additionally, it is essential to review the transformer protection systems as critical and implement mitigation barriers, considering the relocation of personnel from the building, Fire Walls, Oil Containment and fire suppression systems for all transformers to prevent fire spread and escalation.

On the other hand, part of the fireball will exit through the bay gate, as previously mentioned, and may reach the upper part of the building. Therefore, it is suggested to reinforce the windows on the upper floor of the building.

Additionally, it is suggested that safeguards for the electrical protection system and fire-resistant walls be added as critical controls to ensure the designed effectiveness of these barriers throughout the entire lifecycle.

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A Review of Mechanisms of Lightning Injuries

Gabriel Simião dos Santos
Federal University of Mato Grosso - UFMT
Interdisciplinary Center for Studies in Energy Planning - NIEPE
Cuiabá, Brazil
gabriel.santos15@sou.ufmt.br
https://orcid.org/0009-0008-9626-2705

Walter Aguiar Martins Junior
IEEE Member
Brazilian Association for Awareness of the Dangers of Electricity - ABRACOPEL
Cuiabá, Brazil
walter.aguiar@ieee.org
https://orcid.org/0000-0003-1134-0548

Hélio Eiji Sueta
IEEE Member
Institute of Energy and Environment of the University of São Paulo – IEE USP
University of São Paulo
São Paulo, Brazil
sueta@iee.usp.br
https://orcid.org/0000-0002-3079-2040

Ronald L. Holle
Holle Meteorology & Photography
Oro Valley, Arizona
rholle@earthlink.net
https://orcid.org/0000-0001-7448-6224

Mary Ann Cooper
African Centres for Lightning Education Network - ACLENet
University of Illinois
Chicago, Illinois
macooper@uic.edu

Danilo Ferreira de Souza
Electrical Engineering Department - DENE
Federal University of Mato Grosso - UFMT
Cuiabá, Brazil
danilo.souza@ufmt.br
https://orcid.org/0000-0002-1155-1778

***Abstract*— Lightning represents a critical atmospheric hazard, with direct and indirect injury mechanisms well-established in the literature. Currently, six mechanisms are recognized (five direct and one indirect), to which all officially recorded fatalities are ascribed. However, this study highlights that additional deaths occur from secondary effects, such as fires, failures in essential services (e.g., electrical power), and panic in mass gatherings, triggered by electrical discharges. Such fatalities, although linked to lightning as a primary cause, remain underreported due to a lack of proper classification. The application of eligibility criteria in the Scopus database revealed 302 publications by the end of 2023. Of these, 57 fully satisfied the inclusion criteria. The analysis revealed significant underreporting of fatalities associated with secondary effects, reinforcing the gap in existing classifications. The absence of formal categorization for these cases compromises statistical accuracy, impacting risk assessment and public policy formulation. The results highlight the need to expand classification systems to include secondary effects, ensuring a more accurate representation of lightning's societal impact. This restructuring will facilitate the development of more effective protection guidelines, safety standards, and prevention mechanisms. The study concludes that integrating these factors into official statistics is crucial for mitigating risks and saving lives, providing a technical basis for advancements in public safety and disaster management.**

Keywords— Lightning, Victims, Underreporting, Indirect Mechanism, Lightning-related deaths

I. Introduction

Lightning constitutes one of the most well-known and lethal natural phenomena, resulting in significant impacts on both human life and infrastructure. These events occur during the formation of thunderclouds when the dielectric strength of air is exceeded, causing an electrical discharge. In addition to direct physical implications, lightning causes considerable economic and material losses.

The following are examples of lightning impacts documented recently in several countries:

- **China**: Damage caused by atmospheric discharges accounts for annual costs in the millions of dollars.

The most affected sectors include civil engineering and electrical power transmission lines [1].

- **Sri Lanka**: 39 houses were destroyed and 741 were damaged between 1974 and 2019, highlighting that it has historically caused significant losses [2].
- **Brazil**: Regarding human victims, records of deaths and injuries caused by lightning exceed those associated with other natural disasters, such as floods and landslides, among other phenomena [3]. Data from ELAT (Grupo de Eletricidade Atmosférica – Atmospheric Electricity Group) indicate that 835 deaths due to lightning were between 2013 and 2022.
- **Romania**: 724 lightning-related deaths were recorded between 1999 and 2015 [4].

Global scale: the precise estimation of the number of victims remains a challenge due to the lack of systematic information in various regions of the world [5].

Although not always explicitly stated, lightning-related deaths and injuries are attributed to specific mechanisms, i.e., the ways in which victims are struck by electrical discharge. Currently, six established mechanisms are recognized: six direct mechanisms, comprising five of an electrical nature and one non-electrical. However, other forms of death indirectly associated with lightning are not recorded as such due to the lack of appropriate categorization for so-called secondary mechanisms. Situations such as fires, interruptions of essential services, and episodes of panic in mass gatherings illustrate these effects. Therefore, it is necessary to establish parameters that aid in identifying and classifying these occurrences, proposing the category of "secondary effects from lightning" to reduce underreporting and obtain more accurate statistics on lightning-related damage.

Thus, existing mechanisms must be reorganized and improved to encompass new modalities of lightning injury. To substantiate these improvements in the categorization and reporting of secondary effects, this review sought to answer three guiding questions:

- **Research Question 1 - What are the mechanisms of lightning-induced injuries?**
- **Research Question 2 - How should lightning injury mechanisms be classified?**
- **Research Question 3 - What is the percentage of injuries caused by each mechanism?**

A Systematic Literature Review was conducted to answer these three research questions, aiming to identify secondary mechanisms and patterns for their classification.

II. Methodology

The Scopus database was utilized for this research, selected for its extensive coverage of scientific literature and its provision of access to millions of specialized articles. The methodological process was structured in three main stages:

Stage 1 – Initial Search: Once the research questions were defined, this first stage involved conducting a bibliographic search using the string "TITLE-ABS-KEY(Lightning) AND TITLE-ABS-KEY(Victims)". The search, conducted in August 2024, yielded 293 publications. As Scopus retrieves results based on keywords, abstracts, and titles, it was necessary to apply exclusion criteria. This followed an initial screening, conducted by reading the titles, abstracts, and keywords of all retrieved documents, to identify studies with the potential to answer the research questions (RQs).

Stage 2 – Application of Exclusion Criteria: In this stage, the following exclusion criteria were defined and applied to refine the identified set of articles:

1st – Publications in languages other than English or Portuguese;

2nd – Inaccessible articles;

3rd – Studies irrelevant to the research topic; and

4th – Duplicates.

Stage 3 – Analytical Review: Following the application of exclusion criteria, 186 articles were deemed relevant to the research scope. Subsequently, these documents underwent analytical reading, resulting in the final selection of 59 articles. These selected articles offered relevant contributions to the understanding and further investigation of the research topic (Fig. 1).

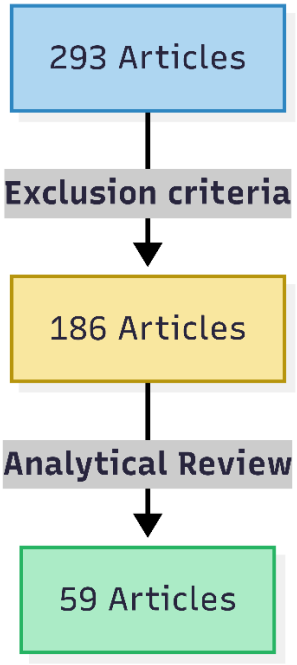

Fig. 1. Methodology summary.

III. Results and Discussions

In cases of electrical accidents caused by lightning, injury mechanisms are classified according to how the victim is exposed to the discharge. Of the six mechanisms described in the literature, five involve direct contact with the electrical current, while only one is considered a direct non-electrical mechanism, occurring when the victim is not directly struck by the electrical current but suffers its resulting effects.

And the side mechanism of lightning: When there was the occurrence of some fatality resulting not from the lightning directly, but rather from its effect.

Research Question 1: What are the mechanisms of lightning-induced injuries?

IV. Side Effects of Lightning

Lightning-related accidents are often attributed to direct mechanisms (electrical or non-electrical), but they also occur through indirect pathways—such as fires, panic in crowded public places, and service disruptions—which do not yet have their own specific classification. This text proposes the recognition of these secondary mechanisms, where lightning does not directly injure victims but instead triggers harmful events.

Lightning-initiated Fire: Wildfires cause serious environmental impacts, generate significant economic losses, and, at certain times of the year, worsen public health. Globally, lightning is responsible for about 10% of these fires, characterizing it as a secondary ignition mechanism [6].

Lightning-initiated fires, though less common than human-caused ones, occur mainly in high-latitude biomes. They are generally caused by dry lightning, which encounters very dry vegetation and starts fires in remote, difficult-to-access locations, often forming multiple ignition points and delaying firefighting efforts. As a way to anticipate these events, computational models can be used to assess regional ignition risk [7].

In Canada, lightning is responsible for a significant portion of wildfires. Between 1986 and 2001, the Council of Canadian Fire Marshals and Fire Commissioners (CCFMFC) recorded 12,244 such occurrences—an average of 815 fires per year. These fires originating from electrical discharges resulted in 47 deaths (an average of three fatalities annually) and 247 injuries (approximately 16 people injured per year), demonstrating that lightning-initiated fires are not isolated events [8].

Fig. 2. People fleeing wildfire sparked by lightning.

In May 2024, a lightning strike hit the roof of a house in Lawrence County, Tennessee, triggering a fire that killed two people: an 18-year-old pregnant woman and a 7-year-old boy. Meteorological sources and witnesses confirmed the electrical discharge as the sole cause of the blaze, with no other agent identified. The rapid spread of the fire prevented immediate rescue, and official investigations ruled out other origins for the incident [9].

Lightning-initiated Panic: In environments with large concentrations of people, the loud clap of thunder caused by a nearby lightning strike can provoke panic, leading to stampedes and, in extreme cases, crushing and trampling. An example occurred in August 1964, when lightning struck near the Morumbi Stadium in São Paulo, as the Figure 3a and 3b represents, generating a stampede at the exits and resulting in one death from trampling. Another case was recorded in 2013 in Malawi, during a religious service, where an electrical discharge caused panic, leading to several deaths during the evacuation of the premises [10].

Fig. 3a. Panic ignited by lightning at Morumbi.

Fig. 3b. trampling victim.

Service Disruption by Lightning: Atmospheric discharges threaten people and structures and can disrupt essential services such as power, communications, transportation and medical care, leading to accidents, injuries and fatalities. This dual impact, causing both physical damage and operational shutdown, is well documented in scientific and journalistic sources [12].

In the literature, lightning has caused potentially fatal disruptions to hospital services. In one case, a direct strike cut power, and when restored, the fire alarm and digital radiology network failed. In another, failures worsened: communication systems, fire alarms, and electronic access became inoperable.

Critical care systems were also compromised, blocking access to medical records and halting automatic medication dispensers [13].

Additionally, a serious railway accident occurred in China on July 23, 2011. An electrical discharge struck the signaling system, causing it to get stuck on green and interrupting communication with the central control system. Consequently, one train stopped on the tracks due to failure. However, another train, receiving the incorrect green signal, proceeded normally and eventually collided with the stationary train (Figure 4). The impact resulted in 40 deaths and left 192 others injured [14].

Fig. 4. Collision and service outage caused by lightning.

In Santa Fe, New Mexico (2016), a lightning strike caused a blackout that disabled the city's traffic lights. The signal failure resulted in a fatal accident when a motorcyclist, stopped at an intersection, was hit by a car. Police confirmed the direct link between the electrical discharge and the death [15].

This event illustrates the secondary mechanism: the discharge itself didn't strike any victims, but by disrupting services, it triggered serious accidents that would have been less likely otherwise.

For protection, lightning protection standards (in Brazil ABNT NBR 5419-2 and globally IEC 62305-2) indicate risk management parameters that directly address this issue, notably in hospitals reliant on powered medical devices.

V. Direct Mechanisms - Electric

Direct Strike

Among lightning injury mechanisms, direct strike is the most well-known and intuitive form. It refers to the electrical impact that occurs when lightning directly strikes the victim's body, establishing a conductive path between the cloud and the ground through the human body. This type of injury generally occurs in contexts where the individual is unprotected outdoors, either due to the inability to find safe shelter or due to negligence or recklessness in the vicinity of an electrical storm [16].

Recreational activities such as golf, soccer, and boating are among the most common scenarios for direct strike accidents [17]. The head — the highest part of the body — is typically the region of greatest impact, especially in fatal cases. Between 2012 and 2020, a retrospective study in eastern Turkey recorded 17 deaths from electrical discharge; as an instance in Figure 5, all involved farmers or shepherds struck during cattle herding [18]. At least some of these could be considered to have involved direct strike, but it is impossible to evaluate the frequency of this mechanism without having carried out detailed examination at the time and place of the events.

Fig. 5. Man grazing cattle.

Another possible scenario for a direct strike is a case from India when a 50-year-old man was struck by a discharge while riding his motorcycle on a rainy night. The lightning struck the rider, and the electrical current was transferred to the motorcycle, as illustrated in Figure 6, causing the vehicle to catch fire and become carbonized. The victim did not survive the multiple injuries and died because of severe burns across his body [19].

Fig. 6. Man riding bike.

Operating motorcycles and other small, exposed vehicles offer no Faraday cage protection against lightning. In a retrospective review of 27 lightning related events between 1971 and 2007 (compiled from newspapers, broadcast media and other reports), 39 riders were struck; nearly half of these incidents proved fatal, resulting in 19 deaths, while the remaining 20 caused nonfatal injuries.

Most strikes occurred while riders were in motion, whether herding animals at slow speeds or traveling on

highways. These incidents frequently led to severe secondary trauma: riders slid into ditches, collided with embankments or barriers, or were thrown from their vehicles after the strike.

In five additional cases, individuals who sought refuge beneath trees, like side flash mechanism, underscoring that nearby tall objects do not offer haven during thunderstorms. This combination of a high fatality rate among moving riders and the absence of any protective enclosure highlights that motorcycles and similar exposed vehicles represent a dangerous setting during lightning storms [20].

A direct strike is often fatal, as the entire energy of the lightning bolt is transferred to the victim intensely and rapidly, compromising vital organs; this mechanism is associated with cardiopulmonary manifestations [21].

Despite its high lethality, there are survivors of direct strike with severe sequelae. In a case from Ireland, a father and his two children were struck by the same lightning bolt: the father suffered a burn, experienced cardiopulmonary arrest, spent 49 days in the ICU (intensive care unit), and was discharged still experiencing muscle weakness and reliance on crutches. The children, affected by a side flash, presented only superficial burns and Lichtenberg figures, without severe complications [22].

Touch Voltage

When lightning hits a metal conductor, it creates a voltage difference with the earth that can drive a fatal current through anyone touching it. For example, on September 29, 2014, in India, three youths sheltering in an unprotected mud hut were injured—one by touching the struck wall and two by ground-spread current [23].

Touch voltage injuries are less common today due to improved grounding in modern buildings. In the past, inadequate grounding in homes led to fatal accidents. However, old or temporary structures still pose a deadly risk through contact with exposed metal [24].

In 2017, a national survey assessed the electrical installations of 999 Brazilian residences and found that only 12% were equipped with Surge Protection Devices (SPDs), leaving 88% of the properties vulnerable to voltage spikes. This deficiency exposes equipment and occupants to the risk of atmospheric or induced overvoltage and increases the chance of touch voltage incidents—such as when handling a telephone connected to a charger or touching energized appliances, as illustrated in Figures 7a and 7b.

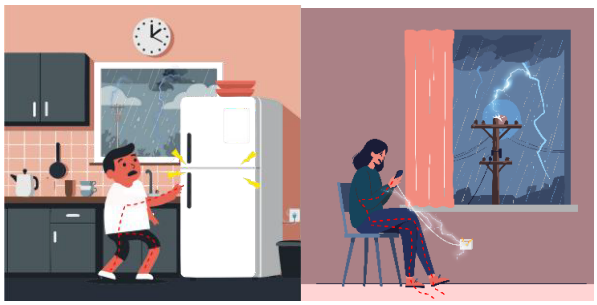

Fig. 7.a) Man holding a fridge handle; b) Girl holding phone at outlet.

This mechanism occurs in various scenarios, but its essential characteristic is contact with energized surfaces. It can occur both outdoors and indoors. For example, when a victim leans against a signpost (as illustrated in Figure 8), they become a conductive path and receive the electrical discharge [25], [26].

Fig. 8. Man holding light pole.

Side Flash

This occurs when lightning strikes an object, such as a tree or building, and travels towards the ground. However, if a victim is near the discharge channel, the current can jump to their body, which then completes its path; this is a current transfer from a neighboring object to the body [27].

Side flash happens when lightning strikes a nearby object and then “jumps” to a person because the human body offers a lower resistance path. In Turkey, for example, a 13-year-old boy was hit when lightning struck a tree and the discharge diverted through him, as illustrated in Figure 9. He lost consciousness instantly; despite receiving medical protocols and advanced therapies, his condition deteriorated, and he ultimately died [28].

Fig. 9. Man close to the tree struck by lightning.

The study reviewed 444 lightning-related incidents, more than half in the United States, recording 362 deaths and 1 101 injuries. In 310 of these cases, victims were within a few meters of trees—either pausing beneath the canopy or simply remaining nearby—while the remainder were struck in open terrain.

These episodes demonstrate how exposed people are when trees attract lightning. On 14 January 2004 in Swaziland, 60 worshippers were hurt after a strike hit a tree during a religious ritual. In August 1978 in Japan, 40 hikers were wounded—two needing hospital care—when a forest tree was struck. On 28 April 2011 in Cambodia, three plantation workers planting pine seedlings died and 30 were injured. Even social outings proved perilous: a 2005 family reunion in Pennsylvania left 30 guests hurt, and a 1994 camping trip in Massachusetts sent 22 campers for medical treatment [29].

Although side flash and touch voltage can occur in similar contexts, they can be similar but are distinguished by the current path through the human body. In touch voltage, the hands—which make direct contact with the energized part—are the affected regions. In side flash, however, the current typically travels along the lateral areas of the torso, i.e., zones excluding the head, hands, and feet [30].

The danger is even greater when the victim is in direct contact with the electricity. A case in Colombia highlights this risk: a soldier was struck by an electrical discharge that entered through his right shoulder, passed through his thorax—where a communication radio was located—and exited via his left elbow. The metallic necklace he was wearing melted due to the Joule effect, causing burns, and the current dissipated to the ground through his mattress [31].

Similarly, another soldier on guard duty in a sandbag shelter was seated when an atmospheric discharge struck a nearby metallic structure. The electrical current was conducted to the soldier's body, entering through the neck region and using a metallic necklace he wore as a conductive path, which caused burns. The current then traveled down his torso to the metallic belt buckle, continuing its path along his right lateral leg until it reached the rifle that was in contact with the ground, as depicted in Figure 10 [31].

Fig. 10. Soldier struck by lightning while standing guard.

It is important to note that an atmospheric discharge can occur without apparent signs of danger, as on June 3, 2017, in Conghua (Guangzhou): a “bolt from the blue” originated from a cloud to the southwest and struck a 13-meter-tall tree—the highest point in the location. The victim, only 1 meter from the trunk, received the current that “jumped” from the tree, striking his head and knocking him down. There were burns on the branches and leaves of this and neighboring trees, but a witness 10 meters away perceived neither lightning nor thunder. This means that even without rain, a person can be struck by an atmospheric discharge [32].

An emblematic case occurred on November 11, 1994, in South Africa, where lightning struck one of the metal poles supporting a 10 × 5 m tent where 26 pre-adolescents, two supervisors, and seven dogs were sleeping. Without direct contact, the impact melted part of the metal and formed an arc at the base of the pole. The closest victims suffered deep burns, fractures, ocular injuries, and tympanic membrane ruptures. Although three mechanisms were suggested—side flash, step voltage, and unconnected upward leader, the report was generic and did not associate each type of injury with its respective mechanism [33].

Thus, side flash manifests as cutaneous lesions and burns of varying degrees, accompanied by cardiopulmonary manifestations—including potentially fatal arrhythmias and cardiopulmonary arrest—in addition to the typical formation of Lichtenberg figures on the arms, shoulders, and torso, among other effects resulting from the passage of electrical current [21], [34].

Step Voltage

In a cloud-to-ground lightning flash, the electrical discharge injects a high-intensity current into the soil. However, soil is not a good conductor—unlike a copper wire—causing the current to spread out, forming equipotential lines. Thus, if a victim is within this area of influence (equipotential lines), a potential difference (PD) can exist between two points on the body, such as between the feet of a person or the legs of an animal, as shown in Figure 11. This PD generates an electrical current flow through the body, potentially causing severe injuries or even death [35].

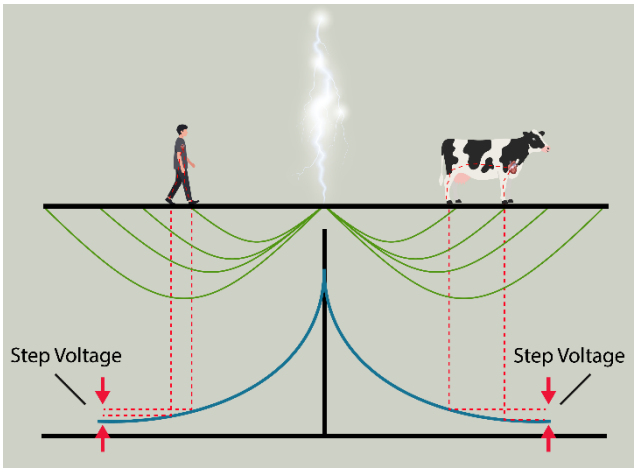

Fig. 11. Step Voltage diagram.

In Tamil Nadu, India, three suspected step-voltage incidents were reported: in 2007, 13 goats died after lightning struck near a tree; in 2008, five rural workers died and seven were injured while sheltering under a tarpaulin; and in 2014, seven agricultural workers were struck while planting in wet soil. Though these cases suggest step voltage, confirmation would require autopsies and soil-resistivity tests. Common to all is the presence of damp or exposed soil, which conducts electricity and creates hazardous potential gradients [36].

Consistent with these patterns, in an incident in Brasília, the capital of Brazil, lightning struck a tree 21 meters from a building where 31 people were present. The victims had

symptoms such as numbness and muscle pain among the individuals. The soil composition, rich in clay and moisture, could be a contributing factor to the propagation of the electrical current over a greater distance [37].

In quadrupedal animals, step voltage is even more dangerous: the leg closest to the lightning strike point is at a significantly higher electrical potential than the others. This potential difference between the limbs increases the current passing through the animal's body, particularly circulating through the thoracic region where the heart is located, drastically increasing the risk of cardiac arrest and severe injuries, as depicted in Figure 11 (shown previously) [38].

These discharges usually injure the feet and legs, leaving burn marks on the ground. Depending on soil conductivity, the hazardous radius can reach up to 10 meters [39][40].

Unconnected Upward Leader — UUL

In cloud-to-ground discharges, the electric field generates upward leaders from the ground, i.e., potential connection points for the lightning flash. A victim located in this region can become a conductive channel for one of these upward leaders and sustain injuries, even without direct contact with the main discharge [41].

During the mature stage of a thunderstorm, collisions between ice and water particles charge the cloud and send a downward leader toward the ground. As this leader nears, it intensifies the electric field at the surface, triggering upward leaders (streamers) from grounded objects. Figure 12 shows some of these upward streamers. When one of the upward leaders is intercepted by the downward leader (this successful upward leader is then called the connecting leader), all other upward leaders (termed Unconnected Upward Leaders or UULs) collapse instantaneously. This collapse can induce a discharge through the body of a nearby living being, potentially causing severe injury or death [42].

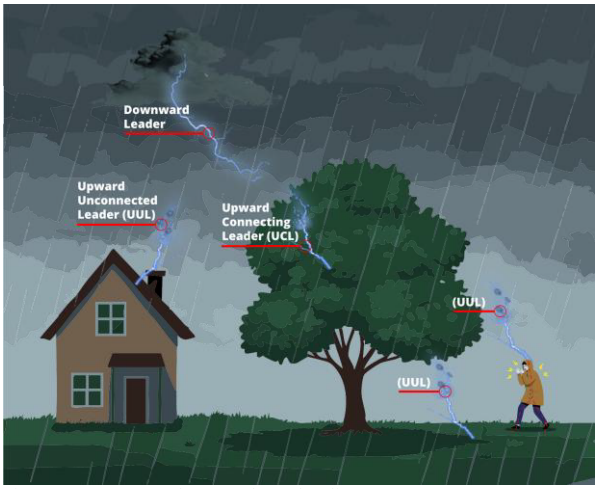

Fig. 12. Unconnected Upward Leader diagram.

The Unconnected Upward Leader mechanism was evidenced in an incident at a stadium in Johannesburg. During a storm's mature phase, charged downward leaders intensify the ground's electric field and trigger upward leaders (streamers) from objects. On October 28, 1998, video footage at a Johannesburg stadium captured such a strike near players—none of whom were simultaneously grounded by both feet— possible ruling out step voltage. Medical exams confirmed head-to-toe current flow (headaches and leg cramps), providing the first clear proof that unconnected upward leaders can injure people [43]. This is possible but is also mixed with ground current.

Initial exposure to the conditions conducive to UUL formation may elicit curiosity in a potential victim due to visible phenomena, such as the hair standing on end in Figure 13, indicating leader activity. This effect, occurring during inclement weather, is precisely a sign of leader electrical activity and, though seemingly innocuous, is associated with conditions that can lead to injury or death from UULs.

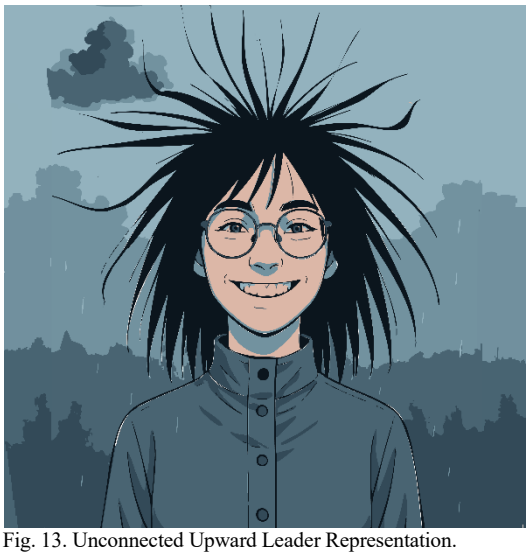

Fig. 13. Unconnected Upward Leader Representation.

Consequently, victims of this mechanism may present injuries like those caused by other lightning phenomena — such as cardiac insufficiency — in addition to paralysis and tissue damage, although typically with a lower degree of severity than that of a direct strike [42],[44].

VI. Direct Mechanisms – Non-Electric

Barotrauma

This mechanism is initially classified as indirect, as the victim is not directly struck by the electrical discharge but rather by its consequential effects, such as sudden air displacement that can hurl debris, cause burns, and inflict other physical damage, as shown in Figure 14 [45].

Fig. 14. Barometric Representation.

Victims of barotrauma resulting from electrical discharges may suffer various injuries, such as bone fractures, tympanic membrane perforations, hemorrhages, pulmonary contusions, and tearing of clothing and footwear. Additionally, these

events can have significant impact on nearby structures. In one documented case in Sweden, a lightning strike on a pine tree produced branching furrows in the ground, formed craters up to 2 meters wide and 75 cm deep, and displaced surrounding rocks [43],[45].

Barotrauma from a lightning strike causes an explosive expansion of air followed by collapse, generating pressure waves that tear soft tissues and force air into the mediastinum. The result is pneumomediastinum — an accumulation of air around the heart, great vessels, trachea, and esophagus — akin to the injury seen in conventional blast events [46].

The sequelae of atmospheric discharges can be severe, especially affecting the auditory system. For example, on Mount Giewont (Poland), a 16-year-old adolescent girl was struck by lightning during a hike; the impact tore her clothes, ripped the soles off her shoes, and caused hearing loss with tinnitus in her left ear, in addition to symptoms of post-traumatic stress disorder [47].

The immediate effects of barotrauma include hearing loss, tinnitus, and unconsciousness. In Turkey, a 31-year-old man lost consciousness for 30 minutes, sustained first- and second-degree burns, and experienced right ear hearing loss and left ear tinnitus, but had no lasting sequelae. In another episode, a 21-year-old youth, approximately 10 meters from a stricken tree, experienced momentary hearing loss without permanent damage. A third patient remained unconscious for five hours and, upon regaining consciousness, complained of dizziness and had hearing loss confirmed as permanent [48].

Finally, barotrauma represents a direct non-electrical mechanism: there is no passage of current through the victim's body, but rather mechanical effects from the discharge. Lightning's shock wave causes rapid air expansion and collapse, producing the injuries seen in this phenomenon [49].

Research Question 2 - How should lightning injury mechanisms be classified?

Direct electrical and non-electrical injury mechanisms are relatively straightforward to classify, based on medical examinations or autopsies and the characteristic injury patterns they produce. In contrast, confirming indirect lightning-related damages, such as a hospital blackout, requires thorough record analysis, forensic investigation, and exclusion of alternative causes (e.g., equipment failure or human error).

Secondary mechanisms, in this context, refer to all injuries or property damage resulting from disturbances caused by an atmospheric discharge.

Figure 15 presents a new proposed classification of these lightning-related injury mechanisms, aiming to organize them more clearly and comprehensively than previous models.

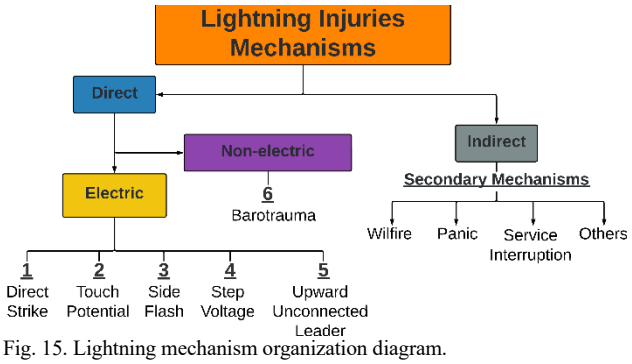

Fig. 15. Lightning mechanism organization diagram.

Research Question 3 - What is the percentage of injuries caused by each mechanism?

An estimated 3–5 % of lightning fatalities result from direct strikes or contact voltage; about 30–35 % from side flash; 50–55 % from step voltage; 10–15 % from unconnected upward leaders; and there are no consolidated estimates for barotrauma. These figures, compiled by Mary Ann Cooper's research group, are supported by clinical experience, literature, and expert consensus [16], primarily apply to developed countries.

However, poor communication between rural communities, the press, and authorities can distort lightning fatality estimates in some regions [54]. Furthermore, recent studies have shown that many accidents previously attributed to ground currents could, in fact, be due to unconnected upward leaders (UULs), based on the distances between the victims and the strike point.

Also, a study by another research group estimates that this distribution differs by an average of nearly 16% compared to medical data. In a review of literature and media data, they attributed 22% of fatalities to direct strikes, 14% to touch voltage, 15% to side flashes, and 17% to unconnected upward leaders, with step voltage remaining the most lethal at 24% [34].

And a recent study from Sri Lanka, 64.7 % of lightning injuries are caused by direct strikes, 6.0 % by contact (touch) voltage, 26 % by side flashes and 3.4 % by non-electrical mechanisms (barotrauma). Data for upward unconnected leaders or step-voltage mechanisms were not reported [2].

In Table 1, lightning accidents predominantly occur in developing countries, driven by open-field agriculture, inadequate healthcare, low public awareness, and scarce storm-safe buildings (Many rural homes lack basic structural protection). Insufficient alerts and firefighting resources raise risk.

Table. 1. Lightning distribution in underdeveloped or developing countries

Mechanism of Injury	References			
	[50], [51], [52], [53]	[54]	[55]	[34]
Direct strike	Between 3% and 5%	64,7%	5%	22%
Touch voltage	Between 3% and 5%	6,0%	5%	14%
Side flash	Between 30% and 35%	26,0%	35%	15%

Step voltage	Between 50% and 55%	~0%	20%	24%
Upward Unconnected Leader	Between 10% and 15%	0,0%	25%	17%
Non-electrical mechanism	Not informed	3,4%	Not informed	8%

VII. Conclusion

The current classification of lightning injuries, confined to direct mechanisms (direct strike, touch voltage, side flash, step voltage, UULs, and barotrauma), is insufficient to capture the full impact of the phenomenon. It is crucial to include secondary effects—such as fires, panic in public places, and service disruptions—to quantify all harm to people and property, as well as other mechanisms not yet officially documented. Recognizing indirect lightning risks will improve accident data, enhance prevention and training, refine fire/evacuation models, and drive technical solutions for infrastructure protection. This will enable detailed research on lightning mechanisms and promote safety policies to reduce casualties and economic losses.

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PÔSTERES

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A Segurança Elétrica no Contexto do ESG – Meio Ambiente, Responsabilidade Social e Governança Corporativa

Edson Martinho
Abracopel
Salto, São Paulo - Brasil
abracopel@abracopel.org.br

ORCID -0000-0003-4934-0797

***Abstract*—**

Este artigo discute a relação intrínseca entre os princípios do ESG (Ambiental, Social e Governança) e a segurança em eletricidade, evidenciando como falhas nesse campo podem comprometer tanto o meio ambiente quanto a integridade física das pessoas. A eletricidade, quando negligenciada, pode ser a causa de acidentes graves, incluindo incêndios, choques elétricos e falhas em dispositivos de proteção ambiental. O trabalho destaca a importância da responsabilidade social corporativa na prevenção desses acidentes, especialmente considerando o número crescente de ocorrências fatais em ambientes residenciais e profissionais. Além disso, ressalta a necessidade urgente de políticas públicas, ações educativas e governança eficaz para garantir o cumprimento de normas técnicas e regulamentações. A proposta central é inserir a discussão da segurança com eletricidade de forma estruturada nas estratégias ESG, ampliando o foco da sustentabilidade para além das questões ambientais, incorporando a proteção da vida humana como elemento essencial.

Palavras-chave: ESG, segurança em eletricidade, responsabilidade social, sustentabilidade, governança corporativa.

This article explores the intrinsic relationship between ESG principles (Environmental, Social, and Governance) and electrical safety, emphasizing how failures in this area can jeopardize both the environment and human life. Electricity, when misused or poorly managed, can lead to severe accidents such as fires, electric shocks, and malfunctions in environmental protection systems. The study highlights the role of corporate social responsibility in preventing such incidents, especially in light of the growing number of fatal accidents in residential and professional settings. It also underscores the urgent need for public policies, educational initiatives, and effective governance to ensure compliance with technical standards and regulations. The central proposal is to incorporate electrical safety more explicitly within ESG strategies, broadening the sustainability agenda beyond environmental concerns to include the protection of human life as a fundamental component.

Keywords: ESG, electrical safety, social responsibility, sustainability, corporate governance.

I. Introdução

No mundo atual em que as ações e atividades das empresas devem ser pensadas e executadas de forma a criar o menor impacto ambiental, social e garantir o atendimento às legislações aplicáveis, a segurança com a eletricidade surge como um ponto de grande importância. No âmbito da sustentabilidade, ou seja, do meio ambiente que representa o E (enviromental) do ESG, a segurança com eletricidade surge como ponto de controle de ações para que não haja nenhuma falha no processo e que possam causar danos ao meio ambiente. Exemplos do exposto é: um acidente de origem elétrica que possa acionar uma válvula errada, um curto-circuito que possa abrir uma comporta, uma

sobrecarga que gere um incêndio e que pode ser de grandes proporções afetando o meio ambiente. No S do ESG, de responsabilidade social, o tema segurança com eletricidade é crucial, pois é o limite entre um incidente e um acidente, que quase sempre causa consequências graves e muitas vezes chega ao óbito. A responsabilidade Social Corporativa nesse caso é o ato de gerar condições para "Preservar Vidas", em resumo são as formas de criar procedimentos que garantem a segurança e monitorarem as atividades. Com relação a Responsabilidade Social Corporativa - RSC, o maior desafio está em garantir que as normas, regulamentações e, legislações pertinentes sejam cumpridas por todos, ou melhor fazer com que os colaboradores compreendam a importância de seguir as normas e regras, garantindo assim a redução da exposição ao risco. Na terceira letra, o G de Governança, a atuação passa pela compreensão das legislações, regulamentações e normalizações pertinentes para cada atividade, estabelecer regras para a aplicação, monitorar essas ações e garantir que não sejam burladas de qualquer forma. Nesses três pontos, a Segurança e Saúde do Trabalho são importantes para que tudo saia dentro do planejado.

O objetivo desse artigo é introduzir esse tema com uma visão sistêmica, para que o todo seja visto de forma intrínseca e cultural, dentro da discussão da segurança do trabalho e que, certamente estará no dia a dia das empresas.

II. O CONTEXTO

O conceito de E.S.G ou em português A.S.G, que vêm das iniciais de Enviromental – Meio Ambiente; Social – Responsabilidade Social e Governance – Governança Corporativa, surgiu no início dos anos 2000 quando o então secretário-geral da ONU [1] , Kofi Annan, através de uma iniciativa que ficou conhecida como "Who Cares Wins" do Pacto Global da ONU, em parceria com o Banco Mundial, lançou um desafio aos 50 CEO dos maiores investidores no mundo, em que, a partir daquele pacto, qualquer ação, investimento ou mesmo financiamento, fosse sempre pensadas de forma a minimizar os efeitos nocivos ao meio ambiente, criar estratégias que pudessem recuperar os recursos ambientais e humanos que são degradados pelas atividades industriais e por fim, mas não menos importante, que toda a comunidade tivesse regras claras sobre como exercer seu papel na sociedade de forma sustentável, além de estabelecer que essas regras fossem compreendidas e seguidas por todos. De forma bem reduzida, foi assim que o E.S.G começou a ganhar corpo e que hoje, mais do que nunca é necessário, para um mundo sustentável em todos os quesitos. O ESG se apoia nos Objetivos do Desenvolvimento Sustentável – ODS, publicado pela ONU e que divide as metas a serem atingidas em 17, como mostra a figura 1. Essas metas subdividem em outras várias metas onde cada país deve trabalhar para atingi-las até 2030.

Figura 1 - Objetivo do Desenvolvimento Sustentável - ONU

Mas a pergunta é: O que o E.S.G tem a ver com a segurança em eletricidade? e a resposta é simples: muita coisa.

Então vamos tentar organizar os conceitos para que possamos apresentar a proposta desse artigo. A primeira é com relação na introdução. Nela fizemos um aparte, onde cito um exemplo de uma válvula que não abre, uma comporta que não fecha e poderíamos citar vários outras condições que podem serem prejudiciais ao meio ambiente e que dependem muito da eletricidade, no caso da eletricidade confiável e segura. De forma simples, podemos dizer que o risco de um acidente com a eletricidade acontecer, como um curto-circuito, por exemplo, e esse afetar o funcionamento de um dispositivo de proteção ambiental é grande. Por outro lado, se olharmos para o contexto da sustentabilidade, uma instalação elétrica corretamente dimensionada e instalada, resulta e menos perdas de energia, sobretudo pelo efeito Joule e com isso reduz o consumo de energia elétrica, reduzindo o consumo de recursos para gerar essa energia.

No contexto da Responsabilidade Social Corporativa, temos que visualizar a segurança com a eletricidade de uma forma mais ampla. No final do século 19, uma propaganda publicada em jornal da época, apresentava a eletrificação dos postes e das casas como um vilão e que mataria muita gente (figura 2). Em certo ponto isso era e ainda é uma verdade, já que a eletricidade possui uma série de riscos e pode levar a óbito, quando não respeitado os limites e não usada com responsabilidade. Nesse caso, todos os envolvidos com a geração, transmissão, distribuição e, consumo de eletricidade tem por obrigação, ou a responsabilidade social de garantir que a eletricidade não ofereça riscos para a sociedade, ou seja, as empresas têm por obrigação, criar ações que garantam a segurança de quem vai utilizar a instalação elétrica, mas também que trabalha com ela. Infelizmente isso não tem sido uma realidade. O Anuário estatístico Abracopel de acidentes de origem elétrica [2] nos mostra que os acidentes continuam a acontecer e pior, estão aumentando dia a dia, causando inúmeras vítimas como mostra a figura 3.

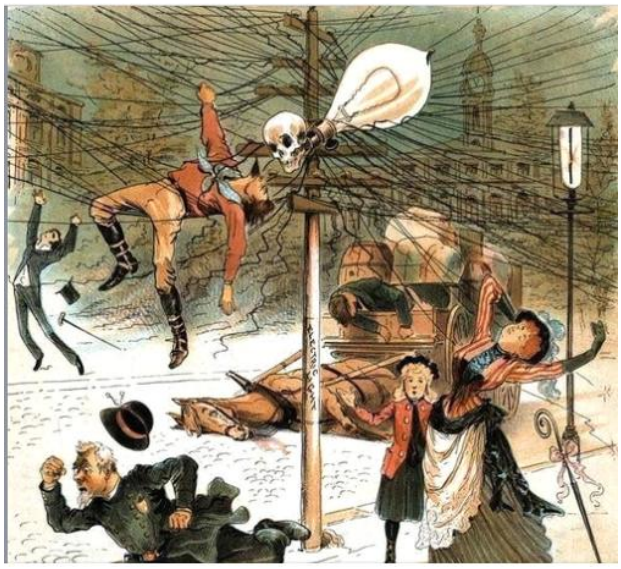

Figura 2 - publicação de propaganda negativa sobre a eletricidade

É possível observar que os acidentes com incêndios são os maiores, mas em termos de fatalidade (mortes) os choques elétricos são os vilões.

Figura 3 - Acidentes de origem elétrica - fonte Abracopel

Esses dados são assustadores, quando sabemos que os acidentes de origem elétrica são, na sua grande maioria, evitáveis, e que identificamos problemas crônicos de falta de conhecimento e descaso com a eletricidade. Os dados de acidentes relacionados a eletricidade e comparados com os ambientes onde acontecem nos mostram que o contexto da responsabilidade social corporativa ainda está longe de ser exercida com a devida seriedade. Isso pode ser conferido quando vemos na figura 4, que das 759 mortes ocorridas por choque elétrico, 293 estão relacionados a toques acidentais nas redes de energia elétrica e 248 acontecem em ambientes residenciais, ou seja, onde esperamos ser o nosso "porto seguro".

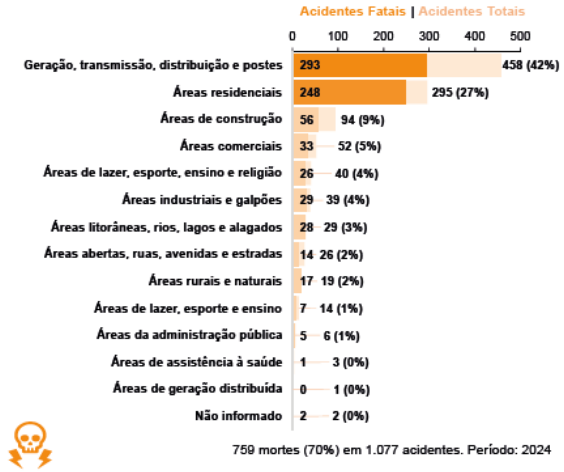

Figura 4 - Acidentes de origem elétrica por choque elétrico x locais de ocorrência

Voltando no contexto da nossa explanação de responsabilidade social corporativa, estamos alertando para a necessidade premente das empresas que gerem, transmitem e distribuem a energia elétrica, se unirem e criarem formas de evitar acidentes nas suas redes de energia. Mesmo sabendo que essas empresas, principalmente as distribuidoras de energia, que atuam em grandes centros urbanos e que são responsáveis para as redes de distribuição de energia, fazem várias ações para informar a sociedade sobre os riscos, e mesmo algumas em algumas regiões mais perigosas criarem mecanismos de inibição de acesso, ainda há muitas pessoas se acidentando dentro de subestações ou tocando em fios nos postes. Essas ações devem ser realizadas em grande escala, em conjunto, coordenadas e com objetivos específicos de informar, coibir e eliminar, ou reduzir drasticamente os acidentes cuja origem é a eletricidade.

Mas o problema não está somente nos muros das distribuidoras de energia, que também tem por contrato a obrigatoriedade de fiscalizar as instalações elétricas de baixa tensão em seus clientes, mas que entendem que não devem fazer e, portanto, não o fazem. Podemos observar que o segundo caso de acidentes fatais está nos ambientes residenciais, o que demanda um trabalho de responsabilidade social corporativa muito maior, já que os "usuários leigos" da eletricidade são as vítimas e que não compreendem os riscos. Um trabalho mais amplo e mais dirigido para esse público deve ser intensificado, como é o caso das ações que a Abracopel [3] realiza. Informar sobre os riscos que a eletricidade oferece, apresentar as formas de evitar os acidentes, definir qualidade mínima para equipamentos e dispositivos de segurança e garantir acesso por todos é uma ação que deve ser ampliada. Programas de microcrédito para reformas das instalações residenciais, disponibilização de produtos de qualidade com preços mais acessíveis, certificação da mão de obra com treinamentos e qualificação de profissionais entre outras ações podem e devem ser desenvolvidas como forma de minimizar o efeito nocivo da eletricidade.

Complementando o contexto, temos uma outra preocupação que encontramos nessa discussão. A figura 5 traz as principais profissões das pessoas que são vítimas de choques elétricos e, o trabalhador da construção civil, principalmente pedreiros e pintores aparecem em primeiro lugar, com 44 mortes seguidos, para nosso espanto dos

profissionais da área elétrica, ou seja, os eletricistas ou técnicos em eletricidade.

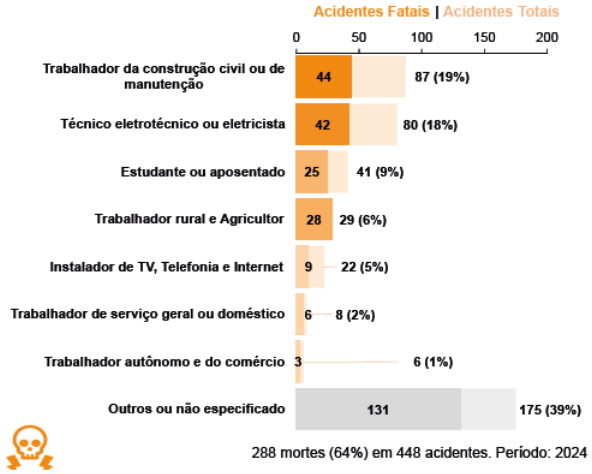

Figura 5 -Acidentes de origem elétrica - choque elétrico x profissão

É nesse caso que o "S" do ESG surge como um dos principais objetivos desse artigo.

Ainda dentro deste contexto a evolução dos acidentes de origem elétrica mostra a necessidade urgente de políticas sociais mais dirigidas. A figura 6 traz esses dados e nos assusta com a evolução rápida

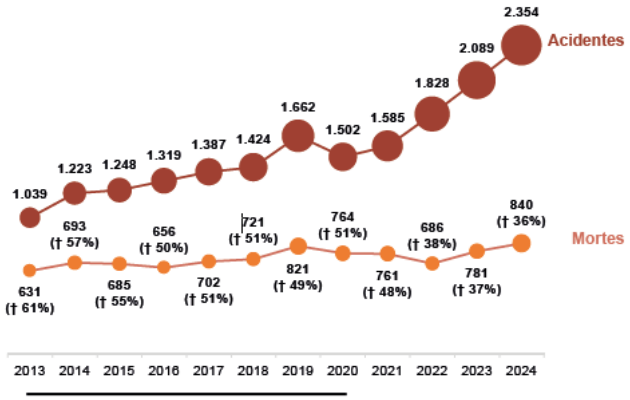

Figura 6 - série histórica de acidentes com eletricidade 2013 – 2025

Entrando pela Terceira letra do ESG, o de Governança Corporativa, encontramos um contexto muito importante, mas que temos identificado como falho na maioria das empresas e entidades. Trata-se do cumprimento de regras, normas, regulamentos, legislações etc. O Brasil, tem na ABNT [4], por exemplo, um acervo de normas considerável que orientam, recomendam, oferecem boas práticas e principalmente limites, e não deixa quase nenhuma margem para aplicações de forma errada, entretanto, a maioria das pessoas ignoram essas normas e acabam se arriscando, realizando ações sem a observância delas. O mesmo acontece com os regulamentos, o Ministério do Trabalho e Emprego por exemplo, têm em seu acervo, 37 normas regulamentadoras que "regulamentam" as atividades práticas como, serviços com eletricidade por exemplo, que é regida pela NR-10 – Norma Regulamentadora n. 10 – Segurança em Instalações Elétricas se Serviços em Eletricidade. Nesse caso um serviço com energia elétrica deve ser realizado por um profissional capacitado e autorizado, seguindo os projetos e os procedimentos de segurança, realizados com base nas análises de risco e nos ensaios definidos. Dessa forma o profissional não se acidenta e garante que os dispositivos de segurança estarão corretamente instalados e assim haverá uma instalação segura para o usuário. Então o conceito de governança diz respeito a garantir que as legislações, normas e regulamentos aplicáveis, sejam conhecidos, e seguidos de forma correta para que a preservação da segurança seja garantida.

III. Conclusão

Foi possível compreender que a prática conhecida pelas letras E, S e G estão diretamente ligadas ao contexto da segurança com eletricidade assim como outras ações. O objetivo desse artigo foi alertar para a premente necessidade de avançar e incorporar o assunto Eletricidade e Segurança nas discussões do ESG e não somente as práticas ligadas a sustentabilidade ambiental.

As discussões de como garantir a sustentabilidade e como engajar as pessoas nas práticas do meio ambiente, da governança e da responsabilidade social, devem sempre ter o componente da segurança das pessoas e animais contra os riscos que a eletricidade oferece, até porque as formas de evitar os acidentes são relativamente simples, mas devem ser usadas de forma responsável.

IV. Referências

[1] ONU – Organização das Nações Unidas – Organização intergovernamental criada para promover a cooperação internacional entre as nações.
[2] Anuário Estatística de Acidentes de Origem Elétrica – Publicado em 2025 com dados de 2024 e série histórica desde 2013
[3] ABRACOPEL – Associação Brasileira de Conscientização para os perigos da Eletricidade – fundada em 2005 para levar informações sobre os riscos que a eletricidade oferece e as formas de evitar os acidentes dessa natureza.
[4] ABNT – Associação Brasileira de Normas Técnicas- único fórum reconhecido para elaboração de normas técnicas no Brasil.

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Analysis of Electrical Fires in Brazil

João Pedro Kiedzerski Silva
Federal University of Mato Grosso
Interdisciplinary Center for Studies in Energy Planning - NIEPE
Cuiabá, Brazil
https://orcid.org/0009-0003-9553-4290

José Barbosa Oliveira
Sentinell Engenharia
Lightning Protection Systems
Belo Horizonte, Brazil
barbosa@sentinell.com.br

Hédio Tatizawa
Institute of Energy and Environment
University of Sao Paulo
Sao Paulo, Brazil
https://orcid.org/0000-0001-7597-7893.

Danilo Ferreira de Souza
Federal University of Mato Grosso
University of São Paulo
São Paulo, Brazil
https://orcid.org/0000-0002-1155-1778

Abstract*— Electrical fires represent a considerable proportion of accidents in Brazil, generating losses and fatalities. The lack of integrated studies and consolidated data makes it difficult to understand these events. This article analyzes data on electrical fires in Brazil in 2024, highlighting the occurrence by region, month, and cause category, based on 1.191 cases and 50 deaths. Homes were the main place of occurrence (528 cases, 44 %) and accounted for 92 % (46) of fatalities. There was an increase of 19 % compared to 2023 (1.004→ 1.191), totaling an accumulated growth of 104 % between 2020 and 2024. The methodology adopted follows the Abracopel protocol, including news collection, validation with the Fire Department and consolidation in a database. The results show a higher incidence in the Southeast (29 %), but a higher mortality rate in the Northeast (8 % vs. 2 % in the Southeast), indicating a disparity in the prevention and emergency response infrastructure. The study provides an up-to-date overview to support prevention and awareness policies.

Keywords*— Brazil, electrical fire, fatalities, electrical installations, risk factors

I. INTRODUCTION

The mastery of fire, around 400,000 years ago, is considered the greatest achievement of primitive humankind, radically transforming the ways in which we heat, cook food, and protect ourselves from predators [2]. However, the mastery of fire has brought with it, since its first uses, the inherent risk of uncontrolled fires, whose destructive power has caused major disasters and, throughout history, killed thousands of people on a global scale [1].

Similarly, electricity, although only incorporated into everyday life at the end of the 19th century during the Second Industrial Revolution, quickly became the central vector of modernization: it electrified industries, means of transport, communications, and homes profoundly altering. consumption patterns and social habits.

Today, without the electricity grid, not only would there be a lack of light, but the right to essential services would also be lost, from running hospitals to refrigerating food, as well as digital connectivity [5], [6].

Despite the millennia of difference between these two "discoveries", fire and electricity are now closely intertwined in the context of risks [2]. Electrical fires account for a considerable proportion of domestic and industrial accidents, with implications for both material losses and fatalities [3]. In Brazil, however, this topic remains little explored in the national scientific literature and is often overshadowed by the emphasis on electric shocks or fires from various causes [4]. The scarcity of integrated studies and consolidated data makes it difficult to understand the circumstances, motives and profiles of the victims involved in these events [4], [5].

Among the few reports on electrical fires in Brazil are the "Raio-X das Instalações Elétricas Residenciais Brasileiras"[5] , "Raio-X das Instalações Elétricas Comerciais Brasileiras"[6] and the “Investigation of the Quality of Electrical Installations in Commercial Properties in Brazil” [7] as well as the " Anuário Estatístico de Acidentes de Origem elétrica"[4]. These documents, published by the Brazilian Association for Raising Awareness of Electrical Hazards (Abracopel), present essential data that shows the seriousness of the problems with electrical installations in the country. Some of the main points raised are:

- The lack of adequate electrical projects.
- The absence of safety devices, such as Ground Fault Circuit Interrupter (GFCI).
- The lack of adequate earthing.
- Excessive use of plug adapters (T-adapter) and extension cords, resulting in overloaded sockets.

The aim of this article is to present and analyze data on electrical fires in Brazil, to answer the following research questions:

- **RQ1**: Which regions of the country are most affected by these accidents?
- **RQ2**: What is the main source of these fires?
- **RQ3**: How have safety measures related to these accidents evolved?
- **RQ4**: How can this study contribute to the social and academic spheres?

II. METHODOLOGY

The stages for the construction of this research are based on the methodology used by Abracopel [4], which is represented in the methodological flowchart (Figure 1). The following were considered:

- Searching national and regional news portals (list of vehicles in the Appendix).
- Filtering by keywords.
- Cross-validation with data from the Fire Department (when available).
- Consolidation in a database from 2020 to 2024.

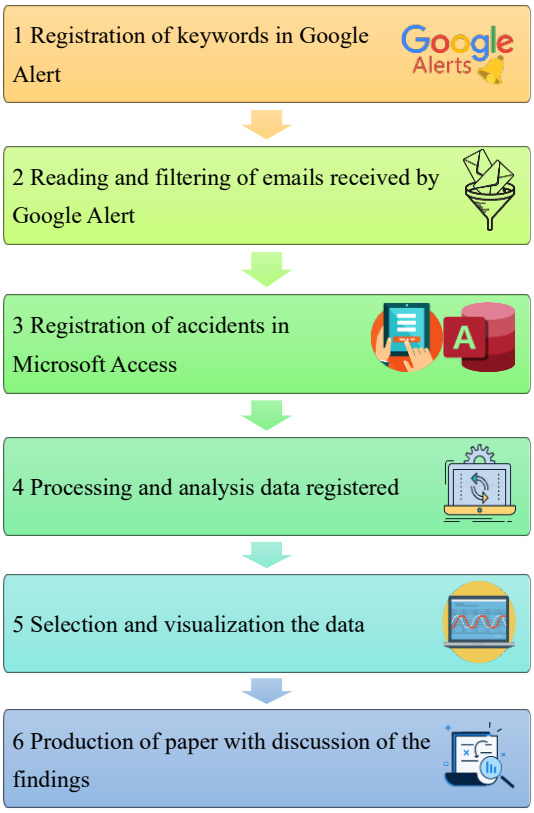

Figure 1. Methodological flowchart of data collection, process, and analysis.

As shown in Figure 1, the first step in constructing this research consisted of registering five ("5") keywords to be used on Google Alerts platform, which sends out notifications.

Alerts platform, which sends email notifications when it finds the latest news or results.

- Fire
- Short circuit
- Electrical Overload
- Electrical Fire
- Class C Fire

Abracopel, the organization responsible for monitoring and recording data on electrical accidents in Brazil, receives an average of more than ten emails a day containing news related to these keywords. However, approximately 70% of these notifications are discarded due to:

- Duplicate alerts.
- Alerts not related to fires of electrical origin.
- Alerts with insufficient information to characterize the event.

The second stage of the research, shown in Figure 1, is characterized by the reading and filtering of e-mails by Abracopel's technical team, with the aim of discarding irrelevant news.

The third stage involves recording information in its own database [4]. In this way, news from different media outlets often complemented each other and helped to consolidate data on the same electrical fire. However, some reported cases do not contain all the necessary information. For this reason, Abracopel makes direct contact with the victims or their families to enrich the database with more precise and detailed information. The information is recorded as follows:

A. Date of the fire.

- Year
- Month
- Day
- Time

B. Location of Fire

- State
- Geographic Region
- City
- Area (urban, rural, commercial, etc.)

C. Victim profile

- Age
- Sex
- Race/color

D. Fire characteristics

- Presence of fatality
- Alleged origin of the fire

The fourth stage of the research consists of verifying the integrity and veracity of the information obtained, through the government or other institutions. The fifth stage consists of structuring and presenting the data obtained in a clear and accessible way, to facilitate visualization of the results, allowing discussion and identification of the main points to be explored in greater depth. Finally, the sixth and last stage involves writing up the research in the form of a scientific article.

III. RESULTS AND DISCUSSION

This section presents and analyzes crucial data collected and systematized from the Abracopel database, addressing the incidence and number of fatalities by location, the demographic profile of victims, detailing sex and age group, the main causes and origins of these electrical accidents, and a comparative analysis of trends recorded over the last five years.

A. Fatalities/number of fires

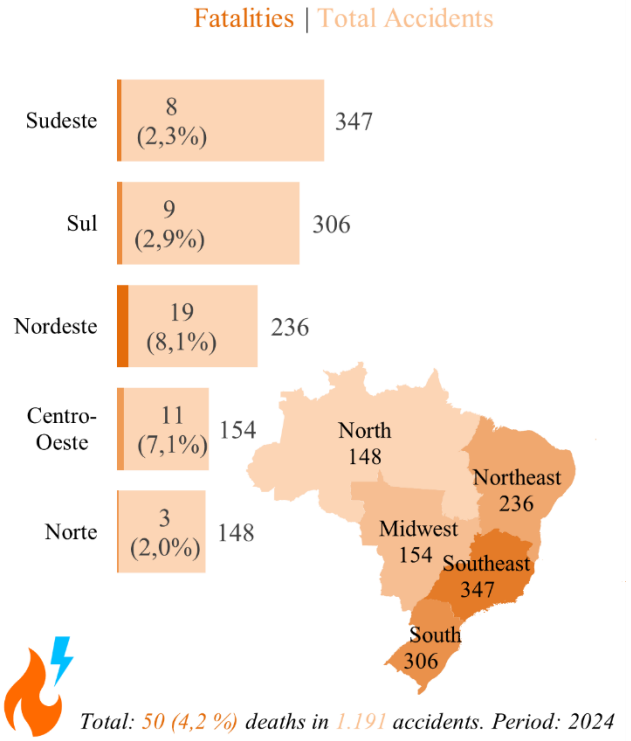

Figure 2 Electrical fires by region 2024.

Figure 2 shows that, throughout 2024, there were 1,191 accidents and 50 deaths resulting from fires of electrical origin throughout Brazil [4], [8]. The Southeast concentrated most of the accident cases (≈ 29 % of the total), followed by the South (≈ 26 %) and Northeast (≈ 20 %). On the other hand, the North and Midwest regions have the lowest rates, with≈ 12 % and ≈ 13 % of cases in Brazil.

A closer look at the graph reveals that the ratio of accidents to deaths varies significantly between regions: while the Southeast has a fatality rate of 2,3%, in the Northeast, this rate rose to 8,1%. These results demonstrate differences in prevention infrastructure and speed of response to electrical fires [6].

Figure 3 shows the national ranking of fires by state. The Southeast region, whose population density exceeds 40% of the national total, has the highest absolute number of accidents. The state of São Paulo has the highest incidence of occurrences, while the state of Bahia has the highest number of fatalities, as shown in Figure 3. When we compare the data in Figure 2, the disparity in safety infrastructure between the regions becomes clear, which would explain both the frequency and severity of fires [6].

An analysis of the top five states with the highest number of total accidents reveals that all are in either the South or Southeast regions. This indicates that population density and the Human Development Index (HDI) are significant factors in the number of electrical fires, given that the South and Southeast regions combined account for over 55% of the Brazilian population [9]. Reinforcing this connection, the average HDI for the states within these two regions is approximately 0.777,[10] placing them well above the national average and highlighting the link between higher development and the incidence of these accidents.

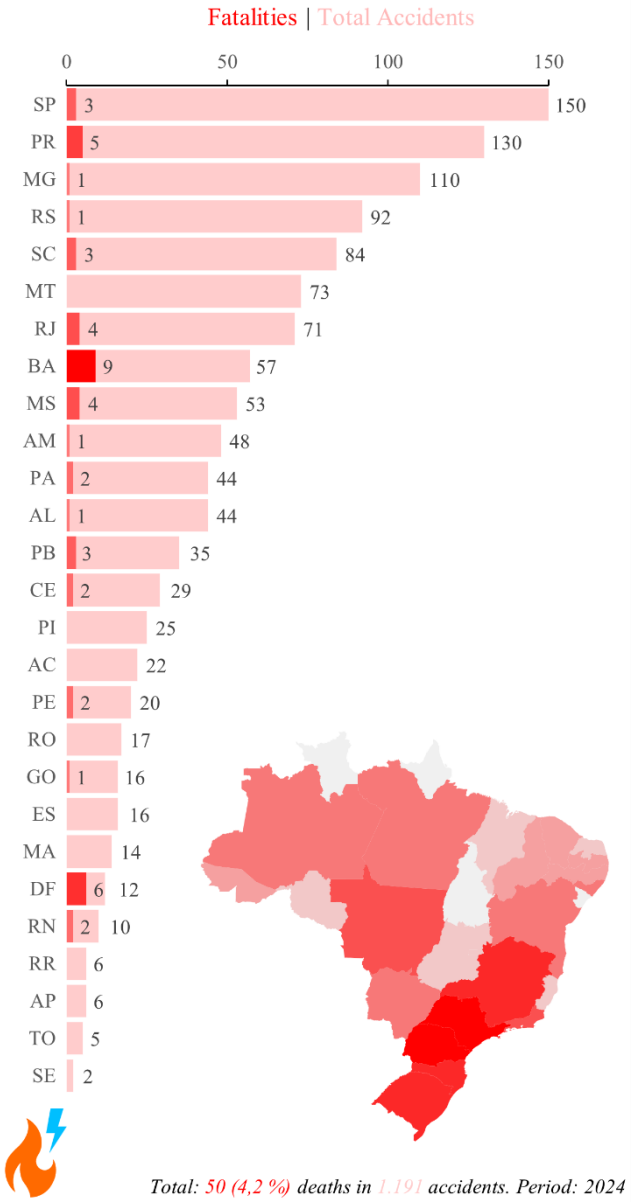

Figure 3. National ranking of electrical fires and fatalities by state 2024.

The analysis in Figure 4 shows that homes remain the main scenario for fires of electrical origin [11], totaling 528 incidents, something close to 44,3 % of the total, as well as concentrating 46 (92 %) of the 50 fatalities, demonstrating a high prevalence of fatalities [12] recorded in 2024. This analysis makes it clear that the vulnerability of the domestic environment stems from three interconnected causes: the inferior quality of the electrical infrastructure, the hiring of non-specialized labor for installations and repairs, and a culture of little to no preventive maintenance.

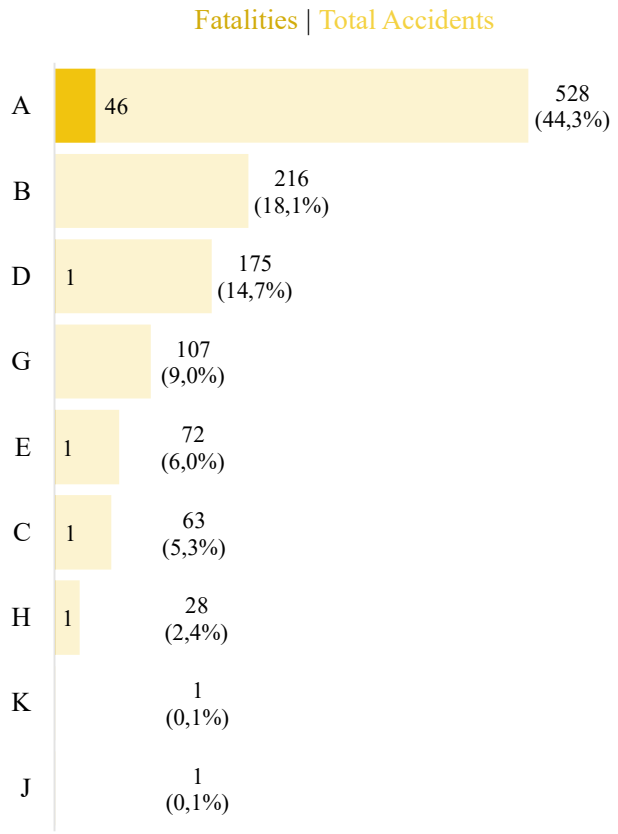

Figure 4 - Electrical fires by place of occurrence 2024.

The analysis in Figure 5 shows that electrical fires are not Sex-specific: of the 85 victims, around 55% are men and 45% are women [11]. Additionally, the overall mortality rate for this type of accident is 58.8%. However, a pronounced vulnerability is observed at the extremes of the age pyramid: children and the elderly are the most affected groups, which stems from their lower decision-making capacity and limited mobility in dangerous situations [10], [15].

This profile contrasts sharply with that of electric shock accidents [10]. In the latter, there is an overwhelming majority of male victims (87%). Furthermore, the lethality is also distinct: the mortality rate for electric shocks reaches 83%, a level significantly higher than the 58.8% recorded for fires.

B. Age and Sex

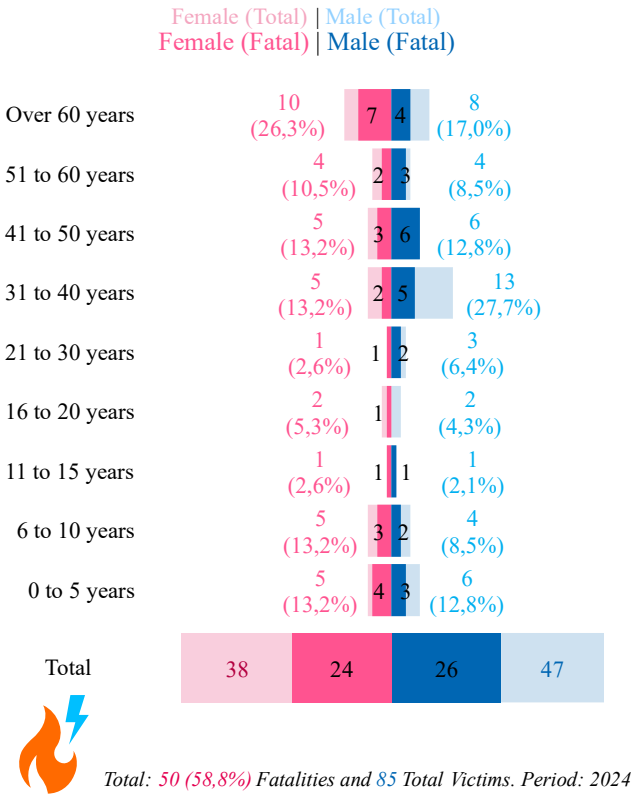

Figure 5 Electrical fire deaths by age group and Sex 2024.

C. Origin

As shown in Figure 6, around 51,6 % of electrical fires are caused by faults in internal electrical installations, 12,9 % by transformers, or poles, 7 12,8 % by air-conditioning systems or fans and 8 % by domestic appliances or electronic equipment [11], [12], [13]. Although indoor electrical installations account for most accidents (614 incidents), they have a lower mortality rate - 29 deaths (approximately 4,7%) - compared to incidents involving air conditioning and ventilation systems. The latter, despite being responsible for 152 incidents, accounts for 15 fatalities, which equates to a mortality rate of 9,9 % [8].

This pattern can be explained, in part, by using cooling appliances during sleep. In this state of unconsciousness, the victims' reaction time is severely compromised, diminishing their ability to perceive danger and evacuate. Consequently, this increases the likelihood of a fatal outcome when a fire starts. [11]

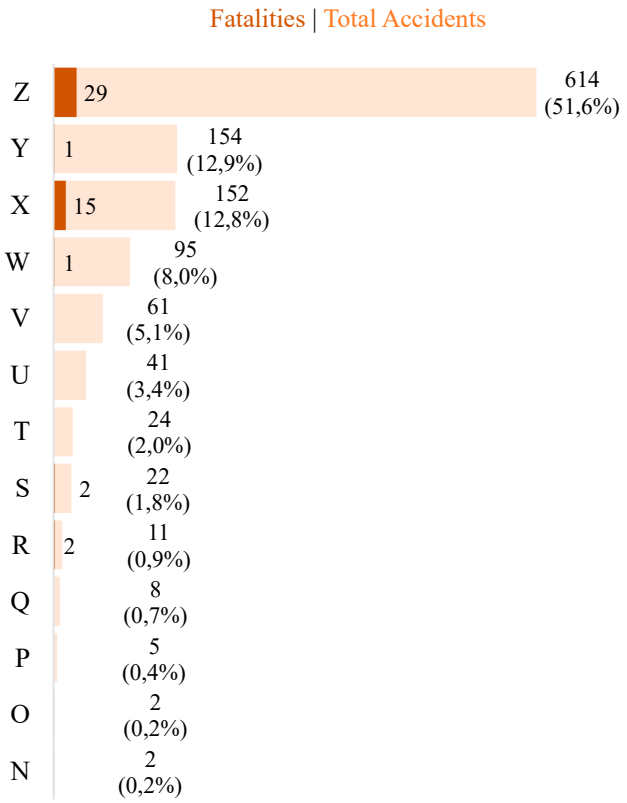

Figure 6. Electrical fires by equipment in 2024.

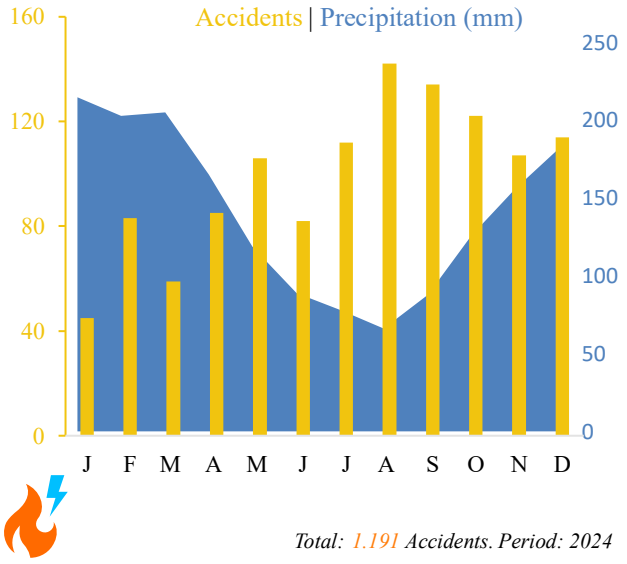

Figure 7. Electrical fires analyzed by month in 2024.

Analysis of the data presented in Figure 7 shows a correlation between the highest incidence of electrical fires and the months of July to October. This period, as indicated by the rainfall data in the same figure, is characterized by low rainfall.

Considering the Brazilian context, periods of drought, which often coincide with winter in various regions, can, due to temperature variations and low rainfall, lead to an increase in the use of equipment such as air conditioning units and fans [8]. As already highlighted by the analysis in Figure 6, these specific devices not only account for a considerable volume of incidents [8] but are also associated with a notable severity in accident outcomes. This intensified use results in greater residential energy demand, which can overload electrical installations [14], and consequently increase the risk of accidents - such as electrical fires - which, in the case of air conditioning equipment, tend to be particularly serious [11].

D. 5-year comparison (2020-2024)

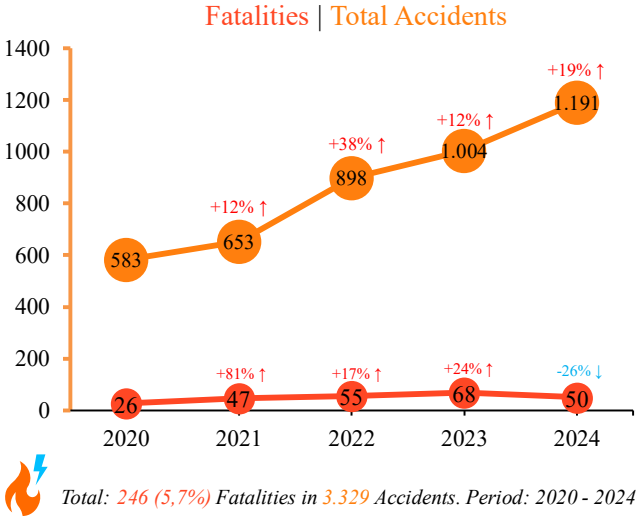

Figure 8. Electrical fires - 5-year comparison (2020-2024).

Figure 8 shows a significant increase in the number of fires of electrical origin. In 2024, there was an increase of 19% compared to the previous year, totaling 1,191 fires caused by electrical faults [8]. Analysis of the 2020-2024 period shows an accumulated growth of 104% in occurrences of this type.

However, when analyzing the data related to fatalities, there was a reduction [15] of 26% in 2024, which may indicate advances in safety measures and response to electrical fires [6]. This data suggests that, although incidents are on the increase, fatalities are decreasing, due to greater awareness, improvements in electrical installations or emergency response.

IV. CONCLUSION

This study revealed that electrical fires in Brazil represent a significant public safety problem, mostly concentrated in residential buildings. Data analysis indicated that deficiencies in internal electrical installations are the main cause of these accidents, contributing to a scenario of risk for the population, peed of response. In addition, equipment such as air conditioning systems and fans emerges as relevant sources of incidents, with their use intensifying in regions with a predominantly arid and dry climate, such as the Northeast, and during the winter at a national level, a period associated with increased energy demand.

The interpretation of these results suggests that, although there is no significant difference in vulnerability by Sex, age is a critical factor: individuals over the age of 60 and children under the age of 11 are more susceptible to fatal outcomes, possibly due to cognitive or motor limitations that compromise their ability to react in emergencies. In recent years, there has been an increase in the total number of electrical fires in the country.In contrast to this trend, there has been a decrease in the number of fatalities, which may indicate a potential improvement in rescue strategies, public awareness, or advances in safety policies.

This article contributes to the frontier of knowledge by providing an up-to-date and detailed overview of the incidence, causes and consequences of electrical fires in Brazil. By identifying the main risk factors, demographic vulnerabilities and temporal trends, this research provides essential input for the development of more effective public policies, the improvement of technical standards for electrical installations and equipment, and the formulation of targeted awareness campaigns. It is hoped that the data and analysis presented here will serve as a foundation for future research, technological innovations and the implementation of legislative measures aimed at the systematic reduction of these accidents, promoting a safer environment for Brazilian society.

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Avaliação da Exposição de Campos Eletromagnéticos Provenientes das Linhas de Transmissão em Áreas Urbanas Utilizando Métodos de Interpolação Espacial Para Geração de Mapas Estimativos.

Caiky Breno Santiago Chaves
Universidade Federal Rural do Semi-Árido
Centro de Ciências Exatas e Naturais
Mossoró, Brasil
caiky.chaves@alunos.ufersa.edu.br

Humberto Dionísio de Andrade
Universidade Federal Rural do Semi-Árido
Departamento de Engenharia e Tecnologia
Mossoró, Brasil
humbertodionisio@ufersa.edu.br

Nickson Saymon de Oliveira Lopes
Universidade Federal Rural do Semi-Árido
Departamento de Engenharia e Tecnologia
Mossoró, Brasil
nicksonsaymon@gmail.com

Pedro Arthur Freitas da Silva
Universidade Federal Rural do Semi-Árido
Centro de Ciências Exatas e Naturais
Mossoró, Brasil
pedro.silva67350@alunos.ufersa.edu.br

Elison Wediley dos Reis Silva
Universidade Federal Rural do Semi-Árido
Centro de Ciências Exatas e Naturais
Mossoró, Brasil
elison.silva@alunos.ufersa.edu.br

***Resumo*— A expansão dos sistemas elétricos de potência (SEP), impulsionada pela crescente demanda energética, intensificou a exposição da população a campos elétricos e magnéticos de frequência industrial. Este estudo tem como objetivo central avaliar a intensidade desses campos, especificamente os gerados por linhas de transmissão (LT) de 69 kV (60 Hz) que alimentam a subestação Belo Horizonte, localizada no município de Mossoró-RN. Para tal, foram realizadas medições *in loco*, em consonância com as diretrizes da norma NBR 25415, e aplicados métodos de interpolação espacial para a geração de mapas de estimativa da distribuição dos campos.**

Palavras-Chave*— *Campos Eletromagnéticos, Segurança Energética, Linhas de Transmissão, Interpolação Espacial.

I. Introdução

O acentuado incremento na demanda por energia elétrica no Brasil, verificado nas últimas décadas em virtude dos avanços tecnológicos e do crescimento populacional, exigiu uma robusta expansão da infraestrutura do setor elétrico. Para garantir a continuidade e a qualidade do abastecimento energético, a ampliação dos sistemas de geração, transmissão e distribuição tornou-se um imperativo. Como decorrência, instalações cruciais como subestações, usinas geradoras e linhas de transmissão, indispensáveis para atender a essa demanda, são comumente implantadas nas adjacências de zonas residenciais nas cidades [1,2].

Contudo, tais instalações são fontes de campos elétricos e magnéticos que resultam na exposição da população adjacente. Investigações científicas indicam uma possível, embora não conclusiva, correlação entre a exposição prolongada a campos magnéticos de baixa frequência e um ligeiro incremento no risco de leucemia infantil. É importante ressaltar, no entanto, que não se dispõe de evidências científicas robustas que vinculem a exposição a campos elétricos de frequência industrial ao desenvolvimento de quaisquer doenças [3,4].

Em resposta a essas preocupações e com o intuito de regulamentar a exposição humana, a Agência Nacional de Energia Elétrica (ANEEL) publicou a Resolução Normativa nº 398 em 23 de março de 2010. Esta resolução adota limites de exposição a campos elétricos e magnéticos que tomam como referência as recomendações da Comissão Internacional de Proteção Contra Radiação Não Ionizante (ICNIRP). Especificamente para a frequência industrial de 60 Hz, os limites para exposição ocupacional são fixados em 8,33 kV/m para o campo elétrico e 1000 µT para o campo magnético. Para a população em geral, os limites são estabelecidos em 4,17 kV/m e 200 µT, para campo elétrico e magnético, respectivamente [5,6,7].

A literatura científica evidencia que o emprego de modelagem computacional, por meio de métodos de interpolação espacial, constitui uma ferramenta eficaz para o mapeamento da distribuição dos níveis de intensidade de campos elétricos e magnéticos aos quais indivíduos são expostos. Tal abordagem permite a análise do comportamento espacial desses campos, considerando a influência de variáveis ambientais relevantes [8,9].

Este trabalho apresenta uma pesquisa realizada no estado do Rio Grande do Norte (RN), na cidade de Mossoró, acerca da exposição de campos eletromagnéticos na faixa de 60 Hz, provenientes das linhas de transmissão que compõe o sistema elétrico de potência. As medições de campo foram realizadas nas proximidades da subestação de Belo Horizonte, seguindo os parâmetros de medição dispostos na NBR 25415. Após a coleta de dados, foi realizada uma análise estatística através de métodos estimativos por intermédio de um *software* capaz de gerar gráficos através de técnicas de interpolação determinísticos e geoestatísticos. Com isso, este trabalho tem como escopo determinar se os níveis de campos eletromagnéticos da linha de transmissão de baixa tensão estão de acordo com as normas regulamentadoras, por meio da modelagem computacional.

II. METODOLOGIA

Este trabalho adota uma abordagem de pesquisa aplicada, quantitativa e experimental. O núcleo metodológico envolveu, primeiramente, a coleta de dados *in loco* referentes aos campos elétricos e magnéticos (60 Hz) emitidos pelas linhas de transmissão que suprem a subestação Belo Horizonte (Mossoró-RN), conforme preconizado pela norma ABNT NBR 25415. Em uma segunda etapa, os dados foram tratados estatisticamente e empregaram-se métodos de interpolação espacial para a elaboração de mapas de distribuição da intensidade dos campos eletromagnéticos na área de interesse.

A. Definição do meio de estudo

As subestações são componentes vitais no sistema elétrico de potência (SEP), que se estrutura nas etapas de geração, transmissão, distribuição e consumo. Sua função primordial é a adequação dos níveis de tensão, essencial tanto para a transmissão em longas distâncias quanto para a distribuição segura aos usuários finais. Em reconhecimento à relevância operacional dessas estruturas e à sua interface com o ambiente, este trabalho concentrou-se nas linhas de transmissão de 69 kV que suprem a subestação Belo Horizonte, em Mossoró-RN, cuja localização é apresentada na Figura 1. O escopo da investigação compreende a avaliação da intensidade dos campos elétricos e magnéticos de 60 Hz gerados por estas linhas.

Fig. 1. 77º Subestação de Mossoró localizada no bairro Belo Horizonte. Fonte: Site Neoenergia.

A subestação Belo Horizonte, em Mossoró-RN, atende a uma população estimada de 300 mil habitantes e é suprida por linhas de transmissão (LTs) de 69 kV, com aproximadamente três quilômetros de extensão, cujo traçado inclui trechos que perpassam o perímetro urbano. Este cenário justifica a presente investigação, cujo objetivo central é quantificar a intensidade dos campos eletromagnéticos nas imediações dessas LTs. Os resultados obtidos serão subsequentemente confrontados com os limites de exposição estabelecidos pela Agência Nacional de Energia Elétrica (ANEEL), a fim de analisar a conformidade com a regulamentação vigente e discutir potenciais implicações.

B. Campanhas de medição

Para uma análise da área em estudo, foi necessário adotar as técnicas dispostas na NBR 25415 que padroniza vários métodos de medição, como também delimita níveis de referência para exposição de campos elétricos e magnéticos. O processo foi dividido em três etapas. Na primeira, realizou-se um estudo no local para quantificar os pontos necessários para efetuar as medições, afim de garantir a cobertura a toda área de interesse.

Na segunda etapa, foi-se utilizado de técnicas de georreferenciamento para obter as coordenadas de latitude e longitude desses pontos. Na terceira e última etapa, as medições de campo elétrico e magnético foram realizadas conforme os métodos dispostos na norma vigente, utilizando um dispositivo gaussiano, que permite captar a intensidade dos campos e exibir esses valores no seu *display*.

Ao final das etapas de medição, foi criada uma planilha contendo os dados das coordenadas dos pontos, e os valores de intensidade dos campos elétricos e magnéticos. Por meio disso, houve a exportação desses dados para o software *Google Earth PRO* para geração de uma imagem via satélite, como ilustrado na Figura 2. Os pontos em azul, verde e rosa espalhados sobre a figura, correspondem aos pontos estudados ao decorrer da linha de alta tensão. Foram estabelecidos 43 pontos na área em estudo, distribuídos em perfis transversais à linha de transmissão, com um espaçamento de 3 metros entre cada ponto de medição, em conformidade com a NBR 25415. É de suma importância destacar que esses pontos abrangem áreas com diferentes características, como vegetação, desníveis de solo, residências e vias de alto fluxo, o que em alguns locais, restringiu o comprimento total das medições.

Fig. 2. Mapa de localização da região em análise. Fonte: *Google Earth Pro*.

Para a realização da coleta dos dados geográficos, cada ponto especificado na planilha foi localizado com a utilização de um *smartphone* com GPS, com auxílio de uma ferramenta de inteligência artificial para maior precisão na captura das coordenadas. Em cada um desses pontos, foi posicionado o medidor de campo eletromagnético TM-190 TENMARS, visualizado na Figura 3, o dispositivo conta com um sensor de campo elétrico e magnético capaz de operar na faixa de frequência de 50Hz até 60Hz. O aparelho foi fixado a uma altura de 1,5 metros com auxílio de um tripé, demonstrado na Figura 4, garantindo seu isolamento em relação ao chão. Para assegurar medições de campo precisas e seguras, o sensor eletromagnético do TM-190 foi alinhado em relação ao objeto de estudo, de modo a possuir a menor distância entre o condutor e o solo. Além disso, o dispositivo requer um curto intervalo de tempo para estabilização dos valores medidos. Após a estabilização, os valores dos campos foram registrados e associados as suas coordenadas geográficas, sendo posteriormente armazenados em uma planilha para posterior acesso computacional.

Fig. 3. Medidor de campo eletromagnético TM-190 TENMARS. Fonte: Site TenMars

Fig. 4. Tripé utilizado para isolar o dispositivo da terra. Fonte: Autoria própria.

C. *Interpolação Espacial*

Para análise estatística e modelagem dos mapas de contorno por meio de métodos de interpolação espacial foi-se utilizado o *software Surfer®*, versão 13, através dos dados da intensidade dos campos e suas coordenadas geográficas. Os valores foram organizados em planilha e importados no programa em forma de *Grid Data*. Após isso, o *software* gerou matrizes de interpolação para os métodos selecionados, no caso do estudo, foi escolhido o método que apresentou menor percentual de erro estimativo através da técnica de validação cruzada.

Além disso, a imagem via satélite da área de estudo foi formatada afim de garantir que os pontos estejam precisamente alinhados com as coordenadas das medições, permitindo sua integração ao software. Em seguida, ocorreu-se a sobreposição da imagem ao gráfico gerado pelo *Surfer 13®*, assegurando a precisão da análise.

III. Resultados e Discussões

Nas Figuras 5 e 6 é apresentado o histograma dos valores obtidos a partir das medições de campo. As intensidades de campo elétrico apresentaram uma variação de 0,158 kV/m a 0,002 kV/m. Já o campo magnético, apresentou-se variações entre 0,02μT a 0,04μT. Comparando-se esses resultados com os limites estabelecidos pela ANEEL, verifica-se que as intensidades medidas estão consideravelmente abaixo dos limites de exposição recomendados. Para a população em geral, o limite de exposição para o campo elétrico é de 4,17kV/m e para o campo magnético é de 200μT; já para a população ocupacional, esses valores são de 8,33kV/m e 1000μT, respectivamente.

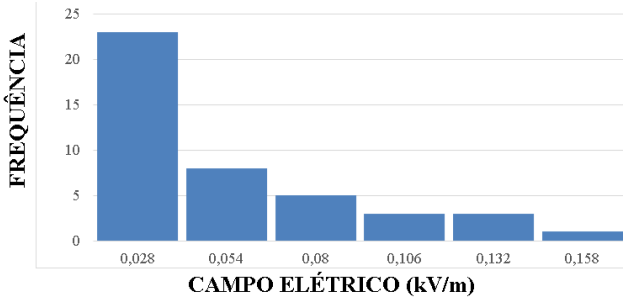

Fig. 5. Histograma das medições em campo elétrico.

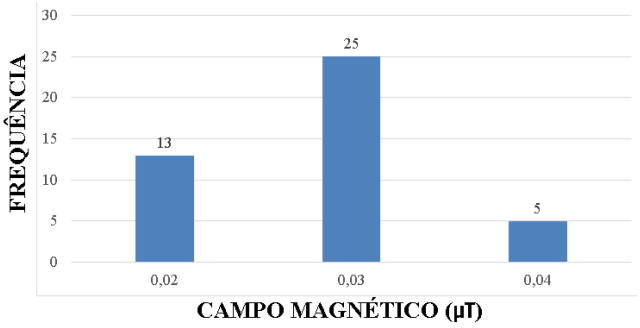

Fig. 6. Histograma das medições de campo magnético.

As Figuras 7 e 8 mostram as intensidades de campo elétrico e magnético respectivamente, em relação a distância dos condutores de fase da linha de transmissão espaçados transversalmente em 27 metros para a primeira medição, 30

metros para a segunda medição e 57 metros para terceira medição, resultando em um total de 43 pontos.

A Figura 7 apresenta o perfil de distribuição do campo elétrico em função da distância em relação ao centro do condutor de fase, com variações entre 0,002 kV/m e 0,158 kV/m. Observa-se que as curvas de intensidade do campo elétrico, referentes às medições 1 e 2, atingem seus valores máximos na região em que o condutor se encontra mais próximo do solo, decaindo progressivamente à medida que a distância em relação à linha de transmissão aumenta. Algumas anomalias detectadas nas medições podem ser atribuídas à presença de vegetação arbórea nas proximidades, que interfere na distribuição do campo. Além disso, determinados pontos apresentaram influência simultânea dos campos gerados pelos dois vãos adjacentes da linha de transmissão.

A Figura 8 ilustra as curvas de intensidade do campo magnético ao longo da mesma distância, com variações modestas, situadas entre 0,01 µT e 0,04 µT. As medições 1 e 3 apresentam maior variabilidade, com elevações pontuais próximas à linha, enquanto a Medição 2 revela um comportamento mais uniforme, sobretudo na região central. Essas diferenças podem estar relacionadas tanto a variações na intensidade da corrente elétrica quanto à influência de elementos externos, como estruturas metálicas, vegetação ou elevação do solo, que afetam a distribuição do campo magnético. De modo geral, os valores observados permanecem baixos, compatíveis com o regime normal de operação da linha de transmissão analisada.

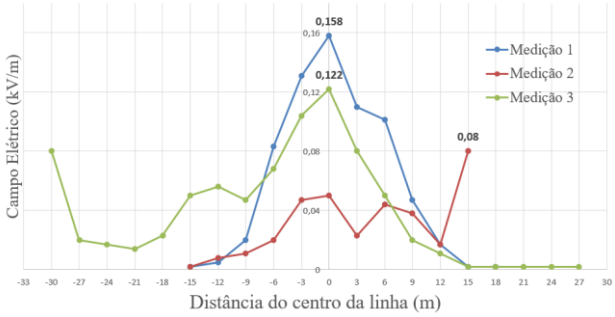

Fig. 7. Gráfico de dispersão dos Campos Elétricos

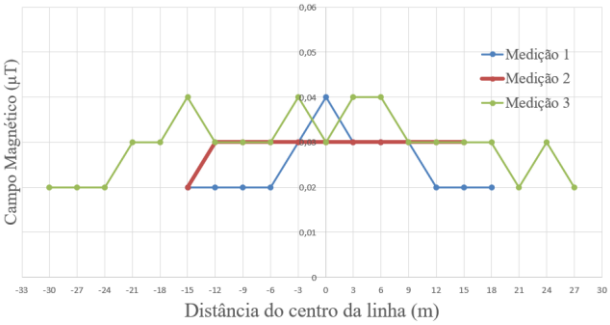

Fig. 8. Gráfico de Dispersão dos Campos Magnéticos

A Figura 9 e 10 apresentam as distribuições dos valores de campo elétrico e magnético, respectivamente, medidos em campo, na frequência de 60 Hz. Os dados foram organizados sob a forma de um *boxplot*, permitindo a visualização da variabilidade e da tendência central das medições.

No gráfico da Figura 9, observa-se que a mediana dos valores de campo elétrico é de aproximadamente 0,023 kV/m, enquanto a média dos dados está em torno de 0,0416 kV/m, representada pelo "X" no interior da caixa. Os valores apresentados pelo primeiro quartil e pelo terceiro quartil são de 0,008 kV/m e 0,068 kV/m, respectivamente, o que indica que 50% dos valores coletados estão dentro desse intervalo. Essa distribuição evidencia que embora a maior parte dos valores estão concentradas em intensidades relativamente baixas, há registros pontuais mais elevados, que estão associados a proximidade do condutor.

No gráfico da Figura 10, observa-se que a mediana dos valores de campo magnético é de 0,02 µT, enquanto a média dos dados está em torno de 0,0281 µT. Os valores correspondentes ao primeiro e terceiro quartil são de 0,02 µT e 0,03 µT, respectivamente, indicando que a maior parte dos valores se encontram nesse intervalo. A distribuição do campo magnético evidencia uma predominância dos valores obtidos próximos ao limite inferior. A baixa dispersão dos dados e a proximidade dos quartis sugerem uma homogeneidade nos baixos níveis de campo magnético, possivelmente associadas a distância da fonte emissora ou a presença de arvores em meio a área de estudo.

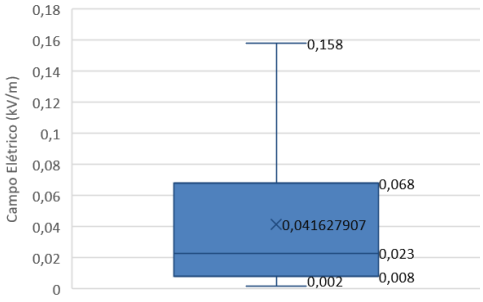

Fig. 9. Gráfico de Distribuição do Campo Elétrico

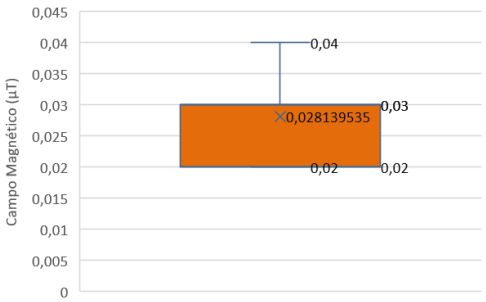

Fig. 10. Gráfico de Distribuição do Campo Magnético

Nas Tabelas I e II são apresentados os índices de Raiz do Erro Quadrático Médio (RMSE) e o Erro Médio Absoluto (MAE) que foram gerados através do método de validação cruzada no *Surfer*® para os campos elétricos e magnéticos. O valor RMSE é calculado através da raiz quadrada da média dos quadrados dos erros, já o valor MAE é calculado por meio do erro absoluto médio. Esses índices são usados como métricas para avaliar a precisão de modelos, sendo que, quanto menor seus valores, mais preciso será o modelo gerado.

O método local de interpolação espacial aplicado ao método de validação cruzada foi a Curvatura Mínima (CM).

Já os métodos geoestatísticos aplicados foram a Krigagem Ordinária Linear (KO-L), Krigagem Ordinária Gaussiana (KO-G), Krigagem Ordinária Esférica (KO-Es) e Krigagem Ordinária Exponencial (KO-Ex).

Através dos dados disponibilizados nas Tabelas I e II, observa-se que, para o campo elétrico, o método que apresentam os menores índices é a Krigagem Ordinária Esférica, com valores de -0,00105064 kV/m para o Erro Médio Absoluto e 0,023473 kV/m para a Raiz do Erro Quadrático Médio. Em seguida, os métodos de Krigagem Ordinária com modelos exponencial e linear apresentaram erros ligeiramente superiores. Já para o campo magnético, o método com maior precisão foi a Curvatura Mínima, apresentando dados de -0,000062493 µT de Erro Médio Absoluto e para a Raiz do Erro Quadrático Médio obteve-se 0,00623051 µT. Posteriormente, os métodos de Krigagem Ordinária com modelos gaussiano e exponencial apresentaram erros ligeiramente superiores.

TABELA I. Índices MAE e RMSE do campo elétrico para diferentes métodos.

Método	Campo Elétrico (kV/m)	
	Erro Médio Absoluto (MAE)	Raiz do Erro Quadrático Médio (RMSE)
CM	-0,00386366428247	0,0252563689865
KO-L	-0,00105064641348	0,023473533205
KO-G	0,00169267307111	0,0450552804656
KO-Es	-0,00105064666046	0,0234735329394
KO-Ex	-0,00105062824147	0,0234734932997

TABELA II. Índices MAE e RMSE do campo magnético para diferentes métodos.

Método	Campo Magnético (µT)	
	Erro Médio Absoluto (MAE)	Raiz do Erro Quadrático Médio (RMSE)
CM	-6,2493091578e-005	0,00623051946856
KO-L	0,000288236095526	0,00576841800858
KO-G	0,000272238117249	0,00661872209107
KO-Es	0,000288235866887	0,0057684179651
KO-Ex	0,000288233299431	0,00576841351692

As figuras a seguir apresentam o mapeamento estimativo dos campos elétrico e magnético na área de estudo, utilizando os três métodos de maior precisão discutidos anteriormente. Nessas representações, é possível visualizar os diferentes níveis de intensidade em pontos específicos, georreferenciados por latitude e longitude no sistema de coordenadas decimais.

O método da Krigagem Ordinária Esférica aplicado ao campo elétrico, visualizado na Figura 11, indicou os maiores valores intensidade de campo no ponto de menor distância entre o condutor e o solo, com valores próximos à 0,16 kV/m, o que é coerente com a realidade esperada. Na região central, onde foi realizada a segunda medição, observou-se uma redução nos níveis de campo elétrico, atribuída pela presença significativa de árvores, que interferiram na captura precisa desses valores. Diante a isso, os valores dos campos elétricos obtidos por meio da modelagem computacional estão 98,08% abaixo do limite estabelecido pela ANEEL para a população ocupacional (8,33 kV/m) e, 96,16% abaixo para a população geral (4,17 kV/m).

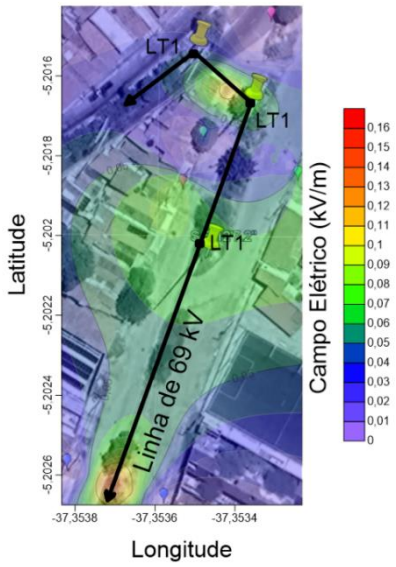

Fig. 11. Mapeamento local do Campo Elétrico utilizando o método de Krigagem Ordinária Esférica.

As Figuras 12 e 13 mostram os mapeamentos locais do campo elétrico com os métodos de Krigagem Ordinária Exponencial e Krigagem Ordinária Linear. Esses modelos apresentaram diferenças de níveis de campo praticamente imperceptíveis, quando comparado ao método com menor erro visto anteriormente. Tal semelhança pode ser atribuída à natureza dos dados coletados, que apresentam uma baixa variabilidade espacial. Além disso, embora os modelos de variograma adotem funções matemáticas distintas para descrever a continuidade espacial do campo elétrico, em contextos com variações geográficas suaves, tendem a gerar superfícies interpoladas com diferenças mínimas.

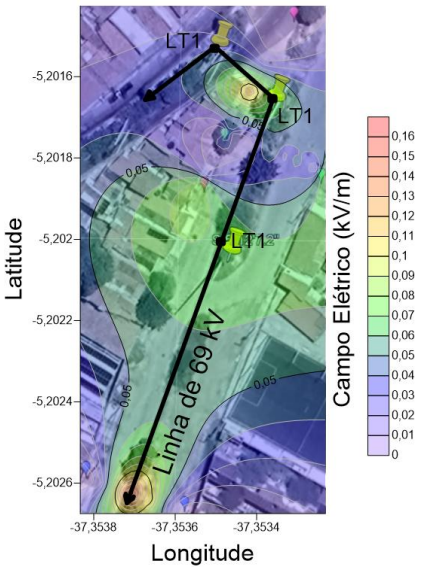

Fig. 12. Mapeamento local do Campo Elétrico utilizando o método de Krigagem Ordinária Exponencial.

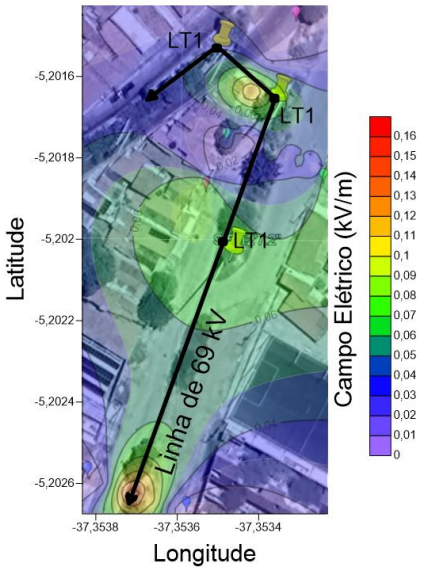

Fig. 13. Mapeamento local do Campo Elétrico utilizando o método de Krigagem Ordinária Linear.

A Figura 14 apresenta o método da Curvatura Mínima aplicada no campo magnético. Esse mapeamento apresenta uma concentração maior nas áreas de menor distância entre o condutor e o solo, apresentando picos de até 0,04 µT, encontrando-se de acordo com a teoria. Esses níveis estão dentro do limite estabelecido pela ANEEL, encontrando-se 99,98% abaixo para a população geral e, 99,996% abaixo para a população ocupacional.

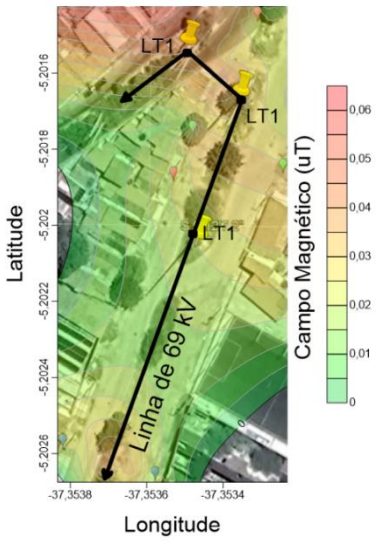

Fig. 14. Mapeamento local do campo magnético utilizando o método de Curvatura Mínima

As Figuras 15 e 16 apresentam os mapas do campo magnético obtidos por meio dos métodos de Krigagem Ordinária Gaussiana e Exponencial, respectivamente. Observa-se que os dois modelos geraram distribuições espaciais distintas dos níveis de campo magnético.

No mapa gerado com o modelo Gaussiano, observado na Figura 15, as intensidades do campo magnético são distribuídas de forma quase linear, com menores valores localizados na região inferior esquerda e maiores valores à direita, variando de 0,023µT a 0,031µT. Esse padrão de distribuição não corresponde ao comportamento teórico esperado do campo magnético em função da geometria da linha de transmissão. Por outro lado, o mapa obtido com o modelo Exponencial, observado na Figura 16, apresenta uma concentração dos picos de intensidade nas regiões de menor distância entre o condutor de fase e o solo, com uma variação de níveis entre 0,018µT a 0,04µT. Esse resultado está mais alinhado com a distribuição teórica do campo magnético gerado por linhas de transmissão de alta tensão.

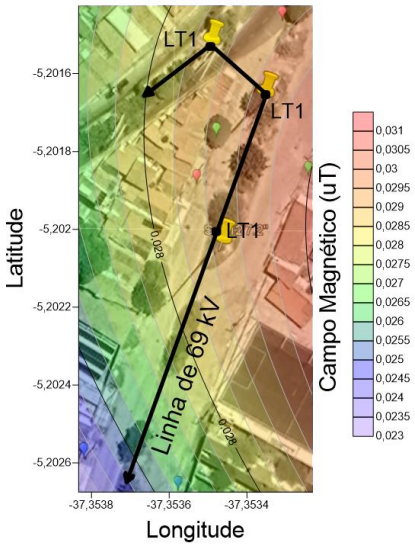

Fig. 15. Mapeamento local do campo magnético utilizando o método de Krigagem Ordinária Gaussiana

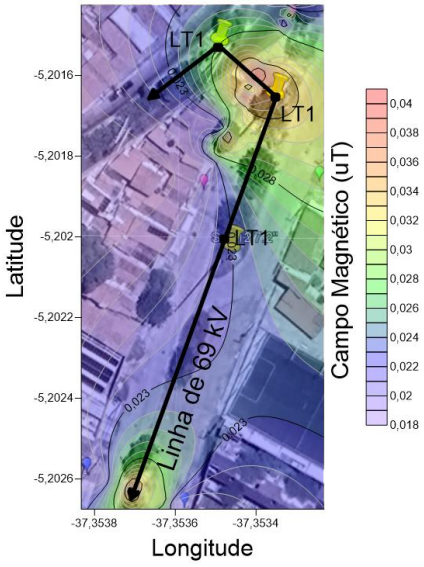

Fig. 16. Mapeamento local do campo magnético utilizando o método de Krigagem Ordinária Exponencial

IV. Conclusões

A investigação dos campos elétricos e magnéticos (60 Hz) gerados pelas linhas de transmissão de 69 kV da subestação Belo Horizonte (Mossoró-RN), realizada por meio de medições de campo e interpolação espacial, revelou que os níveis de exposição se encontram dentro dos parâmetros regulatórios. Especificamente, os valores de intensidade de campo elétrico e de densidade de fluxo magnético apurados foram inferiores aos limites estabelecidos pela ANEEL, tanto para a população em geral quanto para a exposição ocupacional. Tal conformidade com as diretrizes nacionais, que são baseadas em recomendações internacionais de proteção à saúde, indica que a operação dessas instalações, nas condições estudadas, não resulta em exposições que excedam os níveis considerados seguros pelas normativas atuais.

A abordagem metodológica, que integrou métodos de interpolação geoestatísticos e determinísticos e a validação cruzada dos modelos, revelou-se eficaz na caracterização espacial da intensidade dos campos eletromagnéticos. Esta estratégia possibilitou a geração de representações detalhadas da distribuição dos campos e evidenciou o papel modulador de elementos do ambiente urbano em sua propagação.

Em suma, este estudo reforça a utilidade da modelagem computacional como ferramenta para o mapeamento da distribuição espacial de campos eletromagnéticos gerados por infraestruturas elétricas. As descobertas apresentam potencial para subsidiar a formulação de medidas regulatórias e o desenvolvimento de aprimoramentos técnicos no setor de energia. Como direcionamento para pesquisas futuras, sugere-se a expansão das medições para abranger a área interna da subestação e investigar especificamente os campos eletromagnéticos associados ao seu funcionamento, avaliando a exposição da população geral e ocupacional. Tais investigações permitiriam um aprofundamento na análise da segurança eletromagnética nas imediações da subestação Belo Horizonte.

Agradecimentos

Esse estudo foi financiado em parte pelo Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq. Os autores agradecem também, UFERSA, GEPEAT, ao capítulo Estudantil MTTS – UFERSA e a equipe do Laboratório de Telecomunicações e Micro-ondas da UFERSA.

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7 a 9 de outubro de 2025 – São Paulo - SP

Avaliação do Treinamento Proposto pela Norma Regulamentadora NR10

Michael Cruz
Diretoria
Associação dos Engenheiros, Arquitetos e Agrônomos de Salto
Salto, Brasil
engmichaelcruz@gmail.com

Sergio Santos
Engenharia
Lambda Consultoria Ltda.
Sorocaba, Brasil
https://orcid.org/0000-0002-7272-3545

Danilo Ferreira de Souza
Núcleo Interdisciplinar de Estudos em Planejamento Energético (NIEPE/UFMT)
Universidade Federal de Mato Grosso (UFMT)
Cuiabá, Brasil
https://orcid.org/0000-0002-1155-1778

Edson Martinho
Engenharia
Lambda Consultoria Ltda.
Salto, Brasil
https://orcid.org/0000-0002-1554-5172

***Abstract*— Este artigo analisa criticamente a eficácia e a conveniência do curso previsto na Norma Regulamentadora nº 10 (NR10), que trata da segurança em instalações e serviços com eletricidade. A partir da revisão da norma, de literatura especializada e de discussões com profissionais das áreas de engenharia elétrica, segurança do trabalho e eletricidade, busca-se compreender a real contribuição do curso para a prevenção de acidentes e para a formação dos trabalhadores. O estudo destaca que, embora a NR10 não tenha como objetivo a formação técnica, ela é essencial como instrumento de conscientização, principalmente por ser, para muitos profissionais, a única fonte de informação sobre riscos elétricos. A pesquisa também apresenta uma proposta de alinhamento entre o conteúdo programático do curso e a formação dos instrutores, considerando competências específicas de profissionais da engenharia, da segurança do trabalho e da saúde. A obrigatoriedade do curso é amplamente apoiada pelos participantes da pesquisa, que reconhecem seu papel na construção de uma cultura de segurança no ambiente de trabalho.**

Keywords—treinamento, segurança, NR10, qualificação profissional.

I. INTRODUÇÃO

A norma regulamentadora número 10 (NR10) do Ministério do Trabalho e Emprego [1] teve a sua origem na Portaria MTb nº 3.214, de 8 de junho de 1978, sob o título "Instalações e Serviços de Eletricidade", com o objetivo de regulamentar os artigos 179 a 181 da Consolidação das Leis do Trabalho (CLT), conforme redação dada pela Lei nº 6.514, de 22 de dezembro de 1977, que alterou o Capítulo V (Da Segurança e da Medicina do Trabalho) do Título II da CLT. Caracterizada como Norma Especial pela Portaria SIT nº 787, de 28 de novembro de 2018, a redação original da NR-10 estabelecia as condições exigíveis para garantir a segurança das pessoas envolvidas com o trabalho em instalações elétricas, nas fases de projeto, execução, reforma, ampliação, operação e manutenção, além da segurança de usuários e terceiros.

Desde a sua publicação, a NR10 sofreu quatro revisões. Sendo, duas amplas e duas pontuais, e na década de 1990, foi detectada a necessidade de uma nova atualização, devido às transformações organizacionais do trabalho ocorridas no setor elétrico, especialmente a partir de 1998, quando se iniciou o processo de privatização nesse setor.

O texto resultante dessa revisão foi submetido à consulta pública por meio da Portaria SIT nº 06, de 28 de março de 2002. Em seguida, durante a 31ª Reunião Ordinária da CTPP[1], realizada em 7 de agosto do mesmo ano, decidiu-se pela criação do Grupo de Trabalho Tripartite (GTT) com o objetivo de discutir a nova redação da NR-10. O GTT elaborou uma proposta de regulamentação, que foi apresentada na 36ª Reunião Ordinária da CTPP, realizada em 27 e 28 de novembro de 2003, e novamente na 39ª Reunião, em 22 de setembro de 2004. Nessa última reunião, foi alcançado

[1] No contexto da NR 10 (Segurança em Instalações e Serviços em Eletricidade), a CTPP é a Comissão Tripartite Paritária Permanente, um órgão consultivo responsável por acompanhar, revisar e propor melhorias nas Normas Regulamentadoras (NRs) do Ministério do Trabalho. Ela é composta por representantes dos três segmentos sociais envolvidos com o mundo do trabalho: governo, empregadores e trabalhadores, garantindo equilíbrio nas decisões e legitimidade nas mudanças normativas. A CTPP atua de forma colegiada e consensual, sendo fundamental na elaboração e revisão da NR 10, com o objetivo de promover a segurança e saúde dos trabalhadores em serviços com eletricidade.

consenso sobre praticamente toda a norma, com exceção do item 10.7.3, cuja definição final ficou a cargo do então Ministério do Trabalho.

Por meio deste processo, foi publicada a atual versão da NR10 através da Portaria MTb nº 598, de 7 de dezembro de 2004, com o título de "Segurança em Instalações e Serviços com Eletricidade", quando também foi instituída a Comissão Permanente Nacional sobre Segurança em Energia Elétrica (CPNSEE), com o objetivo de acompanhar a implementação e propor as adequações necessárias ao aperfeiçoamento da NR10.

A NR10, após esta revisão, trata das diretrizes básicas para a implementação de medidas de controle e sistemas preventivos, destinados a garantir a segurança e a saúde dos trabalhadores que direta ou indiretamente interajam em instalações elétricas e serviços com eletricidade, nos seus mais diversos usos e aplicações, e quaisquer trabalhos realizados nas suas proximidades.

A terceira modificação da NR10 representou uma alteração pontual, para correção no texto da norma, referente à numeração dos anexos, tendo sido alterada pela portaria MTPS nº 508, de 29 de abril de 2016, conforme decidido por consenso na CTPP, durante a 84ª Reunião Ordinária, realizada em 05 e 06 de março de 2016.

A quarta alteração ocorreu em função da harmonização dos requisitos sobre capacitação, direitos e obrigações previstos na nova versão da Norma Regulamentadora nº 01 (NR01) – Disposições Gerais, trazida pela Portaria SEPRT n° 915, de 30 de julho de 2019, cujo texto fora submetido e manifestado o consenso durante a 97ª Reunião Ordinária da CTPP, realizada em 04 e 05 de junho de 2019.

Conforme agenda regulatória definida também durante a 97ª Reunião Ordinária da CTPP, a modernização da NR10 encontra-se em processo de discussão de forma tripartite, a fim de atender às demandas sociais, tanto no escopo técnico, como na seara da fiscalização do ambiente laboral do setor energético.

II. CURSO NR10

A. Objetivos

Segundo o item 10.6.1 da NR10, as intervenções em instalações elétricas com tensão igual ou superior a 50 Volts (Considerada extra-baixa tensão) em corrente alternada ou superior a 120 Volts em corrente contínua somente podem ser realizadas por trabalhadores que sejam habilitados, qualificados, capacitados ou autorizados, segundo os critérios estabelecidos no item 10.8 dessa mesma norma. Esses trabalhadores devem receber treinamento de segurança para trabalhos com instalações elétricas energizadas, com currículo mínimo, carga horária e demais determinações estabelecidas no Anexo III desta NR. Esse anexo define duas modalidades de curso:

1) Curso básico: Segurança em instalações e serviços com eletricidade, com carga horária mínima de 40 horas e programação mínima definida no anexo.

2) Curso complementar: Segurança no Sistema Elétrico de Potência (SEP) e em suas proximidades.

B. Atribuições profissionais e treinamento na NR10

Acidentes de trabalho relacionados à eletricidade ocorrem, inúmeras vezes, devido à ausência de conhecimento, negligência na aplicação das normas, erros na execução de procedimentos e falta de equipamentos de proteção adequados [2]. Para que os profissionais tenham a compreensão necessária para avaliar riscos, adotar ações preventivas e atuar de forma segura, a NR10 indica capacitá-los e treiná-los de forma adequada [2].

Dentro de uma hierarquia de atribuições, a NR10 considera, em seu item 10.8.1, que um trabalhador qualificado é aquele que tenha comprovadamente realizado curso específico na área elétrica reconhecido pelo sistema oficial de ensino [1] [3]. Segundo o item 10.8.2 da NR10, o trabalhador legalmente habilitado é aquele que previamente qualificado possui registro no seu respectivo de conselho de classe [1] [3]. Na sequência, a NR 10 considera, em seu item 10.8.3, que um trabalhador será considerado capacitado quando simultaneamente receber capacitação sob a orientação e responsabilidade de um profissional habilitado e autorizado e trabalhar sob responsabilidade de um profissional também habilitado e autorizado [1].

No caso da autorização, ela deve ser formalizada, por escrito, pela empresa a qual um trabalhador prestará um serviço em instalações e serviços com a eletricidade, tendo para isso realizado os cursos citados no anexo II da NR10, adequados ao trabalho que será realizado [4].

Dessa forma, a capacitação e treinamento desses profissionais deve-se iniciar já no ingresso deles na empresa, através de cursos e treinamentos, sendo os cursos indicados na NR10 necessários mas não suficientes para a proficiência na área elétrica, algo que ela não indica em nenhum de seus itens, já que seus cursos não devem fornecer títulos ou diplomas, em sentido estrito, mas certificados de participação [4].

Embora possa parecer um detalhe, certificados de participação não dependem de avaliações, mas de frequência, fazendo jus a eles quem esteve presente durante a carga horária mínima, de 40 horas no curso básico. Por isso, o recebimento do certificado não torna automaticamente alguém um profissional capacitado, algo que dependerá do seu empregador considerar satisfatório o aproveitamento do curso, tornando a pessoa um profissional autorizado ou não. Para isso, o empregador, e não o instrutor, deverá avaliar o resultado de provas, a participação do profissional no curso, ou outro critério adicional pré-definido. Em seu item 1.6.2, a NR10 informa explicitamente: A NR-10 não traz detalhes específicos sobre a forma de avaliação, mas, como qualquer treinamento previsto nas NRs, ela segue obrigatoriamente o que está na NR-01, inclusive a exigência de avaliação formal da aprendizagem [1] [5].

Justamente por não estar associado ao sistema oficial de ensino, o curso de NR10 não necessita ser ministrado por uma instituição que faça parte desse sistema. A responsabilidade pelos cursos de NR10 é do profissional habilitado e autorizado, que poderá também ser o responsável pela capacitação [1] [4]. Os instrutores do curso poderão ser profissionais com registro em um conselho de classe, que comprove formação no tema que será ministrado, eletricidade ou segurança do trabalho por exemplo.

Pelo exposto, fica evidente a relação estabelecida pela NR10 entre estudo, atividades profissionais e segurança nos trabalhos com a eletricidade. Por isso é entendível que o curso da NR10 destina-se prioritariamente à conscientização dos trabalhadores sobre os riscos associados ao trabalho com a eletricidade e como enfrentá-los. Os cursos de NR10 só fazem

sentido dentro do contexto dessa norma, não sendo eles um fim em si mesmo, mas uma ferramenta para atingir os objetivos que ela estabelece. Por isso é necessário compreender que o conteúdo programático desses cursos não tem como objetivo fornecer subsídios técnicos de instalação, nem a formação profissional para trabalhos com a eletricidade, mas conscientizar os trabalhadores sobre os riscos associados à eletricidade e como reduzi-los. Mesmo que muitas medidas de segurança estejam diretamente relacionadas a questões técnicas, o tempo dedicado aos aspectos da segurança e proteção não deve ser utilizado para uma revisão de temas da área elétrica essencialmente técnicos.

C. Aspectos economicos da aplicação da NR10

Os fatores humanos são reconhecidos como os principais contribuintes para o risco de acidentes de trabalho, sendo eles fatores psicológicos, sociais e laborais, que interferem no desempenho profissional. Especificamente em relação aos trabalhos com a eletricidade podem ser indicados a cultura da empresa, incluindo as regras não escritas, deficiências cognitivas, problemas familiares e excesso de trabalho. Por esse motivo a conscientização é uma poderosa ferramenta para a redução de acidentes, principalmente quando ela envolve uma empresa como um todo, proprietários, gestores, funcionários e prestadores de serviço.

Como os trabalhadores passam parte significativa de seu tempo no trabalho é fundamental garantir um nível adequado de segurança e conscientização sobre os riscos ocupacionais. Tal objetivo pode ser alcançado por meio de treinamento em segurança do trabalho, sendo necessário reconhecer que um processo de treinamento eficaz é difícil e trabalhoso, por isso é importante escolher o método adequado para alcançar os melhores resultados [6].

A existência de uma cultura empresarial de prevenção de acidentes causados pela eletricidade reduz as possibilidades deles acontecerem e consequentemente os custos diretos e indiretos associados a essas ocorrências [7]. Além desse fato, investimentos na segurança do trabalho têm como externalidades positivas o aumento da produtividade da força de trabalho e da eficiência de uma empresa. O treinamento tem o potencial de criar vantagens comparativas e competitivas quando os trabalhadores adquirem, ou aprimoram, novos conhecimentos e habilidades relevantes, o que justifica o investimento de empresas na educação continuada de sua força de trabalho [5].

Além dos benefícios para as empresas, a qualificação profissional beneficia toda a sociedade, pelo aumento da produtividade e da redução dos custos que ela tem com os acidentes de trabalho através da seguridade social [8]. Justamente por isso, cabe à sociedade legislar sobre medidas para a redução dos acidentes do trabalho, como o que ela faz ao seguir as diretrizes das normas regulamentadoras [9].

III. DISCUSSÃO SOBRE O CURSO DE NR10

Partindo das perguntas básicas sobre a eficácia do curso de NR10 para a redução dos riscos de acidentes e se a sua obrigatoriedade deveria ser mantida, seguem as conclusões obtidas e como se chegou a elas.

Ao invés de um questionário com diversas perguntas, optou-se por discussões abertas com vários profissionais envolvidos com a NR10. Basicamente esses profissionais podem ser divididos nas seguintes categorias:

1) Instrutores do curso de NR10. Profissionais da área elétrica que mesmo atuando em várias áreas ministram cursos de NR10 (figura1).

2) Empresários. Proprietários de empresas de engenharia e/ou instalações elétricas. Algumas dessas empresas ministram cursos de NR10 especificamente para os seus clientes, mas não o oferecem para turmas abertas ao público em geral.

3) Profissionais envolvidos diretamente com a segurança do trabalho com a eletricidade, tendo trabalhado na elaboração da versão atual da NR 10 e/ou da sua revisão.

4) Profissionais da área elétrica, principalmente eletricistas. Trabalhadores que fizeram o curso de NR10.

Figura 1: Curso de NR10 - Fonte. Luiz Alves da Silva Filho.

Para todos que participaram da discussão os cursos de NR10 são uma realidade consolidada, sendo exigido por todas as empresas. Segundo os empresários a quase totalidade dos eletricistas contratados por eles já possuem o curso básico quando entram na empresa, necessitando fazê-lo apenas aqueles que estão iniciando na área elétrica, basicamente como ajudantes. Nesse caso, ao contrário dos eletricistas, o curso básico é o primeiro treinamento formal sobre a eletricidade que eles recebem. Ainda segundo esses empresários, não é possível estabelecer uma correlação forte entre ter feito o curso e trabalhar com segurança, já que todos os eletricistas o fizeram, existindo profissionais mais e menos conscientes sobre a segurança no trabalho. Mesmo assim, com exceção de um único participante que considerou o curso totalmente desnecessário, a quase totalidade dos empresários considerou o curso como benéfico para os seus funcionários.

Em relação ao objetivo do curso ser a conscientização dos trabalhadores sobre os riscos da eletricidade houve um consenso, com todos os participantes concordando sobre essa questão. Para todos, o curso de NR10 não se destina a ensinar a eletricidade aos trabalhadores. Por isso quase todos concordaram que não seria necessária a divisão das turmas em função da qualificação técnica dos participantes, embora houvesse quem defendesse ou praticasse essa divisão. Dividir as classes entre profissionais da área elétrica e trabalhadores leigos nesse tema traria o benefício de respectivamente aprofundar aspectos técnicos para os profissionais qualificados (figuras 1,3 e 4) e ser mais didático para quem não tivesse conhecimentos ao menos básicos sobre a eletricidade (figura 2) .

Figura 2: Turma formada por trabalhadores com diferentes níveis de conhecimento sobre a eletricidade. – Fonte. Michael Cruz.

Figura 3: Turma formada para conteúdo específico. *Fonte. Luiz Alves da Silva Filho.*

Figura 4: Turma de NR10. Fonte. Michael Cruz.

Outro consenso foi obtido sobre a carga horária dos cursos, considerada suficiente para os seus objetivos. Prolongá-los, ou reduzir o prazo para os cursos de reciclagem foi considerado desnecessário, ou prejudicial pelos donos de empresas. Neste caso, é importante observar, que a NR10 estabelece a carga horária mínima dos cursos, mas não como ela deve ser obtida, podendo a relação entre a duração e o número de aulas ser adaptado às necessidades dos trabalhadores que participarão do treinamento.

Independentemente de empresários ou profissionais autônomos, o preço dos cursos de NR10 foi considerado relativamente baixo. Nesse caso a carga horária, seja pelo tempo que um trabalhador deixa de realizar algum serviço para a empresa, ou pelo tempo que ele retira de seu descanso, foi considerada mais relevante. Principalmente quando se cogitou em aumentar a carga horária dos cursos ou diminuir o intervalo entre as reciclagens. Cabe registrar, que segundo o item 1.7.2 da NR01, o tempo despendido em treinamentos previstos nas NR é considerado como de trabalho efetivo [5].

Um aspecto interessante surgido na discussão refere-se a diferença entre os treinamentos padronizados, realizados por empresas de treinamento, e aqueles feitos por firmas de engenharia que treinam trabalhadores de empresas às quais prestam serviços regularmente, adaptando seus cursos para as reais necessidades de seus clientes. Tal fato reforça a principal conclusão dessa discussão, que o curso de NR10, ao ser obrigatório, possibilita ao menos uma conscientização mínima, que pode e deve ser complementada por iniciativas dos próprios empregadores, já que a capacitação em segurança do trabalho é algo do interesse deles.

A grande maioria dos profissionais autônomos ou liberais, sem vínculos empregatícios, ouvidos fizeram o curso de NR10 e as reciclagens devido à necessidade de prestar serviços para empresas que exigiam o certificado. Os profissionais ouvidos que trabalhavam exclusivamente para pequenas empresas, condomínios ou residências nunca fizeram o curso, com uma única exceção, embora reconheçam a sua importância.

Desta forma, o que pode se extrair daqueles que formam a clientela dos cursos exigidos pela NR10 é a sua relevância, sendo ele insubstituível como um contato, muitas vezes único, dos profissionais envolvidos em trabalhos com riscos de natureza elétrica com as questões de segurança. Neste caso houve a concordância de que os cursos valem pelo seu real objetivo, oferecer informações básicas e objetivas sobre os riscos associados a eletricidade, algo que a não obrigatoriedade deste curso não tornaria possível para muitos.

Além do curso inicial, a NR-10 determina que os profissionais autorizados sejam submetidos a um treinamento de reciclagem bienal, ou seja, a cada dois anos, conforme estabelecido no item 10.8.8.2 da norma. Essa reciclagem também deve ocorrer em casos específicos, como mudança de função, retorno ao trabalho após afastamento prolongado ou alterações relevantes nas instalações elétricas. No entanto, mais do que uma simples repetição de conteúdos, a reciclagem deve ser pensada como uma oportunidade estratégica para aperfeiçoamento. Recomenda-se fortemente que esse treinamento considere as características específicas da empresa, incluindo suas operações de maior risco, incidentes ocorridos, quase-acidentes e situações críticas vivenciadas nos últimos anos. Esse enfoque permite personalizar o conteúdo da reciclagem, tornando-o mais eficaz e orientado à realidade do ambiente de trabalho, ampliando assim sua contribuição para a prevenção de acidentes e o fortalecimento da cultura de segurança.

IV. COMENTÁRIOS PÓS DISCUSSÃO

Sendo o objetivo do trabalho obter uma visão qualitativa sobre a eficácia do curso de NR10, seguem observações obtidas pela discussão, para uma reflexão e futuras pesquisas de todos os envolvidos com a segurança nos trabalhos com riscos associados à eletricidade.

O curso de NR10 tem como objetivo específico e insubstituível reduzir os riscos de acidentes associados à

eletricidade por meio da conscientização obtida pelo conhecimento.

Pela sua obrigatoriedade, o curso se torna para muitos o único meio de obter informações básicas sobre a segurança nos trabalhos com riscos de natureza elétrica, mesmo para profissionais qualificados. Sem a obrigatoriedade do curso essas informações não seriam obtidas.

Não é o objetivo do curso formar profissionais da área elétrica, cujo conhecimento técnico deve ser obtido através do sistema oficial de ensino, com cursos e treinamentos de forma continuada. Mas seria algo proveitoso se os cursos para formação de engenheiros (as) eletricistas, técnicos (as) em eletricidade e eletricistas incluíssem uma disciplina sobre a segurança nos trabalhos em eletricidade em seus programas.

Como o anexo III da NR10 apresenta uma programação mínima para os treinamentos, é possível e recomendado desenvolver treinamentos mais direcionados, para cada empresa, grupo de alunos e objetivos específicos.

Também merece ser mencionado um aspecto observado na discussão, com forte impacto na produtividade dos trabalhadores da área elétrica. Quando os empresários admitiam os benefícios do treinamento da NR10 eles referiam-se aos benefícios para os funcionários, mas nitidamente eles dissociavam esses benefícios como sendo também para as empresas. Tal visão revela uma dissociação entre qualificação profissional, segurança no trabalho e produtividade, algo que será mais bem explorado em futuros estudos sobre esses temas.

Finalmente, muitas propostas e sugestões para o aperfeiçoamento dos cursos da NR10 já estão comtempladas na norma NR01, que dedica o seu item 1.7 à capacitação e treinamento em segurança e saúde no trabalho. Enquanto a NR10 trata principalmente da necessidade e conteúdo programático do curso, a NR01 apresenta a metodologia, princípios e aspectos legais para os treinamentos solicitados em todas as normas regulamentadoras.

V. QUE PROFISSIONAIS PODEM MINISTRAR O CURSO DE NR10?

Embora a NR10 não determine formalmente a exigência de formações específicas para os profissionais que ministram os diferentes conteúdos do curso básico de Segurança em Instalações e Serviços com Eletricidade, previsto em seu Anexo III, os autores entendem ser essencial observar a coerência entre os temas abordados e a formação pedagógica e técnica dos instrutores. Essa coerência é fundamental para garantir que os participantes do curso recebam uma formação qualificada, técnica e efetivamente aplicável às suas atividades laborais. Diante disso, com base na análise detalhada dos 15 tópicos previstos no conteúdo programático mínimo do curso básico, propomos uma divisão temática que considera três áreas de formação distintas: engenharia elétrica, segurança do trabalho e saúde.

O primeiro grupo de tópicos — formado pelos itens 1 (introdução à segurança com eletricidade), 2 (riscos em instalações e serviços com eletricidade), 4 (medidas de controle do risco elétrico), 5 (normas técnicas brasileiras) e 10 (documentação das instalações elétricas) — apresenta forte aderência à formação em engenharia elétrica, especialmente na área de sistemas elétricos de potência. São temas que exigem domínio técnico aprofundado sobre o funcionamento, a normatização e as boas práticas nas instalações elétricas. Por essa razão, recomenda-se que esses conteúdos sejam ministrados, preferencialmente, por engenheiros (as) eletricistas com experiência comprovada na área.

O segundo grupo — que inclui os itens 3 (técnicas de análise de risco), 6 (regulamentações do Ministério do Trabalho e Emprego), 7 (equipamentos de proteção coletiva), 8 (equipamentos de proteção individual), 9 (rotinas de trabalho — procedimentos), 11 (Riscos adicionais), 12 (Proteção e combate a incêndios) e 15 (responsabilidades legais e conduta) — trata de temas fortemente ligados à segurança do trabalho e à legislação trabalhista. Nesses casos, o profissional mais adequado para ministrar os conteúdos é o engenheiro (a) de segurança do trabalho, cuja formação proporciona as ferramentas necessárias para tratar desses assuntos com profundidade, clareza normativa e alinhamento com as diretrizes legais.

O item 13 (acidentes de origem elétrica) pode ser abordado tanto por profissionais da engenharia elétrica quanto da segurança do trabalho, uma vez que trata de ocorrências cuja compreensão técnica deve ser acompanhada por uma análise das causas e consequências em termos de segurança laboral.

Já o item 14 (primeiros socorros), por envolver conhecimentos clínicos e procedimentos emergenciais, deve ser ministrado por profissionais da área da saúde, como médicos do trabalho, enfermeiros do trabalho ou técnicos em enfermagem com formação específica em primeiros socorros, assegurando uma abordagem precisa e adequada às situações emergenciais.

No que se refere ao curso complementar previsto no Anexo III da NR10, intitulado *Segurança no Sistema Elétrico de Potência (SEP) e em suas proximidades*, entende-se que a complexidade e o nível técnico dos conteúdos exigem uma abordagem multidisciplinar. Por essa razão, recomenda-se fortemente que esse treinamento seja ministrado por uma equipe composta por, no mínimo, dois profissionais: um (uma) engenheiro (a) eletricista com formação e experiência em sistemas elétricos de potência, e um (uma) profissional da área de segurança do trabalho. Alternativamente, pode-se considerar um (uma) único (a) instrutor (a) que detenha ambas as formações e experiência comprovada na área, o que representa, na visão dos autores, o cenário ideal.

Essa recomendação decorre da análise do conteúdo programático do curso, que apresenta uma divisão clara entre temas que exigem domínio técnico da engenharia elétrica e outros mais voltados à segurança ocupacional. Dentre os tópicos que requerem conhecimento técnico aprofundado em sistemas elétricos, destacam-se:

- Item 2: Organização do trabalho;
- Item 3: Aspectos comportamentais;
- Item 4: Condições impeditivas para o serviço;
- Item 10: Equipamentos de proteção coletiva;
- Item 11: Equipamentos de proteção individual;
- Item 12: Posturas e vestuário de trabalho;
- Item 13: Segurança com veículos e transporte de pessoas;

- Item 15: Liberação de instalação para serviço;
- Item 16: Sinalização e isolamento de áreas de trabalho;
- Item 17: Procedimentos de trabalho — análise e autorização.

Já os conteúdos que, preferencialmente, devem ser conduzidos por profissionais com expertise em segurança do trabalho, incluem:

- Item 1: Organização do Sistema Elétrico de Potência – SEP;
- Item 5: Riscos típicos no SEP e sua prevenção;
- Item 6: Técnicas de análise de risco no SEP;
- Item 7: Procedimentos de trabalho – planejamento, organização e execução;
- Item 8: Técnicas de trabalho sob tensão;
- Item 9: Responsabilidades;
- Item 14: Condições ambientais;
- Item 18: Situações de emergência.

Dessa forma, embora a NR10 permita certa flexibilidade na escolha dos instrutores, entende-se que a qualidade e a eficácia do curso complementar em SEP dependem diretamente da compatibilidade entre os conteúdos programáticos e a formação dos profissionais que o ministram. Alinhar a qualificação dos instrutores à natureza técnica e comportamental de cada módulo, especialmente com base em experiência prática, assegura um processo de ensino-aprendizagem mais consistente, contextualizado e eficaz na prevenção de acidentes e na promoção da segurança dos trabalhadores que atuam em sistemas elétricos de potência.

VI. Conclusões

A partir da análise normativa, da literatura especializada e das contribuições de profissionais diretamente envolvidos com a aplicação da NR10, conclui-se que o curso previsto na norma é uma ferramenta imprescindível para a conscientização sobre os riscos associados à eletricidade. A sua obrigatoriedade deve ser mantida, pois viabiliza o acesso a informações de segurança a trabalhadores que, de outra forma, dificilmente teriam esse contato. Ainda que não ofereça formação técnica, o curso cumpre seu papel ao promover uma cultura de prevenção, desde que ministrado com qualidade e por profissionais qualificados. Recomenda-se que os conteúdos sejam conduzidos por instrutores com formação compatível aos temas abordados, valorizando também a experiência prática na área. Além disso, a reciclagem do treinamento deve ser pensada como oportunidade para personalização e melhoria contínua, baseada nas experiências e riscos reais enfrentados em cada empresa. Assim, a NR10, quando bem aplicada, contribui não apenas para a segurança dos trabalhadores, mas também para a eficiência das organizações e para a redução dos custos sociais associados aos acidentes de origem elétrica.

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Irregularities in residential electrical installations observed during inspections in Maranhão

Amanda de A. Serra Lima
Electrical engineer from CREA-MA
Judicial expert for TJMA and TJDFT
Brasília-DF, Brasil
amandalima.eng@outlook.com

***Abstract* — This article presents the diversity in the safety conditions of electrical installations in Brazil, highlighting risk situations found among the more than 100 judicial expert reports carried out in homes in the metropolitan region of São Luís - MA, mainly in low-income residences. It will address percentages in the use of safety devices against electric shock and damage to property and the perception of users regarding them. In addition, it will address the economic challenges for adapting to a safe installation and the good practices with which the expert in the electrical area can help to improve the scenario, especially through the content of their expert reports.**

Keywords— safety in homes, electrical installations in the Northeast, judicial expert report, protective devices

I. INTRODUCTION

Electrical engineering professionals play a fundamental role in Occupational Safety, as they have a duty to contribute to reducing one of the main causes of accidents, which are those related to electricity. In the legal field, many electrical engineers act as experts appointed in lawsuits related to electricity, in which they are invited to identify problems; and, often, they have direct contact with the electrical installations of one of the parties involved, where they find irregularities that are not always known to the general public, as they are familiar with electricity standards.

In this context, this article presents photos and descriptions of situations that were encountered in my experience as a judicial expert in the metropolitan region of São Luís, which is recognized as a region of Brazil with a population with lower purchasing power in general. The objective is to illustrate, in a concrete way, for professionals in the area, situations of insecurity, and to help the non-specialized public, especially workers, to visibly identify problems in the electrical installations of the place where they live or work, in order to take measures in the short or medium term and thus avoid accidents of electrical origin. It also aims to show the impact that adjustments to electrical installations can have on the budget, so that some are inaccessible to the population of this region and others like it.

Regarding the profile of the houses that were visited in the expert assessments, between 2019 and 2025, they were low-income or middle-class residences; 90% of the cases were initiated against the local utility company to dispute the amounts of the invoices that were supposedly higher than they should be, and it would be necessary for the expert, depending on each situation, to carry out a load survey to simulate consumption, verify the residential installations, analyze the history and test the meter.

II. HIGHLIGHTED ASPECTS

A. Distribution boards

A home distribution board is necessary, even in poorer homes, in order to centralize electrical protection devices and divide at least the lighting and socket circuits, as recommended in the technical standard ABNT NBR 5410 [1], mainly to facilitate periodic or emergency maintenance.

However, almost half of the homes that were visited in the inspections did not have a distribution board, counting only on the standard input circuit breaker. Many of those that did have one had only one main circuit breaker (Figure 1), some of which had not been replaced or maintained for over 20 years.

Among those that had more than one circuit breaker, only two had an electric shock protection device (Residual Current Device - DR). As for the surge and atmospheric discharge device (SPD), this was not seen in any home (only in other types of inspections, involving loads such as elevators and CCTV devices).

Regarding the identification of each circuit breaker, with a name or figure indicating the circuit to which it is connected, less than half were found; when residents were asked what each circuit breaker controlled, they did not know how to say, which is a safety hazard in a situation where immediate shutdown is necessary. Figure 2 shows some of these.

Fig. 1. Distribution boards with only one circuit breaker

Fig. 2. Distribution boards without RCD and without circuit identification

B. *Grounding the sockets*

The grounding wire in the sockets is also mandatory in all electrical installations according to current technical standards, leading to the grounding grid, in order to divert any current leakage from devices to the ground instead of diverting it to a possible human touch and protect electronic equipment. More than 80% also did not have grounding in the sockets, as can be seen in Figure 3, where the sockets were opened for inspection. Of those that did have grounding, the majority were in housing policy buildings (Minha Casa Minha Vida).

Fig. 3. Sockets without grounding wire (only phase and neutral)

C. *Using adapters and extensions*

The lack of an electrical project, without concern for the correct number of sockets and light bulbs, and also sockets that are incompatible with the appliance's plug, leads to improvised installations, such as the use of "T" adapters, extensions and adapters, which often do not have the INMETRO seal or an opening for a grounding pin. Figures 4 and 5 show some photos that were taken during expert assessments and illustrate this topic.

According to the 2025 Yearbook of Abracopel (Brazilian Association for Awareness of the Dangers of Electricity) [2], of the 248 deaths that occurred in 2024 caused by electric shock in Brazilian homes, 96 of them were caused by "connections, extensions and electrical installations", in addition to fires caused by overload or poor contact in these devices. This statistic shows the danger of this type of practice, as people end up having direct contact with devices that may have current leaks and do not always follow INMETRO plug standards [3].

Fig. 4. Use of adapters

Fig. 5. Use of extensions

D. Irregular or old installations

Electrical installations provide comfort and functionality when using household appliances. However, the way in which they are installed is sometimes overlooked, due to the false perception that everything is already resolved if the energy is being supplied, even without the use of conduits and junction boxes, for example, as can be seen in the expert photos in Figure 6. Other very frequent irregularities and problems, in addition to those already mentioned in the previous topics, are: exposed wires, splices without connectors, use of inadequate or poorly placed insulating tape, wiring with inadequate gauge, old or dry wiring, non-standard sockets, irregular (clandestine) connections from the public network or from a neighbor's network.

Many of these irregularities begin as improvisations and end up becoming permanent. They lead to electric shocks due to accidental contact, unsafe adaptations and fires due to current overload in the wiring.

In Maranhão alone, in 2024, there were 14 accidents caused by fires of electrical origin, and 32 accidents due to electric shock (which resulted in 24 deaths). Measures need to be taken so that each year these statistics decrease, and fewer lives are lost.

Fig. 6. Exposed installation, without correct wire colors, absence of junction box

Table I presents a summary of the statistics presented.

TABELA I. ASPECTS OBSERVED IN THE RESIDENCES INSPECTED

Distribution panel	40% had no panel 30% had only one circuit breaker Only 2 had a RCD
Grounding of outlets	80% não possuía aterramento
Use of extension cords	90% were using
Other irregularities	30% had wires outside of conduit

III. ECONOMIC CHALLENGES FOR SAFETY ADJUSTMENTS

The safety measures that need to be taken to correct problems such as those mentioned in this article must be carried out by an electrical technician, such as installing a distribution board, installing a RCD and grounding, inserting new outlets, updating old standard outlets to new standard, or restoring joints. This is due to the need for the professional to be familiar with Regulatory Standard 10 [4], for their own protection and the protection of the installation.

There is also the investment required for the electrical project to avoid incorrect sizing, in addition to the masonry materials for finishing. Therefore, these measures involve considerable investments that, within the reality of families living on a minimum wage, are not immediately possible.

If a more urgent need is to be chosen, priority can be given to installing a RCD in the distribution board (and installing one if it does not already exist, with at least one circuit breaker in addition to the RCD). It is worth noting that the installation of the RCD will not work if there is any current leakage in the electrical installation of the location, so this problem must be investigated and corrected beforehand.

We can also mention small and medium investments and good practices that can be started immediately:

• Use outlet protectors, especially in places with children, to avoid electric shocks, and teach children not to touch outlets;

• Use portable SPDs (surge protection devices) to protect appliances such as refrigerators, computers and microwaves;

• Use minimum Personal Protective Equipment (PPE) such as goggles, insulating boots or detector pens, when in contact with potentially energized surfaces;

• Keep electrical equipment away from water and handle it with dry hands;

• Avoid leaving wires within reach of possible accidental touches as they may have imperceptible cuts that can cause electric shock;

• De-energize appliances in case of maintenance;

• Avoid using extension cords, power strips and adapters as much as possible, and use as few devices as possible at the same time.

IV. THE ROLE OF THE EXPERT ELECTRICAL ENGINEER

The judicial expert has a very clear and objective role in a legal proceeding and cannot go beyond the limit of assisting the judge in a completely impartial manner, answering the questions of the judge and the parties involved through the report. However, the electrical engineer who is the expert in

that proceeding is sometimes the only reliable electrical professional that readers will have contact with for a long time, so what is said in the report is taken into serious consideration.

Aware of this, and as a result of the reflections brought up in this article and proposed to other colleagues in the profession, an annex of one page (maximum) will be inserted into all my reports, with specific safety guidelines on electricity, presenting statistics and information taken from the latest Abracopel yearbook of electrical accidents, aiming to raise awareness among all those who have access to the report, whether judges, lawyers, plaintiffs or defendants in the case, about the need to take care of the installations. This additional material should be merely informative, without interfering with the technical conclusions of the report. This practice does not harm the impartiality of the report and will contribute to the social role that the electrical engineer must assume with the individuals around him or who have access to his textual productions.

Although readers may not be able to implement all the adaptations, for economic or other reasons, it will at least be possible to increase awareness of the dangers involved, making them more alert in the event of an accident occurring.

V. Conclusion

In view of the above, the problems existing in residential electrical installations became evident, based on the installations found in Maranhão, and the difficulties in adapting safety were clarified, with proposed solutions.

It also became evident the need for the social role of the electrical engineer, especially the expert, in raising awareness among the population for improvements in these installations, with the aim of reducing accident statistics, whether in the residential or work environment.

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Maintenance of residential photovoltaic plants: The danger is at home!

BRUNO AUGUSTO GIMENES
ElectricaPro
Bruno@eletricaproengenharia.com.br

SUMMARY

This paper addresses the risks associated with cleaning and maintaining residential solar panels, highlighting the importance of safety and awareness in the solar energy sector.

I. INTRODUCTION

The expansion of photovoltaic energy in Brazil, driven by ANEEL Normative Resolution 482/2012, has brought with it significant challenges, such as the proliferation of unqualified integrators and poorly executed installations. Cleaning the panels, which is often underestimated, involves serious electrical risks such as shocks, current leakage and electric arcs, as well as the dangers of falling from a height. The lack of technical knowledge, the absence of personal protective equipment (PPE) and the "do-it-yourself" culture exacerbate these risks, resulting in frequent and, in some cases, fatal accidents. It is in the face of these challenges that measures to reduce the risks must be implemented.

The residential photovoltaic solar energy segment is currently in statistical limbo, because even with the efforts of ABRACOPEL (Brazilian Association for Raising Awareness of the Dangers of Electricity) to categorize part of the accidents as photovoltaic in origin, informality is still very high, meaning that the data only expresses a small portion of reality.

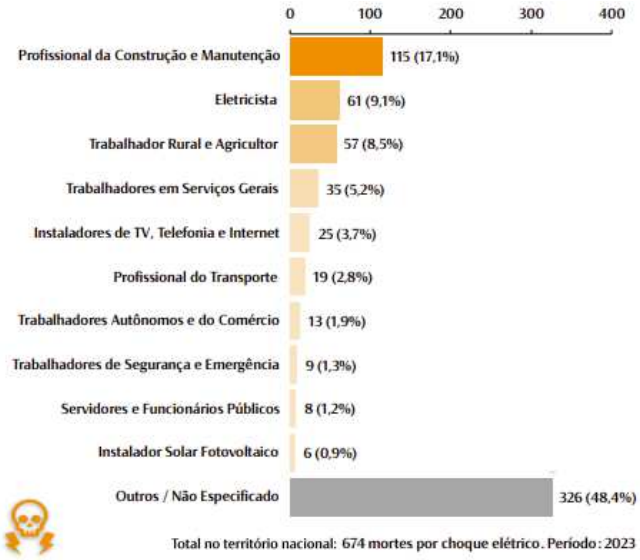

Figure1 - Number of deaths from electric shock and profession in 2023

Source: ABRACOPEL Yearbook 2024.

Based on the laws that underpin the sector and the evolution of this market, we will provide a foundation for understanding the current market in solutions for residential photovoltaic plants, as well as cultural, economic and technical issues.

II. THE BEGINNING - MARKET REGULATION

The regulation of photovoltaic energy in Brazil has been consolidated through specific laws and standards that have allowed it to expand significantly in recent years. The process began with ANEEL Normative Resolution 482/2012, which laid the foundations for consumers to generate and offset their own energy on the grid, a phenomenon known as distributed generation. Later, a series of technical and legal revisions and improvements, including Resolutions 687/2015, 786/2017, 890/2020 and 1000/2021, facilitated access to the grid,

broadened the scope of energy compensation and made it possible to new types of generation, such as solar condominiums, consortia and projects for isolated communities. At the same time, federal laws such as 13.203/2015 and, more recently, Law 14.300/2022 (Legal Framework for Distributed Generation), have boosted the sector by offering tax incentives, legal certainty and defining clear rules for the relationship between generators, consumers and energy concessionaires. As a direct consequence of this regulatory progress, the country has witnessed a strong expansion of the photovoltaic market, with an increase in the number of integrators and manufacturers, the creation of dedicated financing lines, the development of local technologies and the democratization of access to clean energy, making solar generation one of the main alternatives for diversifying the electricity matrix.

III. Market Development

Between 2012 and 2015, equipment distributors had restricted operations and concentrated on international brands, especially inverters and panels, with little variety and availability, while training was practically non-existent and access to lines of financing was limited to large projects, with options such as the BNDES aimed mainly at large plants and strict national content requirements. With the revision of regulatory standards and the increase in demand from 2015 onwards, distributors expanded their portfolios, began negotiating with prominent international suppliers and the first national brands or those with nationalized production of equipment emerged, favoring a drop in prices and diversification of the products offered to the market. In this context, training initiatives began to emerge, initially aimed at integrators and installers, often promoted in partnership with manufacturers or regional events. Around 2018, the entry of new global suppliers and the increase in import volumes accelerated competitiveness among distributors, who began to invest in training professionals, offering specialized training, online courses and certifications, contributing to the technical maturity of the sector. At the same time, financing lines have expanded, with regional banks such as Banco do Nordeste and credit cooperatives launching specific products for solar generation, while fintechs and private banks have started their first operations aimed at small and medium-sized plants. As of 2020, with the market already consolidated and the Legal Framework for Distributed Generation expected, even more professionalized distributors began to enter into exclusive partnerships with major inverter and module manufacturers, bringing technological innovations and facilitating access to cutting-edge equipment. During the same period, training courses took on a digital format, became more comprehensive and specialized, and began to cover commercial management, regulation and operations. Credit lines continued to advance, with new options such as fintechs, consortia, leasing and even *as-a-service* models, making financing more agile, decentralized and adapted to the profile of residential, business and rural customers.

IV. Demand for Sustainability

The demand for sustainability is a growing set of concerns and demands from society in relation to environmental responsibility, the search to reduce energy costs and alignment with global standards of environmental, social and corporate governance (ESG).

Figure2 - ESG and its pillars

Source: AIA Contract Documents - 2025

In the social sphere, residential consumers have come to see solar energy not only as an economic alternative for lowering tariffs, but also as a way to reduce their carbon footprint, contribute to the conscious use of natural resources and actively participate in the energy transition. Environmental awareness movements, educational campaigns and easier access to information have strengthened this perception, making the end consumer a protagonist in the transformation of the national energy matrix.

In the business sector, sustainability has become a strategic factor and a competitive differentiator. Companies of all sizes have signed up to generating their own solar energy in order to reduce their exposure to tariff fluctuations, increase the value of their assets with green certifications (such as the LEED label for sustainable buildings) and meet climate targets set by governments, investors or global supply chains. For many segments - including agribusiness, industry, commerce and services - investment in photovoltaics also responds to the need to serve clients and investors who are increasingly attentive to sustainable practices and transparency in operations.

In addition, large corporations and multinationals have accelerated decarbonization programs, often requiring the entire supply chain to implement robust environmental policies, which has boosted the decentralized growth of solar systems in various states and productive sectors. At the same time, state and municipal governments have adopted tax incentives, clean energy programs and environmental requirements in public tenders and contracts, further expanding the potential market.

From being perceived as a symbol of innovation, modernity and socio-environmental responsibility, solar energy has also become a powerful marketing and relationship tool with society. Companies that invest in solar energy become part of lists of good practices in sustainability and often stand out on the media and institutional scene.

V. The Residential Market

The rapid pace of expansion has exposed structural weaknesses, mainly related to the poor quality of the design,

installation and operation of the systems. The unbridled quest for competitiveness, often focused exclusively on price, has led to the emergence of dubious practices and unprepared professionals, compromising both the safety and efficiency of the systems installed. These problems have a negative impact on the expected performance of residential solar plants, consumer confidence in the segment and, ultimately, the credibility of the national photovoltaic market itself.

A. *Technical Quality*

Poor technical quality has proved to be one of the biggest concerns in the residential context of photovoltaic energy. A significant proportion of projects fail to comply with current technical standards, such as NBR 16274, NBR 5410, NR 10 and the guidelines of the National Electric Energy Agency (ANEEL), resulting in undersized or oversized systems, lack of analysis of roof conditions, poor electrical designs and lack of proper documentation. The shortage of truly qualified professionals exacerbates the scenario: many installers enter the sector without solid technical training or constant updating, disregarding essential criteria such as safe electrical connections, surge protection, correct earthing and shading assessment. Execution, in turn, often disregards good practices, leading to poor installations, poorly fixed structures and a lack of after-sales follow-up. These factors not only compromise energy efficiency, but also expose users to the risk of fire, shock and property damage.

B. *Business professionalism*

If there is one thing that is quite common in the residential photovoltaic energy market, it would be the low degree of professionalism among many companies operating in the field. The rapid growth of the sector has stimulated the emergence of organizations with no previous experience in the electrical sector, migrating from other sectors or creating exclusively opportunistic amateur operations. The lack of internal processes, structured technical support and after-sales responsibility means that many companies neglect to comply with contractual guarantees, operate without minimum certifications and conduct business in disregard of company registrations, compulsory insurance and tax obligations. This lack of organizational maturity harms both the end consumer and the reputation of the sector as a whole, making it difficult to differentiate between serious and adventurous companies in the market.

C. *Unethical Business Practices*

Fierce competition, coupled with consumers' lack of technical knowledge, creates space for companies and professionals to engage in unethical commercial practices. It is not uncommon for excessively low budgets to be presented to customers after essential items for the functioning and safety of systems have been omitted, such as circuit breakers, SPDs (Surge Protection Devices), earthing, earth bonding, stringboxes and suitable fixing materials. Malpractice and negligence also manifest themselves in unfeasible performance promises, omission of maintenance costs, use of dubious brands and certifications and lack of contractual clarity. These practices, in addition to artificially reducing the final value of the bid, mask the real quality and durability of the system, resulting in financial and technical losses for consumers.

VI. Maintenance of Photovoltaic Plants

Despite the initial perception that small solar systems require little intervention over time, practical experience shows the importance of regular care to ensure optimum performance, safety and longevity of the equipment. Among the most common needs are periodic cleaning of the modules, preventive electrical inspections, checking connections, structural integrity, checking the operation of the inverters and updating the inverter firmware. Lack of maintenance can result in technical and performance issues as well as exposing people in the vicinity to danger. Some points are therefore important to consider, as they affect the technical quality of the system and consequently the safety of the people around it.

A. *Need for fulfillment*

Environmental factors such as dust and debris accumulating on solar modules reduce energy generation and require regular cleaning. In addition, periodic inspections of cables, connections, inverters and structures prevent failures and electrical hazards, ensuring the proper functioning of the system. Predictive maintenance, based on remote monitoring, allows problems to be identified quickly, while corrective actions represent greater cost and loss of production. Maintaining preventive routines complies with technical standards, protects guarantees and values assets, as well as reducing the likelihood of accidents involving people.

B. *Quality of Existing Electrical Installation*

Before connecting a solar plant to a property's internal network, it is essential to carry out a detailed assessment of the condition of the existing electrical installation. Old installations with deteriorated wiring, inadequate sizing or a lack of protective devices such as circuit breakers and residual current devices represent a significant risk. Faults in this system can result in overloaded conductors, excessive heating of cables, loss of insulation and the occurrence of short circuits. In addition, the lack of efficient grounding can increase the danger of fatal electric shocks and make the system vulnerable to surges, generating fire risks and structural damage. Neglecting this assessment compromises both the efficiency and safety of the entire photovoltaic system operation.

Figure3 - Small residential electrical panel: lack of compliance with technical standards

Source: Own archive (ElectricaPro)

C. *Quality of execution*

The solar installation stage requires strict adherence to technical standards and good engineering practices. Poorly made connections, the use of inadequate terminals, poor fixing of cables to structures, lack of wire organization and failure to apply the correct torques to screws and connections are frequent examples of faults that increase the incidence of short circuits, electric arcs and premature deterioration of systems. Poor execution can lead to panels and equipment coming loose, exposure of energized parts, malfunctioning of protection devices and lack of correct circuit insulation. Such conditions substantially increase the risk of serious electric shocks, fires and even fatal accidents involving maintenance teams or users of the property.

Figure4 - Consequence of reverse current in a photovoltaic plant

Source: Canal Solar - 2019.

D. *Use of Inappropriate Materials*

With the photovoltaic market booming, it attracts a wide range of inputs, but opting for materials without certification, of dubious origin or sizing incompatible with the system's requirements is extremely risky. Cables that are not up to specification, low-quality connectors, metal supports that are unsuitable for the weather and protection devices that do not perform well can lead to accelerated wear, loss of insulation and reduced mechanical resistance. The use of these materials increases the likelihood of poor contact, localized overheating, insulation failures and, consequently, incidents of shock and fire. As well as putting users and the building itself at risk, these problems impair the useful life of the system and increase maintenance and replacement costs.

Figure5 - Solar panel falls from structure during storm

Source: Canal Solar - 2022

VII. ACCIDENTS WITH RESIDENTIAL PHOTOVOLTAIC PLANTS

The occurrence of accidents in residential photovoltaic plants, although relatively low in relation to the number of systems installed, is a major concern for the physical integrity of users, installers and the property involved. The main incidents are related to electric shocks, fires and falls during installation or maintenance activities. Shocks often result from faulty connections, the absence or inadequacy of the earthing system and accidental contact with energized parts during improper procedures. Fires can be caused both by overloads in pre-existing electrical installations and by the use of low-quality materials or poor workmanship, resulting in short circuits and failures in protection devices. Falls and physical accidents mostly involve workers during the assembly of modules on roofs, caused by a lack of personal protective equipment or inadequate working conditions. Analysis of recorded cases shows that most of these accidents could have been avoided by strict compliance with technical standards, the use of certified materials and the qualification of the professionals involved.

A. *Aggravating factors: the do-it-yourself culture and the informality of services*

Do-it-yourself attracts many consumers due to the feeling of control over the installation and maintenance of solar systems, as well as providing an initial cost reduction. However, the installation and maintenance of photovoltaic systems involves technical complexities that require specialized knowledge. Faults in execution, such as improper electrical connections, the absence of an adequate earthing

system and the poor fixing of modules, can result in serious accidents or fires.

Informality in services, on the other hand, is related to the emergence of unqualified professionals and companies, operating outside of regulations and recommended practices. These services, usually offered at competitive prices, attract unsuspecting consumers who prioritize cost over quality.

B. Fall from a height

The maintenance of residential solar power plants, which are generally installed on roofs, i.e. at height, involves significant risks, especially related to falls. Working on roofs and elevated structures exposes workers to potentially serious accidents, since falls from height are one of the main causes of injury in the construction and maintenance sector. The absence of personal protective equipment, such as safety harnesses and lifelines, amplifies this risk. In addition to falls, working conditions can be adverse. Sloping, slippery, unstable or aged surfaces can compromise safety. Additional weather factors, such as wind, rain and snow, also affect the stability of workers, increasing the danger of accidents during solar maintenance activities at height. Another aggravating factor is electric shock, whose characteristic response is muscle contraction, which leads to stiffening of the lower limbs and, respectively, a fall.

Figure6 - Accident at height in residential solar systems

Source: UOL - 2024.

C. Electric shock

Washing solar plants involves significant risks of electric shock, especially when inadequate procedures are adopted. The presence of water, an excellent conductor of electricity, increases the danger of shocks, and this is exacerbated if the system is not properly grounded, because sometimes an electrical/mechanical fault in the solar panel will cause a current leak that is small in relation to the size of the plant, and will not generate an error in the supervisory system, but this current is high enough to cause damage. In addition, poorly made electrical connections or damaged equipment can expose energized parts, putting workers at risk.

Another critical risk is proximity to the power grid when using extension cords to clean modules. This equipment, if not handled correctly, can come into contact with nearby power lines, causing electric shock. It is essential to be aware of your surroundings and keep a safe distance from the power grid throughout the cleaning process, ensuring that safety regulations are strictly followed to protect workers from serious accidents.

Figure7 - Accident during washing of solar modules: shock on contact with airborne RD

Source: Globo.com - 2024.

D. Electric arc

The risk of arcing in residential solar plants is a serious problem that can compromise the safety of occupants and the integrity of the system. In photovoltaic systems, this risk increases due to loose connections, inadequate insulation or damaged components. The presence of moisture and dirt can aggravate the situation by facilitating paths for electricity. As these systems operate continuously, even minor problems can develop into significant failures if they are not addressed quickly.

To mitigate the risk, it is crucial to carry out regular inspections, ensure that all connections are tight and well insulated, and use components of the right quality and certification. Implementing arc flash protection devices can also help detect and stop potential arcs, preventing further damage. By following these practices, the risks of arcing can be considerably reduced, ensuring a safe and efficient environment.

E. Fire

Faults in the electrical installation are one of the main sources of danger. Poorly made connections and inadequate insulation of components can lead to overheating and electric arcs, which have the potential to start fires.

The use of unsuitable materials also represents a major risk. When low-quality or uncertified components are used, they become more prone to failure, as they may not be able to withstand the required operating conditions or may deteriorate more quickly, increasing the danger of fire.

Poor maintenance is another critical factor. Without regular maintenance, dirt and debris can build up on the modules and connections, which increases electrical resistance and the risk of overheating.

In addition, environmental factors such as high humidity, dust or soot can exacerbate these risks. These conditions can contribute to short-circuiting and the development of fires, as they promote unsuitable operating conditions.

SETOR FOTOVOLTAICO

Incêndios em placas solares causam alerta e especialistas listam cuidados

Corpo de Bombeiros e Inmetro recomendam dispositivos de segurança para evitar as falhas no sistema

Kethlyn Moraes

Figure8 - Fire in photovoltaic modules

Source: RDNewes.com.br - 2023

VIII. Risk Mitigation

There are existing methods for controlling and managing electrical risks during maintenance of solar power plants. Therefore, from a technical point of view, the risks are manageable, there is suitable PPE on the market, work procedures and various techniques and equipment available.

While it's not the lack of technical expertise that causes accidents, it's the human factor that weighs heavily. Non-electricity companies operating in the sector, customers who are not properly informed about the risks and who have too much self-confidence, end up exposing themselves and suffering accidents.

To reduce the number of lay people cleaning photovoltaic plants, it is essential to apply methods of education, awareness-raising and technical regulation. Offering training and certification courses, along with workshops and educational materials, can adequately train professionals. Awareness campaigns and partnerships with industry associations are important to promote awareness of the risks of unsafe practices. In addition, implementing mandatory certifications and strict technical standards, along with effective inspection, can ensure the professionalization of the sector and reduce incidents.

IX. Conclusion

There has been rapid growth in the residential photovoltaic energy market, driven by the search for sustainable and economical energy sources. However, this unbridled growth has resulted in the entry of many companies that have no experience in the electrical sector, leading to installations carried out outside the required technical standards. Such practices compromise the safety and efficiency of the systems, putting both installers and homeowners, who are generally lay people, at risk when carrying out maintenance on these inadequate installations.

These individuals often lack the necessary training to understand the potential dangers, which increases the likelihood of accidents and damage to systems. To meet this challenge, it is essential to invest in comprehensive training and awareness strategies. Offering specific, certified courses can ensure that professionals have the right technical knowledge.

In addition, education campaigns can help make owners aware of the importance of hiring qualified professionals to install and maintain their plants. Implementing rigorous inspection is also essential to ensure that the work carried out meets safety and quality standards.

Only through these coordinated measures - training, awareness, education and efficient inspection - will it be possible to minimize the risks and guarantee the safe and effective use of residential solar energy.

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Reducing Arc-Flash Risk: A Review of Engineering Controls

Marina Camponogara
Institute of Energy and Mobility (IEM)
Federal University of Santa Maria
Santa Maria, Brazil
marina.camponogara@acad.ufsm.br

Julia Possebon Spellmeier
Institute of Energy and Mobility (IEM)
Federal University of Santa Maria
Santa Maria, Brazil
julia.possebon@acad.ufsm.br

Pedro de Oliveira Bacin
Institute of Energy and Mobility (IEM)
Federal University of Santa Maria
Santa Maria, Brazil
pedro.bacin@acad.ufsm.br

Daniel Pinheiro Bernardon
Institute of Energy and Mobility (IEM)
Federal University of Santa Maria
Santa Maria, Brazil
dpbernardon@ufsm.br

Vitor Cristiano Bender
Institute of Energy and Mobility (IEM)
Federal University of Santa Maria
Santa Maria, Brazil
vitor.bender@ufsm.br

Carlos Almeida Simoes
Engineering Department
CPFL Energia
Campinas, Brazil
cas@cpfl.com.br

Gilnei José Gama dos Santos
Engineering Department
CPFL Energia
São Leopoldo, Brazil
gilnei.santos@cpfl.com.br

Jiyong Chai
Supply Department
CPFL Energia
Campinas, Brazil
chaijiyong@cpfl.com.br

Sheng Xu
IT Department
CPFL Energia
Campinas, Brazil
xusheng@cpfl.com.br

***Abstract*—Arc flash (AF) is a phenomenon characterized by the release of a massive amount of energy, mainly thermal, and due to its potential to cause damage, it is as an electrical risk that should be assessed and controlled. Risk control follows a six-level hierarchy, which focuses on engineering controls, measures that aim primarily to reduce incident energy (IE) or, if this is not feasible or sufficient, minimize worker exposure. The aim of this paper is to review the main engineering controls, which act to reduce the AF duration, reduce its current, and increase the working distance. From in-depth research of the specialized literature, these main engineering controls are examined, considering their application in practice and the extent of their effects in reducing AF risk. Also, a comparison regarding popular engineering controls is presented, along with a brief discussion about other measures that effect in reducing AF risk too and a case study showing the practical results of applying two distinct engineering controls. The results show that the most efficient way to mitigate the IE is to reduce the AF duration, because it guarantees both personnel and material protection. Another option is increasing the working distance, although it does not prevent material damage, reduces the worker's exposure to risk. Reducing the arc current can be counterproductive, so it is an approach that should be analyzed carefully. Finally, the discussions presented in this paper confirm that no individual solution will eliminate all the risks of working near or on live parts, and any measure dedicated to reducing the AF risk must be evaluated considering aspects such as applicability, effectiveness, and cost.**

Keywords—arc flash, engineering controls, electrical risk, incident energy, mitigation techniques

I. Introduction

An arcing fault is more common than a bolted fault [1], and occurs when current flows between phase bus bars, neutral or system ground through an originally insulating medium, normally the air. This type of fault involves the rapid release of energy [2] in three forms (light, heat, and mechanics) [3], resulting in a phenomenon called arc flash (AF). The destructive power of an AF can be immense [2], and the consequences arising from it are varied, including thermal burns, molten metal particles, shrapnel, explosions, pressure waves, intense light and sound, fires, toxic vapors, gases and effects of plasma and magnetic fields [2,4–8].

The occurrence of an AF is an inherent possibility when working with or near live parts [9], so the hazard (possibility) is always present. Also, considering that this phenomenon causes damage to equipment and humans [3] (severity potential), it is classified as an electrical risk that must be assessed and controlled. The risk assessment considers how dangerous is an AF from a quantity called incident energy (IE). It quantifies the thermal risk associated with the AF [1], and when exceeds the acceptable risk level, indicates the need to control that risk [10].

Risk control is based on a six-level hierarchy of risk control methods [11], a widely accepted system promoted by safety organizations worldwide [10] and generally presented in the form of an inverted pyramid. These methods are organized from most (widest part) to least (narrowest part) effective: elimination, substitution, engineering controls,

awareness, administrative controls, and personal protective equipment (PPE).

Elimination of the hazard by de-energizing is the highest priority [1] but, unfortunately, is often impractical to perform due to demand for continuous equipment operation [10]. The same happens to substitution approaches, especially to existing systems. So, the next recommended preference is the engineering controls, which may have a substantial impact on risk [12]. These measures primarily aim to reduce IE or, if this is not feasible or sufficient, minimize worker exposure. Awareness and administrative controls, as well as PPE, do not affect the source of the risk – awareness and administrative controls seek to modify worker's behavior, while PPE is the last line of defense against AF risk [13]. So, the engineering controls are the focus for AF mitigation.

In view of this, this paper reviews the main engineering control methods presented in literature, discussing their applicability in practice and the extent of their effects in reducing AF risks. In addition, a comparison regarding the most recurrent engineering controls is presented, as well as a brief discussion about other measures applied to decrease AF risks too. Finally, a case study with the application of two engineering controls is presented to show the practical effects of these controls.

II. Engineering Controls

The engineering controls are the focus for AF mitigation because they give great deal of options to efficiently reduce the risk under an acceptable level [10]. These reduction techniques are available in various formats ranging from simple to complex solutions [12] but, in general, they involve decreasing the arc duration or current, besides of increasing the working distance, as discussed in [10,12–15]. In this section, these three approaches are presented in detail, exploring their application in practice and effects in AF risk.

A. Reducing Arc Duration

According to [13], the best way to lower IE levels in the system is reducing the arc duration. This statement is well accepted since the direct relationship between the AF released energy and the arc duration was established by [16].

The arc duration is defined as the fault clearing time, the calculated time needed by the protective device to completely clear the fault and extinguish the arc [17], so decreasing this time includes reducing the detection time (protection scheme operating time), the clear time (interruption time), or both. Clearing the fault quicker by causing the overcurrent protective device (OCPD) to trip faster is the most efficient method for lowering IE [14], and it can be achieved through:

- Defining appropriate trip settings considering AF levels: the protective device coordination study is used to determine the proper tripping time to mitigate AF exposure [18].
- Proposing alternative protection adjustments dedicated to maintenance activities [2,10,19].
- Upgrading devices to achieve the desired IE level [13,17].

Also, it may be necessary to improve the existing protection scheme or use supplementary protection, especially to ensure faster actuation times without compromising the coordination and selectivity of the protection devices. In this scenario, many options appear, such as:

- Zone selective interlocking (ZSI): it is a blocking scheme used to remove the effect of the required coordination delays from protection time [20], originally developed as a more cost-effective alternative to bus differential protection [21]. It is cited as a solution by [1,3,10,14,17,19,21–24].
- Bus differential protection: mentioned as a solution by [10,13,21,22], it is a protection scheme based on Kirchhoff's node law, once it sums the currents coming in and going out of a node such as bus or a transformer [24]. It provides sensitive protection because it identifies fault location without adding arbitrary delays or desensitizing pickups [24], but requires additional relays, current transformers, and wiring [13].
- Energy reduction maintenance switch (ERMS): it is cited as a solution by [2,10,14,21,22,25], being installed jointly with overcurrent protective devices [2,14] to provide a reduced tripping time to an OCPD installed upstream to the ERMS [14]. The ERMS is used by personnel only when they are required to perform a procedure on energized equipment [14] once it causes miscoordination [13].
- AF detection relay: an AF detection relay uses light associated with AF, in addition to current confirmation, to detect an AF and then reduce the trip time [13,19]. It is cited as a solution by [10,12,17,19,23–26] and has as advantage the fact that guarantees that IE will decrease in all cases without compromising system selectivity [12].

B. Reducing Arc Current

In electrical terms, energy is calculated as the product of voltage, current, and time [13]. As previously explained, lowering arc duration is the most efficient way to reduce the energy release by an AF event. But it is possible to achieve this decrease by reducing the arc current.

Arc current can be limited through the limitation of fault currents, using current-limiting devices as high-impedance transformers, in-line reactors, current-limiting fuses [14] and other traditional approaches as system equipment upgrade and open bus ties or disconnect sources [15]. The appliance of maintenance mode and dividing the busbars into more sections are also other ways of decreasing arc current [10].

However, this approach can be counterproductive: a reduction in the fault current (and, consequently, in the arc current) may not cause a decrease in the IE once trip time of protective device increases at reduced fault current, which can cause a rise in the IE [25]. Given this, reducing arc current is usually little explored as a solution to mitigate AF risk. It should be analyzed carefully to guarantee that the IE lowering due to arc current limitation outweighs the increase of this energy resulting from the addition of arc duration.

C. Increasing Working Distance

Although increasing working distance is considered an engineering control like reductions in arc duration and current, it differs from them in that it mitigates or removes personal exposure to AF risk but does not prevent damage to equipment

[23]. There are several approaches that allow the operator to work at greater working distances or, if possible, remotely.

The simplest way to implement a greater working distance is using technologies or tools that allow to work in a greater distance from energized equipment [10]. The most well-known tool for this application is the maneuvering pole, but another solution is the use of remote racking devices [10,13,23,25], a type of mobile device that can be employed to rack breakers from a distance [23]. In both cases, the use of these devices can permit to the worker standing outside the AF boundary.

The remote operation, when possible, is a better option because it clears the worker's AF exposure. It is possible through technologies such as remotely mounted control panels, human-machine interfaces, and supervisory control and data acquisition systems [13].

III. Comparing Engineering Controls

As previously explained, engineering controls are based on three actions: reducing the arc duration, reducing the arc current and increasing the working distance. The first two act on the arc extinction time. Therefore, the IE decrease resulting from their implementation not only guarantees a mitigation in worker's exposure, but also the system equipment protection (material protection). Increasing the working distance, on the other hand, has the consequence of reducing or even eliminating worker exposure, but does not guarantee material protection.

This does not mean, of course, that increasing the working distance should not be used as an engineering control, since the focus of modern protection is protecting personnel [24]. Furthermore, it has already been previously commented on how the implementation of measures that imply the arc current reduction are counterproductive. Therefore, the comparison of engineering controls in this work, considering how they are implemented and the extent of their effects, considers only the controls for reducing arc duration and for increasing the working distance, although reducing arc duration is a valid option for any activity and increasing working distance is only applicable to some types of tasks.

This comparison is based on what is set out in [13], which lists the different technologies for mitigating the AF risk, considering aspects such as IE reduction, protection against intentional and accidental exposure, implementation and operating costs, and implementation complexity.

About engineering controls focused on reducing the arc duration:

- ZSI: it results in a significant IE decrease, implying the guarantee of protection against both intentional and accidental exposure. Its implementation costs are low, while operational costs are medium. Its implementation complexity is medium.
- Bus differential protection: it results in a significant IE decrease, leading to the guarantee of protection against both intentional and accidental exposure. It presents high complexity to implementation, so it has high capital costs. The operational cost is average.
- AF maintenance switch: it results in a moderate IE decrease, implying a limited protection against intentional exposure. Protection for accidental exposure is not guaranteed. Its capital costs are low, while operational costs are medium. Its implementation has a medium complexity.
- AF detection relay: it results in a significant IE decrease, implying the guarantee of protection against both intentional and accidental exposure. Its implementation is highly complex. Both costs (implementation and operational) are medium.

About engineering controls focused on increasing the working distance:

- Remote racking device: it does not result in an IE reduction but provides limited protection for intentional exposure (in this case, the limitation concerns both personal safety − since the worker is in the presence of the AF, even if far away − and material integrity). For accidental exposure, it does not guarantee protection. As far as costs are concerned, the expenses related to the equipment acquisition are low, but its operating cost is medium. Its implementation complexity is low.
- Remote operation: it does not result in an IE reduction, but it provides limited protection for intentional exposure (in material terms, since the operation is remote the person is safe). For accidental exposure, it does not guarantee protection. As far as costs are concerned, the expenses related to equipment acquisition are high, but its operating cost is medium. Its implementation complexity, as well as operating costs, is average.

IV. Other Solutions For Reducing AF Risks

Engineering controls aim to reduce IE, which implies both personal and material protection (for controls dedicated to decreasing or the arc duration or its current) or, at least, worker protection (through controls dedicated to increasing working distance). Although these controls are the greatest focus within the implementation of the methods provided by the risk control hierarchy, it is possible to use other methods that do not influence the IE itself, but that help reduce the AF risk.

Statistically, AF events occur due to human errors, mechanical wear of equipment, corrosion on electrical parts and contactors, faulty connections, wiring failure, pollution, dust, leakage, or other substance that may create an accidental electrically conductive connection [12]. Therefore, prevention and containment measures can be taken, both in the project phase and retrofit, with the aim of removing or reducing the possibility of occurrence of this phenomenon (prevention) or, in the impossibility of this type of measure, contain the AF effects (containment). Two examples of prevention measures are the use of insulated buses [27] and compartmentalization application [13,18]. The most popular containment measure is the use of arc-resistant equipment [13,22,27].

About these measures:

- Insulated bus: it decreases the AF likelihood, and the sustained arc duration when compared to bare bus [27].
- Compartmentalization: it decreases the AF likelihood by compartmentalizing equipment and insulating energized parts [13]. On the other hand, it is important to consider that reducing compartment dimensions

can increase IE. So, compartmentalization positively impacts on AF probability (reduction) but negatively impacts the severity of this event (IE).

- Arc-resistant equipment: it is designed to provide an additional degree of protection for personnel performing normal operating duties in proximity to the energized equipment during an AF through of directing energy away from the worker [13,14,27].

V. Applying Engineering Controls For Reducing AF Risks – A Case Study

To demonstrate, in practice, how engineering controls can be applied to reduce EI or, at least, worker exposure to AF risks, a case study is presented in this section. It should be noted that, as shown in the previous sections, there are numerous approaches to achieving these objectives, and the case study presented here presents only two of them.

This case study is based on a scenario presented in the IEEE Std 1584-2018 guide [28], with a modification in relation to the adopted protection device. This scenario, called the original scenario, has its characteristics presented in Table I. The IE and AF boundary (AFB) (radial distance, from the AF source, from which the IE level is equal to or less than 1.2 cal/cm²) calculated according to the method provided in [28] are also included in the table.

TABLE I. Original Scenario.

Parameter	Value	Unit
Electrodes configuration	VCB	-
Open-circuit voltage (line-to-line)	480	V
Three-phase bolted fault current	45	kA
Electrode gap	32	mm
Working distance	609.6	mm
Enclosure width	610	mm
Enclosure height	610	mm
Enclosure depth	254	mm
Arc duration	650	ms
Incident energy	25.89	cal/cm²
AF boundary	4.17	m

Based on the original scenario, two different scenarios are proposed:

- Modified scenario 1: in this scenario, reducing the arc duration is used as an engineering control. This result is achieved by replacing the existing protective device with another that acts faster.
- Modified scenario 2: in this scenario, the engineering control used is to increase the working distance, using a remote racking device.

Table II and Table III present, respectively, modified scenarios 1 and 2 parameters. The parameters whose values differ from the original scenario are in bold to facilitate their identification.

TABLE II. Modified Scenario 1.

Parameter	Value	Unit
Electrodes configuration	VCB	-
Open-circuit voltage (line-to-line)	480	V
Three-phase bolted fault current	45	kA
Electrode gap	32	mm
Working distance	609.6	mm
Enclosure width	610	mm
Enclosure height	610	mm
Enclosure depth	254	mm
Arc duration	**400**	ms
Incident energy	**15.93**	cal/cm²
AF boundary	**3.07**	m

TABLE III. Modified Scenario 2.

Parameter	Value	Unit
Electrodes configuration	VCB	-
Open-circuit voltage (line-to-line)	480	V
Three-phase bolted fault current	45	kA
Electrode gap	32	mm
Working distance	**9140**	mm
Enclosure width	610	mm
Enclosure height	610	mm
Enclosure depth	254	mm
Arc duration	650	ms
Incident energy	**0.34**	cal/cm²
AF boundary	4.17	m

Comparing the original scenario with the modified scenario 1, the arc duration reduced 250 milliseconds by replacing the original fuse (arc duration equal to 650 milliseconds) with a faster-acting fuse (arc duration equal to 400 milliseconds) – such modification considers that coordination has been maintained. The arc duration directly influences both IE and AFB, so this reduction in time implies a decrease in the IE (in this case, of approximately 10 cal/cm²) and the AFB (reduction of 1.1 meters for this scenario). It is important to highlight that, in this scenario, the IE reduction implies a mitigation in the capacity for damage to both the electrical installation (equipment) and the worker exposed to AF event.

In modified scenario 2, the working distance was increased to approximately 9.14 meters by using a remote racking device. Comparing the results of the original scenario and the modified scenario 2, the IE estimated for the modified scenario is much lower than the IE estimated for the original scenario, as there was a substantial increase in the working distance. The relationship between IE and working distance is inversely proportional, so the greater the distance, the lower the IE: it ensures that the further away from the arc source the worker is, the lower his/her exposure (greater safety). On the

other hand, the AFB did not change. It is because the arc source remains unchanged: with the same characteristics as in the original scenario, its destructive capacity (function of the voltage, current and duration) remains the same – so, increasing the working distance ensures reduced risk for the worker (because at the working point, IE is much lower than in the original scenario) but does not reduce material damage.

Finally, it should be highlighted that the AFB can be used as a guiding parameter in choosing a safe working distance. Taking the 4.17 meters AFB as a reference, any working distance greater than this value will guarantee the worker's thermal safety – in this second scenario, the working distance resulting from the remote racking device use is more than twice the estimated AFB.

It is important to clarify that AFB establishes a safe area solely in terms of heat transfer, once other hazards associated with AF, such as the emission of molten material, toxic fumes, extremely intense light, and noise harmful to the auditory system, among others, can occur beyond the limits of the AFB. Unfortunately, it was not possible to verify the existence of clear regulatory guidance regarding the management of these other hazards associated with AF, including beyond the boundaries of the AFB. Brazilian standards either do not address the issue (as in the case with [29]) or only briefly mention it – [30] clarifies that arc rating clothing does not protect against the AF mechanical hazards and recommends a case-by-case assessment of this type of hazard but does not provide further clarification. In [11] (an US standard) is there a recommendation to use PPE whenever there is a danger of injury from exposure to AF or from flying objects resulting from electrical explosions, but there are still no clear recommendations for scenarios outside the AFB. So, for these other hazards, the authors understand that the use of PPE may be necessary even at distances considered safe from the perspective of the AFB parameter.

VI. Conclusions

AF is a phenomenon characterized by the release of a massive amount of energy, and is classified as an electrical risk, as it presents the potential for personnel injury and material damage and its possibility of occurrence is inherent to the operation of electrical systems. The AF risk must be assessed and controlled following a hierarchy of risk control methods, with engineering controls being the main practical focus of this.

Engineering controls aim to reduce IE or, if this is not feasible or sufficient, minimize worker exposure. This work proposed a review of engineering controls, based on decreasing the arc duration and arc current, as well as increasing the working distance, addressing their practical implementation and the extent of their effects on reducing IE. This investigation ratified that the most efficient way to mitigate the IE is reducing the arc duration, which can be done through adjustments to existing protection, adoption of supplementary protection, and replacement of protective devices. Another solution is increasing the working distance, an alternative that, although it does not reduce IE (and does not prevent material damage), minimizes the worker's exposure to risk. To this end, tools or technologies can be used that allow the task to be performed at a safe distance from the energized equipment or even remotely. Finally, although reducing the arc current has a direct impact on reducing IE, it is proved to be a counterproductive alternative, due to the inverse relationship between current and time.

In addition to engineering controls, other measures that have an impact on reducing the AF risk were presented, such as the use of insulated busbars, compartmentalization, and the arc-resistant equipment. All measures reviewed and mentioned here are used in practice (to a greater or lesser extent, alone or combined) with the primary objective of ensuring the personnel and equipment safety against the AF risk.

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Risk Analysis and Safety Measures in the Use of Temporary Grounding in Electrical Networks

Emanuel Filipe Galdino Alves
Vale S.A.
Belo Horizonte, MG
emanuel.alves@vale.com

Larissa Andrade de Almeida
Vale S.A.
Conselheiro Lafaite, MG
larissa.almeida1@vale.com

Paula Silva Duarte Pinto
Vale S.A.
Belo Horizonte, MG
paulasdpinto@vale.com

Rodrigo Souza Rossi
Vale S.A.
Belo Horizonte, MG
Rodrigo.rossi@vale.com

***Abstract*— Temporary grounding is a critical safety measure for electricians and field technicians during maintenance activities on electrical networks. As mandated by NR-10 (Regulatory Standard for Safety in Electrical Installations and Services), grounding is compulsory in de-energized circuits that are susceptible to accidental re-energization, serving as a primary protective mechanism against electric shock and arc flash hazards. This study investigates the risks associated with the absence or failure of temporary grounding systems, drawing upon real-world incidents and the lessons learned from them. Non-compliance with this safety protocol not only endangers worker safety but also exposes organizations to serious legal consequences and regulatory penalties. Best practices aligned with NR-10 are presented, including technical criteria for selecting grounding equipment, routine inspections, and comprehensive training programs to ensure proper implementation by qualified personnel. The research also underscores the importance of standardized procedures and safety checklists to ensure that the installation and removal of temporary grounding are conducted safely and efficiently. By emphasizing the necessity of compliance with NR-10, this study aims to foster an organizational culture centered on electrical safety, thereby mitigating risks and reducing the incidence of workplace accidents. The adoption of safe temporary grounding practices not only safeguards operational integrity but also ensures the protection of personnel and adherence to regulatory standards.**

Keywords*— *Temporary grounding, Electrical safety, Electrical accidents.

I. Introduction

Safety in electrical power systems (EPS) is one of the key points in current electrical engineering, especially when we talk about maintenance and operation in high-voltage networks. Even when de-energizing circuits to protect workers, there are still risks, such as accidental re-energization, electromagnetic induction, and human error. Therefore, temporary grounding is an essential collective measure, because, when applied correctly, it helps to reduce electrical hazards.

In this article, we will show the risks that can arise when temporary grounding is not performed or presents failures. We will also present the best practices and standards that guide the use of this resource, following guidelines such as NR-10 and ABNT NBR 16384:2020. Through a real case study, we will highlight the importance of good risk management, technical training, and an organizational culture that values safety in the electrical environment.

II. Importance of Temporary Grounding

Safety in maintenance interventions on electrical power systems (EPS) is a fundamental pillar of engineering, and procedures on de-energized circuits, although perceived as inherently safe, conceal complex and significant risks. A de-energized installation is susceptible to a series of hazards, including accidental re-energization due to human error or equipment failure, inadvertent contact with adjacent energized circuits, and the effects of lightning strikes, even if distant. In addition to these transient events, there is a continuous and often underestimated hazard: voltages induced by electromagnetic coupling of transmission lines that share the same right-of-way [1]. Faced with this range of threats, the temporary grounding set transcends its function as a simple accessory to establish itself as a collective engineering protection system, whose correct application is the main barrier between worker safety and a potentially fatal accident. The primary function of temporary grounding is to provide a robust defense against the highest potential energy event: accidental circuit re-energization. When properly installed, the assembly establishes a low-impedance path between the phase conductors and the grounded structure, creating an equipotential zone at the workplace. The fundamental purpose of equipotential bonding is not to zero the structure potential, which is impossible during a fault, but rather to ensure that the potential difference across the worker's body is minimized to safe levels. This action

accomplishes two vital objectives. First, it limits the touch voltage to values that do not cause ventricular fibrillation, according to the criteria established by studies such as those of Dalziel [2].

Even if the structure and cables rise to a dangerous potential with respect to earth, the worker, being in contact with interconnected components, does not experience this dangerous voltage. The low impedance path ensures that the short-circuit current reaches a magnitude high enough to sensitize the system's protection relays (overcurrent, differential, etc.), ensuring the circuit is interrupted in the shortest possible time. The ability of the earthing assembly to withstand the immense electromechanical and thermal stresses, without disintegrating, is critical, since its failure would result in the formation of an uncontrolled electric arc, with projection of plasma and molten metal directly onto the personnel. At the same time, temporary grounding plays a continuous role in mitigating induced voltages, a persistent phenomenon in multi-line corridors. Induction occurs through two mechanisms: capacitive coupling, analogous to a network of capacitors between the energized and de-energized circuits, which depends on the electric field and is present even without a load on the inductor line; and magnetic coupling, similar to the action of a transformer, which is a function of the magnetic field generated by the load current on the adjacent line. Although of smaller magnitude than a fault current, the induced current is a constant risk. Computer simulations demonstrate that, even in parallel stretches of a few kilometers, the current that can flow through a worker on an ungrounded circuit can easily exceed the "do not let go" threshold, estimated at approximately 16 mA [1]. Above this value, tetanic muscle contraction prevents the individual from voluntarily letting go of the energized point, prolonging the exposure and drastically increasing the severity of the shock. Temporary grounding, by short-circuiting the phases and connecting them to earth, drains this induced current safely, keeping the potential at the workplace at negligible values.

The criticality of this equipment is so high that its use is mandatory under Brazilian law. Regulatory Standard 10 (NR-10) — Safety in Electrical Installations and Services [3] — establishes in its item 10.5.1 that an electrical installation can only be considered effectively de-energized and released for work after a series of steps have been completed, culminating in the "installation of temporary grounding with equipotentialization of the phase conductors". The standard itself defines the procedure as an "effective, reliable, adequate and intentional electrical connection to ground". Each of these terms carries a technical weight: "effective" means that it must provide a path of low real impedance; "reliable" implies that its components cannot fail under stress; "adequate" refers to the correct dimensioning for the system's short-circuit current; and "intentional" reinforces that this is a deliberate engineering action, and not an optional accessory. Therefore, the legislation codifies the physical principles of protection, making the correct application of temporary grounding a non-negotiable legal requirement, the absence of which characterizes a condition of serious and imminent risk.

III. RISKS ASSOCIATED WITH THE ABSENCE OR FAILURE OF TEMPORARY GROUNDING

The lack of or incorrect installation of temporary grounding in substations and transmission lines can pose a serious risk to both the safety of workers and the integrity of electrical system equipment. The use of temporary grounding is a collective protection measure, as provided for in standards such as NR-10 and IEEE Std 80-2013. The objective is to ensure that, during interventions, any residual or induced energy is properly dissipated into the ground. [4].

A. Potential Impacts

Failure to use temporary grounding or applying it incorrectly can lead to impacts such as:

- *Serious or fatal accidents*: If there is no low-impedance path to ground, the fault current can pass through the human body. Research shows that being exposed to step and touch voltages that exceed safe limits can result in ventricular fibrillation and even death [5] and [6]

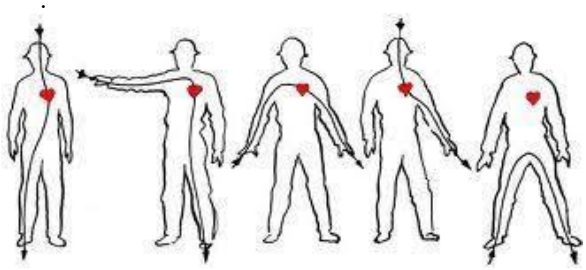

Figure 1 - path taken by the fault current in the human body

- *Electric arc:* The lack of grounding allows the formation of electric arcs during accidental energization or by electromagnetic induction, causing damage such as: severe burns, hearing loss and irreversible consequences for workers [6].

- *Non-compliance with legislation:* Regulatory Standard No. 10 (NR-10) suggests that measures be adopted to control electrical risk, such as the use of temporary grounding during the de-energization process, as indicated in section 10.5.1. Ignoring this recommendation may lead to fines, violation reports and even suspension of activities by inspection agencies.

IV. GOOD PRACTICES IN ACCORDANCE WITH NR-10

Regulatory Standard No. 10 (NR-10) establishes basic rules and conditions to protect the safety and health of those who work with electrical installations and services. When we talk about temporary grounding, NR-10 determines that preventive measures must be taken to eliminate the risk of electric shock during any intervention, whether in systems that are on or off. Thus, the objective is to ensure that everyone can work with greater peace of mind and safety.

A. Criteria for the Selection of Grounding Equipment

- Short-circuit withstand capacity: Cables and connections must be able to withstand the maximum current that can flow in the event of a fault, in accordance with the calculations in IEC 61230.
- Voltage compatibility: Equipment must be suitable for the type of voltage in the installation, whether low, medium or high.
- Low electrical resistance: Conductors must have the lowest possible resistance so that the fault current is dissipated quickly.
- Material and construction: Clamps must be made of a corrosion-resistant metal alloy that conducts electricity well. Hot rods must be insulated and undergo regular testing.

Source: CELESC (2024)

Figure 2 - Medium Voltage Temporary Grounding Set (Clamps, Conductors and Rod)

Furthermore, ABNT NBR 16384:2020 recommends that these devices be certified and meet the mechanical and electrical performance standards defined by technical standards [7].

B. Equipment Inspections and Care

Another recommendation of the standard is the regular inspection of collective protection equipment (CPE), including those used for temporary grounding. To ensure safety, it is important to follow some good practices:

- Visual inspection: Always observe cables, clamps and connections to identify signs of wear, corrosion, cracks or any deformation.
- Electrical tests: Perform measurements of the electrical resistance of cables and connections, following the frequency defined in the company's internal procedures.
- Registration and traceability: Each piece of equipment must have a unique identification and an updated history of inspections and maintenance performed.
- Correct storage: Store devices in dry, clean places, protected from impacts and weather conditions.

These practices follow the principles and recommendations of the ABNT Conformity Assessment, whose main objective is to ensure that products and processes comply with technical standards and guarantee correct functioning [7].

C. Continuous Training of Workers

In order to ensure and comply with the above criteria, it is extremely important to carry out training as recommended by NR-10. Professionals need to be prepared to:

- Identify electrical hazards and follow safety procedures correctly.
- Install and remove grounding devices safely, using appropriate sticks and PPE.
- In emergencies, act according to knowledge acquired in training in cases of grounding failure or accidental energization.

V. CASE STUDY

On June 17, 2021, at approximately 11:10 a.m., a worker from a contracted company was performing maintenance on a 220kV transmission line, on the stretch between Matambo and a mining company located in Mozambique. The line was supposedly de-energized and grounded, and the work was taking place on Tower 59, which can be seen in Figure 3. While removing a jumper on the upper phase of circuit B10, the worker suffered an electric shock and died, even after being rescued and taken to an external clinic.

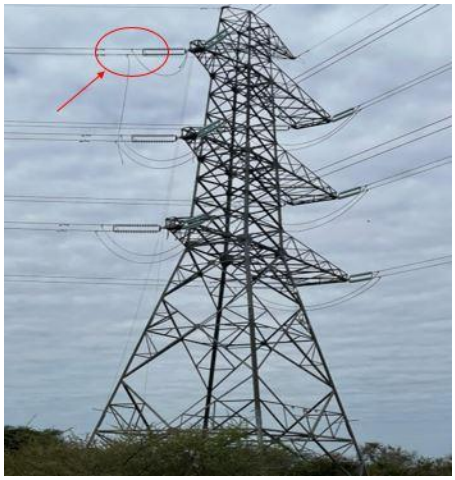

Figure 3 – Tower 59, of the 220 kV transmission line in Mozambique. Maintenance location indicated in red.

The intervention was part of an emergency action associated with the 66kV line revitalization project, which aimed to mitigate the risk of collapse of nearby towers. Although the line was considered de-energized, subsequent analysis showed that there was electromagnetic induction from the adjacent circuit and the absence of effective grounding at the point of intervention.

A. Cause Analysis

The investigation into the incident identified several systemic and human failures that contributed to the accident:

Immediate Causes:

- Lack of temporary grounding at the intervention point (violating item 10.5.1 of NR-10, which requires collective protection measures, such as grounding conductors before beginning the intervention) [OBJ].
- Inadequate isolation of hazardous energy, as the team believed that the line was safe, disregarding the possibility of electrical induction from neighboring circuits.
- Communication and risk perception failures, where workers did not correctly understand the instructions and underestimated the dangers of the activity, which also contradicts item 10.8.8 of NR-10 on worker training.
- Absence of a safety team on site and lack of adequate structure for emergency response in remote activities.

Systemic Causes:

- Ineffective change management: changes in scope and execution of tasks outside the original project were not formally assessed, which goes against the principles of operational control and change management (RS02 and RS08 of the company's management system) [OBJ].
- Confusing assignment of responsibilities: there was no clear separation of responsibilities between the operations area, projects and contractors, creating gaps in the direct supervision of activities in the field.
- Insufficient technical qualification of the performers: the field team did not have adequate proficiency in the local language or certified technical knowledge to carry out interventions on high-voltage networks.

B. Corrective Actions Adopted

Following the incident, the mining company implemented a comprehensive action plan to mitigate future risks in similar activities:

1. Formal prohibition of interventions in transmission lines with energized circuits or with risk of electrical induction, decided by a technical committee (as revised by RAC10).
2. Implementation of mandatory risk analysis checklists (HAZOP) for all phases of the transmission line (design, commissioning, maintenance and decommissioning).
3. Inclusion of technical requirements for contracting companies, requiring proven qualifications of professionals involved in electrical services.
4. Creation of periodic refresher programs on de-energization and temporary grounding procedures.
5. Mandatory presence of a safety professional specialized in electrical risks during activities on transmission lines.
6. Safety documents in multiple languages (Portuguese and English) for teams working in Mozambique and other international locations.
7. Periodic field inspections with supervision by leaders and safety professionals, recorded in a logbook.
8. Review of RAC10 training content, including case studies of real accidents, in accordance with good organizational learning practices and lessons learned.

C. Legal and Regulatory Compliance

The occurrence and causal factors are directly linked to non-compliance with NR-10, especially in the following points:

- Item 10.5.1: Mandatory collective protection measures, including blocking, signaling and grounding of electrical conductors.
- Item 10.8.8: Worker training must ensure the ability to safely perform services.
- Item 10.2.8: Requirement for risk analysis, with preventive measures before intervention.
- Item 10.2.9: Prohibition of execution of electrical services by unqualified or unauthorized workers.

In addition, the lack of application of the Change Management (GoM) procedure, a mandatory item in integrated management systems, compromised the assessment and mitigation of the risks involved.

VI. ANALYSIS

The fatality that occurred during intervention on a 220kV transmission line clearly demonstrates the risks inherent in electrical activities, even when there is the assumption of de-energization. The incident analyzed was not the result of a one-off error, but rather the result of a combination of structural, technical and organizational weaknesses. The lack of temporary grounding at the intervention point, combined with deficient risk analysis, the lack of qualifications of the executing team, ineffective communication between areas and the lack of change management, created a critical scenario that culminated in a fatal accident.

From the detailed analysis, it is clear that simply de-energizing the line is not enough to guarantee the safety of the intervention. Induction from neighboring circuits, especially in high-voltage systems, must be treated as a dangerous energy source as provided for in NR-10, which requires that, before the intervention begins, collective protection measures be adopted, such as blocking, signaling and grounding of electrical conductors (item 10.5.1).

Furthermore, the episode reinforces the importance of implementing robust change management processes, as established by NR-10, and integrated management systems. Changes in scope or operational decisions outside the project require formal analysis, technical approval and multidisciplinary planning. The absence of such control, combined with the lack of clarity in responsibilities between areas (projects, operations and safety), demonstrated how organizational disarticulation can be as dangerous as the absence of physical barriers.

The action plan adopted by the company after the event presents significant advances, such as the prohibition of interventions in lines with the possibility of induction, the requirement of technical qualifications for contractors,

increased training in RAC10, and the mandatory inclusion of specialized safety professionals in the field. However, more than implementing controls, it is necessary to develop an organizational culture that recognizes the invisible risks of electricity, values strict compliance with standards, and promotes active listening among teams.

This case study provides valuable lessons for the entire industry. Electrical safety is not based solely on documented procedures, but on a combination of technical rigor, shared responsibility and active leadership. This reinforces the urgency of maintaining temporary grounding as a non-negotiable practice in interventions on electrical lines and equipment, as well as the continuous strengthening of organizational training and surveillance so that tragedies like this do not happen again.

VII. Conclusion

The analysis conducted in this article shows that temporary grounding goes far beyond a technical procedure: it is a fundamental barrier to protect lives in environments with high electrical risk. Serious accidents, such as the case studied, make it clear that failures in this measure — whether due to lack of knowledge, carelessness or lack of management — can have irreversible consequences. Complying with NR-10, following good practices in technical standards and always investing in training professionals are essential steps to ensure safety in interventions on electrical networks. More than that, it is important to adopt a broad vision, which encompasses everything from planning to field supervision, creating an organizational culture where safety is an absolute priority. Therefore, temporary grounding should not be seen only as an obligation of the standard, but as an ethical and technical commitment to preserving life.

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Trajectory and Influence: A Bibliometric Study on the Scientific Production of the Electrical Safety Workshop

Jhoni Soares Raymundo
Interdisciplinary Center for Studies in Energy Planning – NIEPE
Federal University of Mato Grosso
Cuiabá, Brazil
jhoni.raymundo@sou.ufmt.br
https://orcid.org/0009-0009-7767-7064

Márcio Bottaro
Institute of Energy and Environment of the University of São Paulo – IEE USP
University of São Paulo
São Paulo, Brazil
marcio@iee.usp.br
https://orcid.org/0000-0002-0898-4601

H. Landis Floyd II
Electrical Safety Group
University of Alabama at Birmingham
Elkton, USA
lfloyd@uab.edu
https://orcid.org/0000-0001-7419-4870

Danilo Ferreira de Souza
Electrical Engineering Department - DENE
Federal University of Mato Grosso
Cuiabá, Brazil
danilo.souza@ufmt.br
https://orcid.org/0000-0002-1155-1778

Abstract **— The Electrical Safety Workshop (ESW) is the leading international forum dedicated to promoting the safe use of electrical energy. Since its inception in 1991, with its first edition held in 1992, the event's mission has been to reduce the risk of injuries caused by electrical accidents in the workplace, as well as to foster innovation and drive technological advancements aimed at accident prevention. Despite the significant relevance of the ESW, a systematic bibliometric analysis that highlights the evolution of research presented at the conference is not yet available. Given this gap, this study aims to analyze the trajectory of scientific production presented at the ESW and indexed in databases, mapping its temporal evolution, the most relevant themes, main authors, and involved countries. The analysis was conducted based on publications indexed in the IEEE Xplore, Web of Science, and Scopus databases, totaling 444 documents found from 2003 to 2024. For visualization and network mapping, the VOSviewer software was used, allowing the identification of patterns of scientific collaboration, academic influence, and thematic trends in the field of electrical safety.**

Keywords — Electrical Safety, Bibliometric Analysis, ESW Conference, Network Mapping, Research Trends

I. Introduction

The evolution of human civilization is intrinsically linked to the continuous increase in energy demand [1]. From the earliest uses of simple sources like muscle power, wind, and wood, energy consumption has accompanied and driven social, technological, and economic development [2]. From the Industrial Revolution onwards, this dependence intensified, accelerating significantly after 1950. It is estimated that in the post-1950 period, humanity consumed more energy than in all previous millennia combined [3]. Although this increasing energy dependence has enabled numerous advancements, it has also amplified the risks associated with electricity.

Approximately 2.5 million people annually suffer electricity-related injuries, with the most common being those caused by arc flashes, fires resulting from equipment failures or inadequate conditions in industrial and residential installations, and explosions caused by the incorrect use of devices in environments with flammable gases [4]. These events contribute significantly to cases of permanent disabilities and fatalities. In the United States, between 2011 and 2023, there were 1,940 fatalities resulting from electrical accidents, representing 5.6% of all workplace deaths. Of this total, 74% involved individuals not directly working in the electrical sector [5].

In Brazil, the scenario is even more concerning, and in the historical series of electrical accidents between 2013 and 2024, 18,779 accidents were recorded, resulting in 8,741

fatalities classified as electrical shocks, fires of electrical origin, and atmospheric discharges [6].

The ESW was created by the IAS Petroleum and Chemical Industry Committee (PCIC) in 1991, with its first edition held in 1992 [7]. From 1995 onwards, the event began to occur annually, totaling 32 editions by 2025. Since its inception, the ESW's mission has been to foster a culture of electrical safety, promote technical discussions, and drive the development of technologies aimed at preventing electrical accidents and injuries [8].

The analysis of scientific production presented at the ESW allows for a systematic understanding of how discussions about the safe use of electricity have evolved over time and in different contexts. In addition to identifying the historical trajectory, such an analysis provides support for reflecting on current debates and possible future directions in the field. To achieve this understanding, this study is based on the following research questions:

RQ1. How have the temporal trends of publications at the ESW evolved?

RQ2. What is the impact of publications presented at the ESW and what are the most influential works?

RQ3. Who are the main authors and professionals leading contributions at the ESW, and what factors sustain this leadership?

RQ4. How is the scientific production related to the ESW geographically distributed, and what local factors influence this production?

Despite the conference's importance in the field of electrical safety, there are still no studies that explore the evolution of the themes presented over these 33 years of activity, nor that qualify and quantify this scientific production. Given this gap, Scientometrics emerges as a valuable area of knowledge, allowing us to understand and map scientific advancements, research quality, and cooperation networks [9]. Scientometrics and bibliometrics are approaches that have gained prominence by enabling a structured analysis of scientific production [10]. Bibliometrics, in turn, is more focused on the statistical measurement of publications, citations, and publisher patterns, serving as a basis for scientometrics. Both operate using quantitative indicators, which can be obtained from databases [11].

II. Methodology

To gather the largest number of studies presented at the ESW conference since its first edition, three consolidated scientific literature databases were used: Scopus, Web of Science, and IEEE Xplore. These databases, in addition to offering broad coverage, ensure rigorous curation of indexed content and are widely adopted in bibliographic reviews [12] [13] [14]. The IEEE Xplore database was established as the main reference source, as it is maintained by IEEE itself, the official organizer of the Workshop, in order to ensure that the largest possible number of studies presented at the event would be identified.

Subsequently, the study was structured using the ProKnow-C (Process of Knowledge Development – Constructivist) method [15]. This study applied the first two stages of the method: (i) the structured selection of a representative bibliographic portfolio and (ii) the bibliometric analysis of the selected articles. The third stage, referring to the systemic analysis, which requires an investigation of the theoretical and methodological content of the publications, was not conducted, as the focus of this study is on mapping and characterizing the scientific production presented at the Electrical Safety Workshop conference.

Although there is a diversity of software for bibliometric analysis, the use of VOSviewer is justified by its consolidated ability to visually represent large volumes of bibliographic data, thus facilitating the identification of patterns, relationships, and structures in scientific production [16]. Developed specifically for bibliometric analysis, VOSviewer allows for the creation of co-authorship, keyword co-occurrence, co-citation, and bibliographic coupling maps with graphical precision [17]. Furthermore, the tool is widely adopted in research involving science mapping and knowledge network analysis, being considered one of the most robust and reliable solutions currently available for this type of investigation [18].

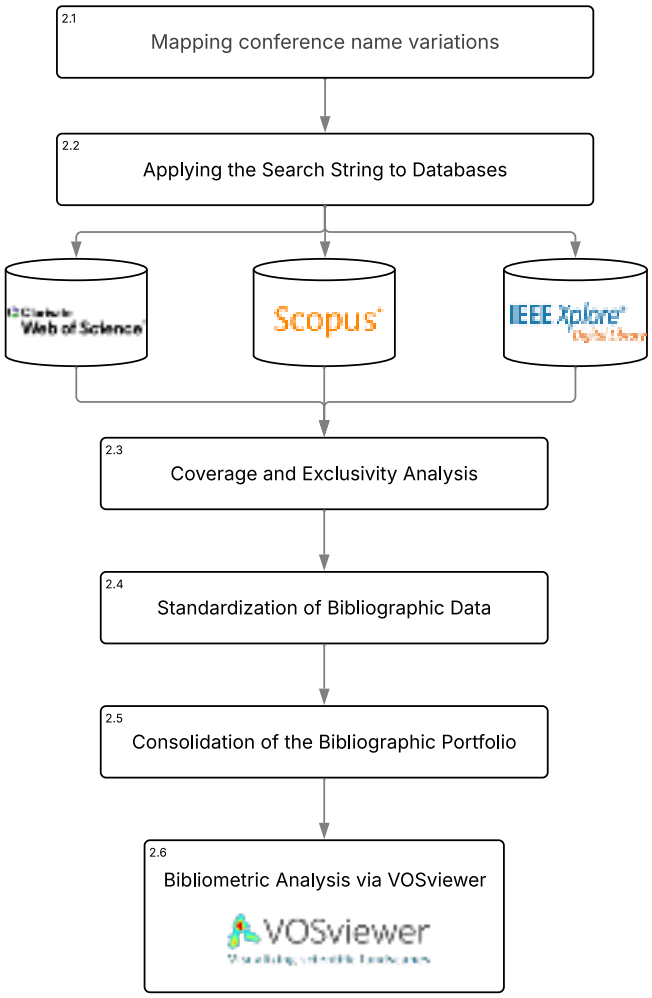

Fig. 1. Methodological flow.

2.1 Mapping Variations in Conference References

The first step consisted of identifying the different ways the conference IAS Electrical Safety Workshop may have been referenced over the years in the databases. Possible variations in the event's name were considered: "IAS Electrical Safety Workshop, Electrical Safety Workshop, IAS

ESW, IEEE ESW, IEEE Electrical Safety Workshop, or IEEE IAS ESW." Based on this survey, the search string CONF ("IAS Electrical Safety Workshop" OR "Electrical Safety Workshop" OR "IAS ESW" OR "IEEE ESW" OR "IEEE Electrical Safety Workshop" OR "IEEE IAS ESW")" was constructed, which combined the terms with Boolean operators to maximize the retrieval of publications relevant to the study.

2.2 Application of Search Strings and Initial Export of Identifiers

The constructed search strings were applied to the IEEE Xplore, Scopus, and Web of Science databases. The number of articles retrieved was 439, 438, and 293 respectively. However, no records of articles prior to 2003, nor those presented in 2006, 2007, and 2008, were found. Initially, the number of articles found in each database was compared. Subsequently, the digital object identifiers (DOIs) of the retrieved articles were exported. This export aimed to perform a cross-check with the IEEE Xplore database, adopted as the main reference, to verify the presence or absence of records in the other databases.

2.3 Analysis of Coverage and Exclusivity Across Databases

Based on the extracted DOIs, a comparative analysis was performed between the results obtained from the three databases. It was observed that 2 of the articles found in the Web of Science database were also available in the IEEE Xplore database, but not in the Scopus database. Comparing with the IEEE Xplore database, only four articles were identified as exclusive to this database, meaning they were not present in the other consulted sources.

2.4 Standardization of Exclusive Bibliographic Data

The bibliographic data (Figure 2) of the 438 articles returned from the Scopus database were exported in .CSV format.

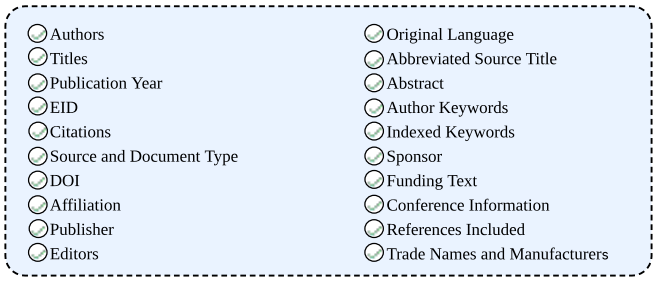

Fig. 2. Selected bibliographic data.

The six articles that could not be found in the Scopus database were manually standardized; two were obtained from the Web of Science database and four from IEEE Xplore. To ensure the uniformity of these records for analysis, a normalization process was carried out. In this process, the bibliographic data was adjusted to match the same structural format provided by Scopus. This involved reorganizing fields such as title, authors, year, publication source, keywords, and abstract, ensuring consistency across all analyzed records.

2.5 Consolidation of the Bibliographic Portfolio

After standardization, the data from articles exclusive to the IEEE Xplore database were integrated into the overall set of collected publications. The complete bibliographic portfolio was then exported in .CSV format, ensuring the preservation of the necessary fields for the next analysis stage.

2.6 Bibliometric Analysis via VOSviewer

To map the collaboration networks, VOSviewer software was chosen to perform the bibliometric analysis and generate the maps that support the answers to the proposed research questions. Visualizations were created for co-occurrence of keywords indexed by authors, tables through co-citation of sources and authors, co-authorship among institutions and countries, and cited references.

These data allowed for a structured and visually accessible representation of the scientific production's behavior [19] associated with the conference.

III. Results and Discussions

The Results and Discussions section is structured to address the four research questions, utilizing both tables and mapping of the ESW scientific output. Initially, a sample illustrating how the performance of publications presented at the conference has changed over time will be presented. Following this, we explore the mapping of keywords indexed by authors to identify themes discussed throughout the years at the conference, the most cited articles, the most prolific and impactful authors, and the location of institutions responsible for the publications. Figure 3 shows how the number of papers presented at the ESW has varied each year, highlighting periods of growth, stability, and decline in scientific production over the years.

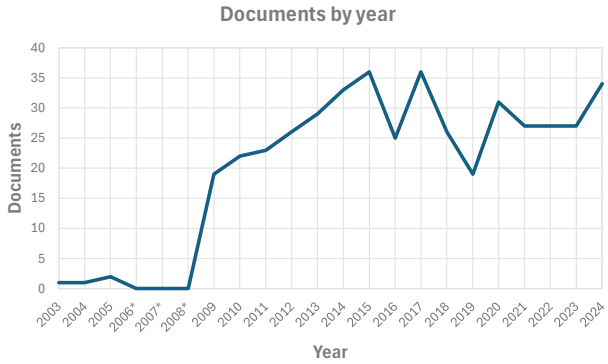

Fig. 3. Annual evolution of publications in the Electrical Safety Workshop.

The graph shows significant growth starting in 2008, which is explained by the absence of records for articles presented at the conference from 2006 to 2008, as well as the reduced number of documents found in 2003, 2004, and 2005, even though editions were known to have taken place during that period. From 2009, there's a consistent increase in the number of publications until 2015, reaching 35 documents. There were two sharp drops in publications in 2016 and 2019. The peak occurs in 2017, with 36 publications. In recent years, 2021, 2022, and 2023 showed some stability, with 27 documents each year, increasing again in 2024 with 34 publications, nearly matching the previous peak.

To understand the temporal and thematic trends that have shaped the scientific output of the ESW, and to go beyond just the annual publication volume, the first research question is addressed below, using a map derived from the co-occurrence analysis of keywords indexed by authors.

RQ1. How have the temporal trends of publications at the ESW evolved?

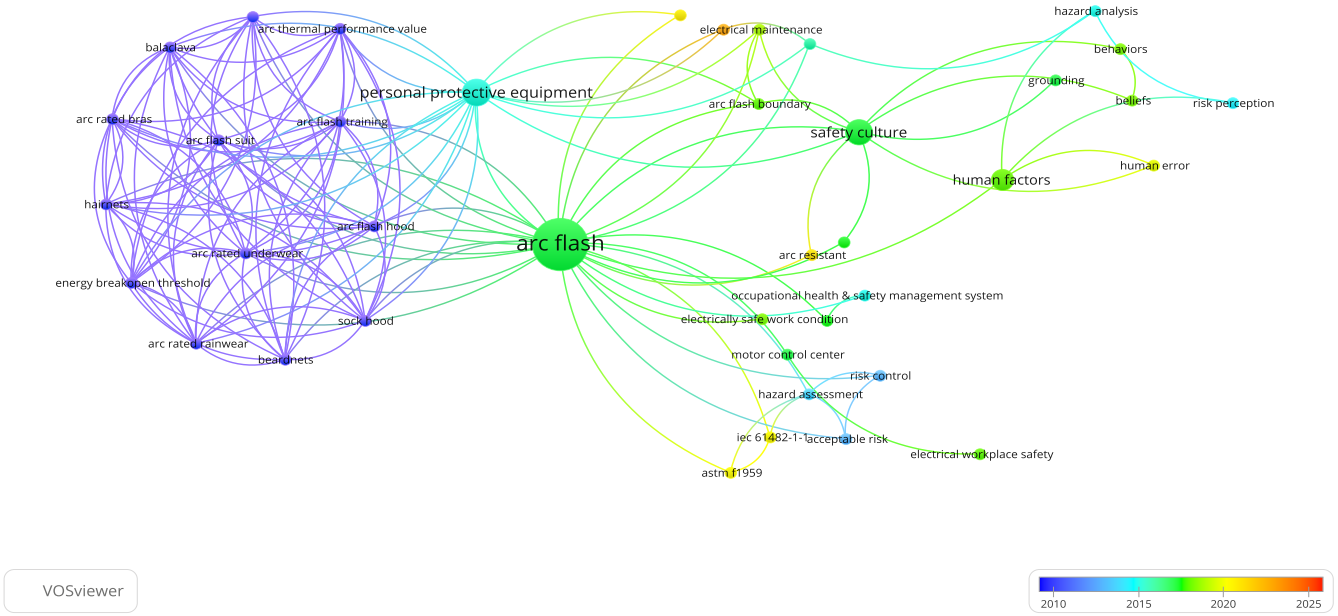

Fig. 4. Co-occurrence map of keywords indexed by authors in Electrical Safety Workshop publications.

Figure 4 presents the co-occurrence network of keywords indexed by the authors of articles presented at the ESW, generated in VOSviewer software based on the consolidated bibliographic portfolio of the research.

This type of representation can show the dynamics of scientific publications, allowing us to answer questions related to the thematic evolution of each specific research field [20].

By identifying the most frequent terms and their interrelationships (nodes), this approach enables the contextualization of a particular research axis's trajectory [21], highlighting emerging trends, consolidated themes, and potential gaps for investigation [22]. To construct the map, a minimum of 10 occurrences for each term was considered, in order to preserve only the most relevant concepts in the dataset. The generated network is organized into distinct thematic clusters, and when associated with a temporal scale, this type of analysis enhances its effectiveness by allowing us to track the development of research topics over the years and identify periods of intensification, stagnation, or decline of certain studied themes [23]. The temporal analysis of scientific production trends is supported by the color scale (from blue to red), which indicates the average period of occurrence for each term [24].

As represented in Figure 4, the importance of the term "arc flash" is evident, standing out with the largest individual node and occupying a central position in the network. This demonstrates that, over the years evaluated, the topic remains relevant and highly discussed. The various connections this node maintains with other terms only confirm its leading role in the research field investigated at the ESW. Associated keywords, such as "personal protective equipment," "electrical hazard classification," and "arc flash boundary," appear interconnected and indicate a deepening of discussions on the arc flash boundary (or safe approach limits regarding the arc flash radius), personal protective equipment, and procedures aimed at risk mitigation.

The consolidated thematic clusters, such as the one represented by the color orange, group technical terms focused on electrical work protection, including "induced current," "temporary protective grounding," "line workers," and "arcing faults." These concepts, mostly concentrated in a period prior to 2015, indicate that the early editions of the ESW had a more technical and operational focus. The purple cluster, with words like "arc flash suit," "incident energy," and "gloves," represents a thematic concentration around clothing and exposure limits, focusing on the quantitative characterization of risk and safe operating limits.

In addition to the consolidated themes, the map reveals a thematic and methodological transition in recent years. Terms like "risk assessment," "acceptable risk," "job safety analysis," and "occupational health & safety management system" appear in light blue, representing a more recent focus (from 2020 onward). This evolution points to a broadening of the event's scope, with greater attention to systemic, integrated approaches aligned with safety management standards and policies. The presence of the terms "IEC 61482-1-1" and "ASTM F1959" reinforces an orientation towards technical standards for the characterization and performance of protective materials in more recent publications.

It's also important to highlight the emergence of expressions related to human and behavioral aspects, such as "human error," "risk perception," "behaviors," and "safety culture." These terms appear interconnected in a greenish cluster that gains prominence from 2016 onwards. This

movement signals a growing recognition that the effectiveness of electrical safety strategies extends beyond purely technical aspects, also incorporating human factors. This aligns with standards that emphasize the relevance of risk perception of these factors in accident prevention, such as NFPA 70E. This indicates a more comprehensive understanding of safety applied in the context of electricity.

RQ2. What is the impact of publications presented at the ESW and what are the most influential works?

To understand the importance of studies presented at the ESW and identify the most influential ones, the ten most cited articles were selected (Table 1). Citation counts are widely recognized as an indicator of a study's influence and visibility within the scientific community, especially in technical areas such as electrical safety [25][26].

However, beyond just the volume of citations, studying the content of these articles also allows us to identify which topics have been most valued and demanded by the community, revealing research priorities in the field [27].

Titles	Citations	Authors	References
Occupational electrical injuries in the US, 2003-2009.	23	Cawley J.C.; Brenner B.C.	[28]
Proper application and maintenance of molded case breakers to assure safe and reliable operation.	23	Higginson M.; Durocher D.B.	[29]
Design of arc Flash protection system using solid state switch, photo detection, with parallel impedance.	21	Panetta S.	[30]
Enhancing electric safety by improving system resiliency in face of extreme emergencies.	18	Dehghanian P.; Aslan S.	[31]
Combination AFCIs: What they will and will not do.	18	Engel J.C.	[32]
Update of field analysis of arc flash atorntes, PPE protective performance and related worker injuries.	18	Doan D.R.; Hoagland IV E.; Neal T.	[33]
A complete electrical hazard classification system and its application.	17	Gordon L.B.; Cartelli L.	[34]
OSHA arc-flash injury data analysis.	15	Wellman C.M.	[35]
DC arc flash calculations – Arc-in-open-air & arc-in-a-box – Using a simplified approach (Multiplication ator method).	14	Fontaine M.D.; Walsh P.	[36]
Hazards in the installation and maintenance of solar panels.	12	White J.R.; Doherty M.	[37]

Table. 1. Most cited studies.

Seeking to understand these prominent works presented at the conference, one can find a notable influence on the evolution of specific safety practices, especially in areas not fully covered by traditional standards. In article [34], one of the most impactful studies, suggests a more detailed system for classifying electrical hazards in research and development environments. This proposal aims to address issues not covered by NFPA 70E and OSHA standards by considering risks from specific equipment, such as capacitors, RF systems, and high-power DC sources. The relevance of this system is proven by its use in several U.S. Department of Energy laboratories, being based on over a hundred years of studies on electricity-related injuries and its ability to serve as a source for future national standards. The article also stands out for its technical depth and practical importance, directly affecting how hazards are evaluated in highly complex environments.

In [32] another relevant article, which offers a critical analysis of the National Electrical Code's (NEC) requirement to use combination-type AFCIs (Arc-Fault Circuit Interrupters). The study stands out by questioning current technical standards and encouraging an analysis of the true effectiveness of these protective devices, pointing out possible weaknesses in identifying series arcs and a lack of protection against ground faults in certain versions. The study not only adds value in the technical aspect but also encourages the involvement of the electrical engineering community in regulatory processes, supporting a critical and participatory attitude in the development of more efficient standards for residential safety.

In the analysis of arc flash hazards in direct current (DC) systems, the study [36] stands out for proposing a simplified technique. This approach is based on a multiplying coefficient that establishes a relationship between open-air and confined arc flash scenarios—in a box. Although considered an initial solution, the proposal fills a significant gap in current standards, such as IEEE 1584, which only addresses three-phase alternating current (AC) systems. The suggestion gained significant visibility by offering a practical way to estimate incident energy in DC systems, which are increasingly used in industrial contexts and alternative energy sources.

Also focused on arc flash mitigation, and with the aim of alleviating its effects, the study [30], presents a protection solution featuring high-speed protection operation, which uses semiconductors and light sensors. By reducing the protection operation time to less than 9 milliseconds, the system presented represents a significant advance in mitigating worker injuries and preventing equipment damage in arc flash accidents. The technological progress discussed here offers real solutions to the problems of conventional circuit breakers, and can be used in locations with high energy concentration and elevated safety requirements.

Moving now to a more systemic approach. In [31] adopts a broader perspective, recognizing that the recovery capability of electrical grids is vital for safety during crises. Highlighting the importance of contextual awareness and constant supervision as pillars of a safety culture, the text promotes a shift in mindset, integrating system strength with protection against unforeseen events in high-risk situations.

In the article [37] the increasing importance of decentralized electricity generation is the central theme, exploring how traditional hazard analysis methods apply to solar energy. The prioritization of power shutdown as the primary control method and compliance with NFPA 70E demonstrate an initiative to adapt proven safety practices to innovations in the energy sector. It also emphasizes that safety is fundamental not only for professionals but also for emergency response services, such as firefighters.

Craig Wellman's in study [35], stands out for examining real data from 532 accidents recorded between 1984 and 2007.

The author seeks to relate the voltage level, the electrical equipment involved, and the number of injuries resulting from the accidents. The study offers truly valuable insights for the creation of preventive standards. The work aids in optimizing safety approaches by identifying situations most prone to arc flashes, especially at low voltage levels (480–700 V), drawing an essential statistical portrait to focus investments in the sector and protective actions.

RQ3. Who are the main authors and professionals leading contributions at the ESW, and what factors sustain this leadership?

Identifying the authors who actively participate in the ESW allows us to understand which professionals contribute most to the development of the conference and the discussion on electrical safety. Evaluating the number of papers published by each author (Table 2) and their respective citation counts (Table 3) helps to identify not only the most active authors in scientific production but also those who generate the greatest influence and impact within the Community.

While the number of publications reveals an author's activity level in the field, the total number of citations indicates the degree to which their work is valued and used by other professionals. The average impact per publication, on the other hand, allows us to identify those who, even with a smaller quantitative output, manage to generate highly relevant and frequently referenced contributions [38].

Table 2 presents the ten most prolific authors on electrical safety and related topics. Although the themes addressed are, to some extent, technical, all are intimately related to a daily reality: the safety of workers who deal with electricity, whether in companies, civil construction, or the energy sector. These researchers investigate how to prevent accidents, improve protective equipment, and make electrical systems safer.

Ranking	Author	Documents	Main Research Areas
1º	Hoagland, Hugh	25	Electrical Safety, Arc Flash, Personal Protective Equipment
2º	Landis Floyd, H.	18	Occupational Safety, Risk Assessment, Electrical Engineering, Occupational Health
3º	Doherty, Mike	12	Human Factors, Cognitive Performance, Safety in High-Risk Industries, Human Error
4º	Rachford, Joe	12	Occupational Safety, Electrical Circuits, Protective Devices, Medical Equipment.
5º	Crow, d. Ray	11	Electrical Safety, Safety Audits, Safety Culture, Federal Regulations
6º	Eblen, Marcia	10	Accident Analysis, Transmission Systems, Electrical Safety, Labor Statistics
7º	Lee, Wei-jen	10	Distribution Systems, Power Quality, System Reliability, Electrical Faults
8º	Roberts, Daniel	10	Risk Management, Occupational Safety, Protective Equipment, Incident Energy
9º	Brenner, Brett	9	Safety Statistics, Electrical Injuries, Human Behavior, Occupational Factors
10º	Doan, Daniel	8	Power Systems, Renewable Sources, Electrical Safety, Energy Transition

Table. 2. Most published authors.

The most published author, Hugh Hoagland, focuses on protection against arc flash effects. Some of his studies address the measurement of thermal energy and pressure generated by the arc, the behavior of the arc in different configurations, and the development of appropriate PPE. The second most productive author, Landis Floyd, dedicates his research to identifying workplace risks and ensuring safety standards are met, as well as proposing improvements in occupational health policies.

Some authors, like Mike Doherty, direct their investigations toward human factors in accidents. Their focus is on understanding how aspects such as stress, fatigue, or distraction affect professional performance, and what can be done to prevent these issues, especially in high-risk operations. Their contributions help companies rethink not only equipment but also training, working conditions, and people management. Wei-jen Lee and Daniel Doan deal with topics more closely related to power system technology. They study ways to make the electrical grid more reliable, safer, and better prepared to handle energy generated from renewable sources, such as solar and wind power. This research area is relevant for the future of energy grids, as the trend is towards increasing reliance on smart and sustainable grids [39].

Others, like D. Ray Crow and Marcia Eblen, analyze accident data and safety audits to understand where the biggest problems lie, analyzing statistics, past cases, and proposing changes to company standards and practices, showing how electrical safety can be improved not only with new technologies but also with good management and oversight.

In terms of citations (Table 3), Hugh Hoagland also appears as the most cited author, reinforcing not only his high productivity but also the relevance of his studies on Arc Flash.

Following closely, Brett Brenner, though not among the most productive, clearly has significant academic influence, and his research is relevant, underscoring that understanding accidents goes beyond technical aspects to also encompass the behavior and social context of workers.

Ranking	Author	Citations	Main Research Areas
1º	Hoagland, Hugh	55	Electrical Safety, Arc Flash, Personal Protective Equipment
2º	Brenner, Brett	49	Safety Statistics, Electrical Injuries, Human Behavior, Occupational Factors
3º	Landis Floyd, H.	43	Occupational Safety, Risk Assessment, Electrical Engineering, Occupational Health
4º	Gordon, Lloyd	40	Arc Flash, Electrical Safety, Empirical Models, Electrodes, Arc Current
5º	Doan, Daniel	39	Power Systems, Renewable Sources, Electrical Safety, Energy Transition
6º	Neal, Thomas	35	Arc Flash, Protective Equipment, Thermal Radiation, Occupational Safety
7º	Durocher, David B.	34	Industrial Applications, IEEE Standards, Technical Reviews, Paper Industry, Electrical Engineering
8º	Eblen, Marcia	29	Accident Analysis, Transmission Systems, Electrical Safety, Labor Statistics
9º	Crow, d. Ray	27	Electrical Safety, Safety Audits, Safety Culture, Federal Regulations
10º	Domitrovic, Thomas	27	Electrical Safety, Human Behavior, Environmental Design, Protective Equipment

Table. 3. Most cited authors.

Landis Floyd, H. is also present as one of the most relevant authors, which highlights the importance of discussions on occupational risks, safe practices, and safety culture in the electrical environment. Lloyd Gordon, who wasn't previously among the most productive, now holds a prominent position with his contributions on physical and theoretical arc flash models, demonstrating that more technical and specialized research can also have a great impact. Daniel Doan reaffirms his relevance here with his studies on energy transition, renewable sources, and safety in modern systems, especially at a time when these topics are gaining momentum with climate change and the search for sustainability. The same can be said for Thomas Neal, whose work on thermal protection and radiation generated in electrical accidents is clearly relevant to the field of equipment and safety standards.

Among the authors who stand out in the citation ranking but not among the most productive is David Durocher, whose studies focus on technical standards, reviews, and industrial applications, demonstrating that research connecting theory and practice also has a strong impact in the field. Thomas Domitrovich joins Mike Doherty with studies that involve not only technical aspects but also human behavior. Finally, Marcia Eblen and D. Ray Crow reappear, proving that data-driven safety management is an essential pillar for effective accident prevention in the electrical sector.

RQ4 How is the scientific production related to the ESW geographically distributed, and what local factors influence this production?

The distribution of scientific production across the world reveals significant inequalities among countries. This disparity is caused by factors such as research investment, academic infrastructure, and scientific collaboration capacity [40]. Regions with more resources and consolidated institutions tend to have higher academic output and, consequently, greater scientific performance [41].

Furthermore, regional aspects like technical standards and legislation, industry demands, and local safety practices also guide the research topics, especially in applied areas such as electrical safety [42] [43].

Table 4 shows the geographical distribution of the scientific production discussed at the ESW, revealing a strong concentration of output in the United States, which leads by a large margin with 349 publications, compared to the second-place Canada, with 72 documents.

Countries	Publications	Citations
United States	349	701
Canada	72	163
Japan	7	24
Brazil	7	14
Finland	4	14
China	4	9
Italy	4	8
Australia	2	7
India	2	6
Taiwan	2	6
South Africa	3	5
Hungary	2	4
United Kingdom	1	4
Netherlands	1	2
Costa Rica	1	1
Denmark	1	1
Germany	1	1
United Arab Emirates	1	1
Poland	2	0
Austria	1	0

Table. 4. Countries with most publications in ESW.

The significant difference between the top two positions highlights the traditional North American leadership in global academic research, supported by renowned universities, robust investment in science and technology, consolidated international collaboration networks, and, in this specific case, by the US's position as the host country of the Electrical Safety Workshop.

Following this, countries like Brazil and Japan appear with 7 publications each, showing a relevant, though modest, presence at the ESW within the global landscape of the field. Other countries, such as China, Finland, and Italy, show specific contributions (4 documents each), followed by a diversity of nations with one or two publications, including India, South Africa, Hungary, Poland, Costa Rica, United Arab Emirates, and Denmark, among others. Although these numbers are low, they indicate that the North American leadership in the discussion on the safe use of electricity is

reaching multiple nations, influencing international standardization in forums like the IEC (International Electrotechnical Commission) and strengthening collaborations between countries to leverage and improve these discussions.

This pattern of publication concentration in the ESW is consistent with results from other bibliometric reviews, which point to the predominance of scientific knowledge in developed countries [44]. Beyond scientific production, this scenario of concentration is repeated in the realm of citations.

Countries with a higher volume of publications also tend to register the greatest impact in terms of academic recognition. The United States, in particular, as the host country of the Electrical Safety Workshop, not only leads in the number of documents but also concentrates the majority of total citations, reinforcing its centrality in the production and dissemination of knowledge in the field of electrical safety. Canada, though on a smaller scale, also stands out in this aspect.

IV. Conclusion

This study's main goal was to characterize the evolution of scientific output presented at the ESW over its 30 years. We aimed to provide a comprehensive view of research trends, key themes, and the most influential authors and countries in this important forum for electrical safety discussions. Through this bibliometric analysis, we identified several relevant patterns. We observed a thematic evolution over time, with a gradual shift from a predominantly technical and operational focus to a broader approach that incorporates aspects of risk management, safety culture, and human factors. The co-occurrence analysis of keywords revealed a strong presence of "arc flash" as a theme, along with the growing importance of topics like "risk analysis" and "safety culture".

Regarding scientific output at the ESW, the United States stood out as the most productive country, reflecting its strong tradition in research and development, in addition to hosting the conference. Canada also has solid participation in the discussion due to its proximity to the host country and the prominent presence of the Canadian arc flash laboratory, Kinectrics, the setting for many scientific investigation works in the area of individual and collective protection. However, it's also worth noting that several other countries are contributing to the scientific output at the workshop, albeit on a smaller scale, but in a growing manner, indicating an internationalization of the conference. The citation analysis identified the most influential articles and authors, revealing the works that had the greatest impact in the field.

It's also important to acknowledge the limitations of this study. The analysis was based on data indexed in the Scopus, Web of Science, and IEEE Xplore databases. Furthermore, the conference includes presented studies that were not indexed in these databases, or those indexed under other name variations, thus excluding a significant amount of data that would be extremely relevant to the study.

For future research, we recommend expanding the analysis to include data from articles not indexed in the databases to enrich the study. Additionally, we suggest conducting complementary qualitative analyses to project future research directions and anticipate the emergence of new areas that may be crucial for technological advancements and sustainable policies to promote safety in the use of electrical energy.

V. Acknowledgment

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Transforming Electricity Safety Training and Culture using active methodologies

Alan Gustavo Magalhães
Colabor Consulting and Training
alan@grupocolabor.com.br

Emerson Franco
Colabor Consulting and *Training*
emerson@grupocolabor.com.br

SUMMARY

This article aims to present the benefits of adopting active methodologies in electrical safety training, revolutionizing the way electrical professionals assimilate and apply knowledge by making the process more dynamic, practical and engaging. It will show details of the active methodologies used, such as virtual reality simulations, gamification, prototyping, and problem-solving. This means that training ceases to be passive and becomes more engaging, making it easier to understand and retain relevant content.

This change in the training model directly contributes to reducing accidents, increasing risk perception, and strengthening a preventive safety culture in which each employee becomes a protagonist in ensuring their own safety and that of their colleagues

Keywords: training, active methodologies, engagement, virtual reality.

I. Introduction

The Brazilian electricity sector has been undergoing a continuous process of expansion, driven by growing demand for energy, the need to diversify the energy matrix, and technological advances. Among the regions most notable for this growth, the Northeast stands out, having expanded its electricity generation capacity more than any other in recent years—especially through renewable sources such as wind and solar energy.

Following the evolution of the electricity sector in recent years, Brazil has seen a worrying increase in the number of accidents involving electricity.According to the Brazilian Association for Raising Awareness of the Dangers of Electricity (Abracopel), 2,354 accidents involving electricity were recorded in 2024, with the Northeast region leading the way in fatal electrical accidents.

Professional training is one of the most effective tools for reducing accidents involving electricity and ensuring electrical safety

More assertive training requires the use of active learning methodologies, which place the participant at the center of the learning process, making the experience more dynamic, engaging, and efficient. Rather than just passively receiving information, participants interact, solve problems and apply knowledge in practice.This approach improves learning retention and prepares participants for the real challenges encountered in the field when working with electricity.Realistic simulations—such as those using virtual reality and prototyping—help develop preventive thinking and reinforce correct responses to electrical hazards. These simulations replicate everyday scenarios, allowing professionals to practice without unnecessary exposure to risk.

II. Active Learning

A. Andragogy

Andragogy is the science that studies the best ways to teach adults, differing from pedagogy, which focuses on children's education.

Proposed by Malcolm Knowles, andragogy starts from the principle that adults learn differently from children; they bring previous experiences, are motivated by clear objectives, value the immediate applicability of content and prefer to participate actively in the learning process. In this way, it proposes a more practical, collaborative and contextualized approach, promoting the role of the learner and valuing the prior knowledge of each individual (KNOWLES, 1980).

Figure 1 shows the differences between andragogy and pedagogy.

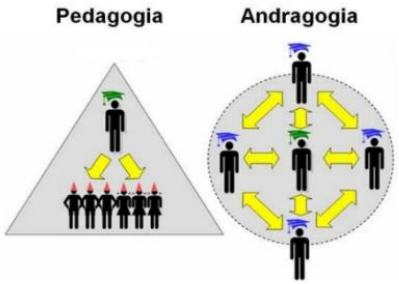

Figure 1 - Andragogy

Its importance in professional training, especially in subjects such as occupational safety and electricity, is fundamental. By adopting andragogical strategies such as problem solving, case studies, and practical simulations, training becomes more effective, with greater knowledge retention and participant engagement.
This strengthens not only technical learning, but also the safety culture, encouraging more conscious and preventive attitudes in the professional environment.

In high-risk areas such as those involving electricity, this can be the difference between preventing and experiencing accidents.

B. Learning Pyramid

During the 1960s, the American psychiatrist William Glasser developed a pyramid known as the "learning pyramid", which describes how learning takes place more effectively through a method that relates the degree of learning to the means used to learn, and that the retention of this knowledge also depends directly on the participation and commitment of the student.
In other words, learning is not about memorizing; it's about experiencing, being part of, practicing.
This is made explicit in Glasser's words: "Human beings are born learners, but in order to learn, you have to want to; learning must take place from the inside out."

Figure 2 shows Glasser's learning pyramid, which clearly demonstrates how active learning enhances knowledge retention. According to Glasser, we only learn 10% of what we read and 20% of what we hear, while retention increases significantly when we actively participate in the process; reaching 70% when we practice and up to 95% when we teach someone something.
These data reveal that traditional methods, based only on passive exposure to content, are less effective than strategies that involve the learner in a practical and meaningful way.

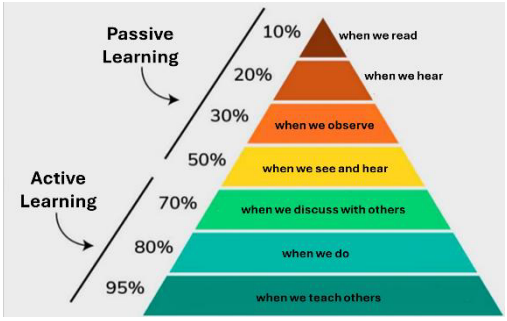

Figure 2 - Glasser's pyramid

III. ACTIVE METHODOLOGIES

Active methodologies have been transforming the way we conduct electrical safety training, making the process more dynamic, effective, and connected to the worker's reality. These methodologies include the use of virtual reality, which makes it possible to simulate risk environments in complete safety, and gamification, which brings elements of games to stimulate engagement and motivation during learning. Both strategies make a significant contribution to retaining technical and preventive behavioral content related to safety in electrical installations and services.

Another innovative resource is prototyping, which allows participants to interact with physical representations of equipment and actual work situations found in the electrical environment.
This allows professionals to visualize dangers, test decisions, and understand the consequences in a practical and contextualized way, which increases their sense of responsibility and perception of risk.
This experience contributes directly to consolidating safer and more preventive attitudes in daily operations, which is essential when dealing with the complexity and risks of electricity.

By integrating virtual reality, gamification and prototyping as active learning tools, electrical training becomes more attractive and much more effective.
The worker is no longer a passive agent, but actively participates in the construction of knowledge with experiences that simulate failures, decision-making and safe practices in a controlled environment.
This results in greater retention of information, a change in behavior, and a strengthening of the electrical safety culture in companies.

A. Virtual Reality (VR)

Electrical safety training has become much more engaging and effective with the use of virtual reality, as it makes it possible to simulate high-risk scenarios in a safe and realistic way.
This allows professionals to train critical procedures such as switching off high and medium voltage circuit breakers, maneuvering panels and Electric Power Systems (SEP) without exposure to electric shocks or other accidents.
In addition, the immersion provided by VR increases participant engagement, improves knowledge retention and enhances real-time decision-making, essential factors for ensuring efficiency and safety in the electrical work environment.

Figure 3 shows a practical training session with the VR where the employee is immersed inside a substation.

Figure 3 - Immersion inside the substation

Figure 4, the worker is challenged to identify the risks when maneuvering an HV (High Voltage) panel and correctly select the appropriate PPE, according to the energy incident on the panel, such as: insulating gloves, clothing according to the degree of risk, a hood and goggles. The experience allows them to visualize the consequences of an incorrect choice or negligence in the use of PPE, including identification of equipment conditions, promoting learning through controlled error and strengthening awareness of the importance of personal protection in preventing electrical accidents.

Figure 4 - Immersion inside the substation

The application of the six steps of lockout/tagout is an innovative and highly effective way of training employees in activities involving electricity. Within the virtual environment, the professional goes through all the stages, switching off, blocking, verifying the absence of voltage, temporary earthing, protecting energized elements, and signalling in a practical and immersive way. The simulation allows them to experience the complete process, identify faults, correct actions and understand the logic of each stage without real risks, but immersed in a real environment, as can be seen in Figure 5.

Figure 5 - Execution of 6 de-energizing steps

Figure 6 shows training in the Electric Power System (SEP), allowing employees to train in critical operations in a safe and realistic way, facing operational challenges that faithfully simulate the high-voltage environment. Professionals can practice identifying components, correctly sequencing maneuvers and complying with safety protocols, all in an immersive and interactive scenario. This approach not only increases the employee's confidence and technical competence, but also reduces operational errors and strengthens the culture of prevention in one of the most sensitive sectors of electrical safety.

Figure 6 - SEP inspection

Figure 7 shows the simulation of faults in a substation electrical room using virtual reality, which is a powerful strategy for developing risk perception skills and decision-making of professionals working in highly critical environments. In the virtual scenario, the employee is exposed to realistic situations such as panels with open drawers, abnormal noises in equipment, identification of hot spots, presence of venomous animals, accumulation of conductive dust, and signs of humidity in panels. These occurrences are reproduced in an immersive way, allowing the worker to develop the ability to identify and react correctly to deviations before they develop into serious faults or accidents.

As well as enabling training without exposing the employee to real risks, this approach strengthens the practical understanding of preventive inspections, encourages active communication between teams, and contributes to the development of a safety culture centered on anticipating failures.
The virtual environment also records the participant's successes and mistakes, offering immediate feedback at the end of the immersion, which renders learning more effective and personalized.

Figure 7 - Proposed challenges

B. Prototyping

The use of prototyping in electrical safety training represents a significant advance in the way professionals assimilate technical concepts and develop practical skills.

By building and interacting with physical models that represent real components of electrical systems, such as panels, transformers, and circuits, participants have the opportunity to learn in a more concrete, visual and tactile way. This makes it easier to understand complex structures, connections and how devices work, in a more tangible way and meaningful learning.
Figure 8 shows a practical session using prototypes to assimilate the concepts of safety distances according to the voltage level of the installation, demonstrating the risk, controlled and free zones as established in ANNEX II of the Regulatory Standard (NR10).

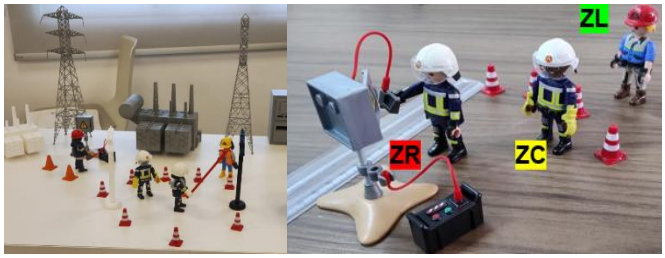

Figure 8 - NR10 safety distances

A great advantage of prototyping is the possibility of training procedures safely, allowing workers to practice critical activities in a simulated environment, without real risks.This fosters the development of practical skills with greater confidence and control. At the same time it encourages logical thinking, risk analysis and compliance with regulations.

Another important point is the encouragement of collaborative work. With prototyping, it is possible to develop group activities in which participants collaboratively build solutions, test hypotheses and share knowledge. This model strengthens not only technical skills, but also behavioral skills that are important in the workplace, such as communication, cooperation and team decision-making, which are essential for the safe execution of electrical services, especially, in high-voltage contexts and Electric Power Systems (SEP).
Finally, prototyping strengthens the safety culture by enabling training that is more aligned with the reality of work. This practical experience contributes directly to increasing operational efficiency, reducing accidents and valuing training as a strategic tool in organizations that work with electricity.

C. Gamification

Gamification has proved to be a powerful ally in active learning during professional training.

By transforming complex content into interactive experiences, it enhances participant engagement in a more natural and effective way.
Unlike passive methods, where employees only receive information, gamification encourages action, decision-making and problem-solving in real time, which promotes more meaningful and lasting learning.
In addition, it increases motivation.
The typical elements of games, such as scoring, challenges, rewards, and rankings, arouse interest and create a healthy competitive environment that encourages continued participation.
This is especially useful in mandatory training, which is often seen as a monotonous task. Gamification breaks down this barrier, making the learning process lighter, more engaging and rewarding.
Gamification contributes to the development of cognitive and behavioural skills.
Games require quick thinking, cooperation between teams, time management and adaptation to simulated scenarios; all fundamental skills for day-to-day work.
By practicing these skills in safe and controlled environments, employees feel better prepared to apply them in the actual work settings.
Figure 9 shows the gamification applied during a training course, in a question-and-answer game linked to the previously discussed contents of "Safety in Electrical Installations", where players create a path to follow.

Figure 9 - Reflection in Action game

Figure 9 shows the gamification applied during a training course, in a question-and-answer game linked to the previously discussed contents of "Safety in Electrical Installations", where players create a path to follow.
Finally, gamification allows immediate feedback, which is essential in active learning.

Instead of waiting until the end of the training to find out if they are meeting the learning objectives, participants receive instant feedback on their actions, understanding their mistakes and successes as they occur.
This enhances continuous learning and facilitates knowledge retention, strengthening the professional's autonomy in the construction of knowledge.

IV. Results

The electrical safety training carried out using the active methodology provided significant gains both in the assimilation of the content, and in changing the perception of employees.

This has resulted in greater knowledge retention, the development of critical thinking in the face of electrical risks, and an increase in risk perception, contributing directly to accident prevention and the construction of a solid and participative safety culture in organizations.

Figure 10 shows the first class trained in this model in February 2024.

Figure 10 - First class applying virtual reality in training

According to Figure 11, in 2024, 3,632 hours of training were given to 1,446 students, representing a significant investment in safety and learning.

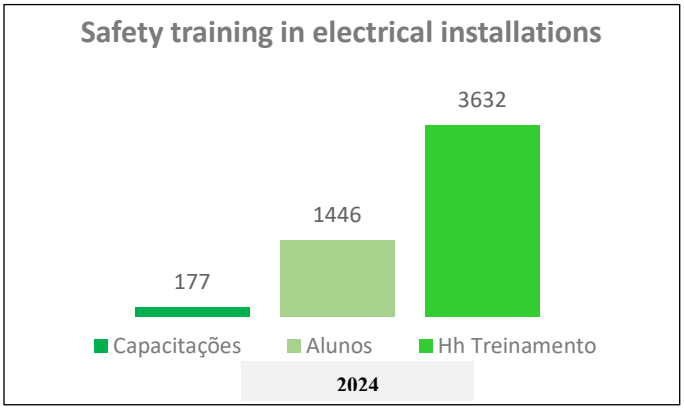

Figure 11- Graph Safety training in electrical installations

Acknowledgments

We would like to thank all the participants who made this work possible, especially the development companies, engineers, technicians, instructors, safety managers and electricians who enriched the training sessions with their insights and active engagement. Their contributions helped demonstrate how active learning can positively influence safety culture in environments with electrical risks.

This article is the result of collaborative efforts by professionals committed to prevention, innovation and continuous improvement. Each contribution, whether in virtual reality sessions, group dynamics or moments of reflection, was essential in demonstrating that transforming the safety culture is possible when we put the human being at the center of the learning process. To everyone, our sincere thanks.

Conclusions

The implementation of active methodologies in electrical safety training has proven highly effective in promoting behavioral change, improving learning outcomes, and enhancing risk awareness. Tools such as VR, gamification, and prototyping place learners at the center of the process, making training more practical, immersive, and aligned with real-life scenarios.

The training outcomes show that this approach increases knowledge retention, develops critical thinking, and strengthens a culture of safety. By actively engaging participants, the methodology promotes lasting behavioral change that extends beyond the classroom.

Therefore, transforming safety culture in electrical environments goes beyond compliance—it requires an andragogical approach that respects adult learning, promotes real-life simulation, and encourages constant practice. Active methodologies have demonstrated that it is possible to merge technology, engagement, and meaningful learning to protect the lives and well-being of professionals working with electricity.

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Health risks of electromagnetic fields from power transmission lines: Evidence and mitigation

David Michael Mendes da Silva
Department of Electrical Education
Federal Institute of Technology in Sao Paulo, IFSP
Sao Paulo, Brazil
d.silva@aluno.ifsp.edu.br

Wagner de Aguiar
Department of Electrical Education
Federal Institute of Technology in Sao Paulo, IFSP
Sao Paulo, Brazil
w.aguiar@ifsp.edu.br

Carlos Alberto Mitio Hirano
Department of Electrical Education
Federal Institute of Technology in Sao Paulo, IFSP
Sao Paulo, Brazil
carloshirano@ifsp.edu.br

Ivan Rezende de Souza
Department of Electrical Education
Federal Institute of Technology in Sao Paulo, IFSP
Sao Paulo, Brazil
ivan.rezende@aluno.ifsp.edu.br

Hermom Leal Moreira
Department of Electrical Education
Federal Institute of Technology in Sao Paulo, IFSP
Sao Paulo, Brazil
hermom.leal@ifsp.edu.br

***Abstract*— Currently, the problems caused by the occupation of areas beneath power transmission lines continue to cause health risks associated with exposure to electromagnetic fields (EMFs). This study aims to assess the potential health risks associated with such exposure, raise public awareness, and highlight the urgent need for coordinated efforts among utilities, regulatory authorities, and academic institutions to develop evidence-based safety policies. Our methodology involved a comprehensive review of the scientific literature on the biological and epidemiological effects of EMF exposure, with particular attention to populations residing in proximity to power transmission corridors. This was complemented by the analysis of case studies, including investigations on the incidence of leukemia among children and adults living near these facilities. The research was structured in sequential phases: an extensive literature review, research scoping, systematic data collection and analysis, and the development of an informational guide aimed at public dissemination. The main contributions of this study include the identification of quantifiable health risks associated with EMF exposure and the recognition of the critical need to inform and engage the affected population. The results support the development of specific educational materials and practical guidelines for residents near transmission areas, as well as the implementation of preventive public health policies. Ultimately, this work seeks not only to elucidate risks, but also to catalyze proactive measures that promote community well-being and minimize potential environmental and health impacts.**

Keywords—electromagnetic fields, hazard analysis, power transmission lines, public safety, health and safety

I. INTRODUCTION

In recent years, the growing urbanization of cities, in that next 2050, the global population will reach 9.7 billion, will live in urban areas [1] associated with the large increase in population in rural areas has significantly increased the consumption of electrical energy from alternating current systems coming from large hydroelectric plants. This recent phenomenal is presented like mega-urbanisation [2] and to meet this growing demand, important actions were taken, such as expanding the electrical energy transmission system of the concessionaires and increasing the energy demand of the current power transmission lines [3]. Lack of control over geographic space, lack of planning and infrastructure policies, lack of safety information, inefficiencies in insulation by concessionaires, and irregular occupation of easements and areas surrounding power transmission lines (TLs) are risk factors in the vicinity of TLs where communities are exposed to electromagnetic fields due to the circulation of electric currents that run through the conducting cables. Studies suggest possible harmful effects on health and the development of diseases, in addition to the risk of accidents [4]. The growing number of irregular occupations in the easements is becoming alarming and puts at risk the health of many people who lack information, guidance, and assistance from the government. It is necessary to raise public awareness of the adverse effects on individuals' health and, as a precautionary principle, adopt actions to mitigate the risks. The relevance of the topic occurs for several reasons, such as: effects on public health, scientific evidence, disease prevention, concessionaire responsibility, public awareness, and respect for standards and laws [5]. The contribution of this article consists of investigating the topic, seeking to highlight the health risks, preventive measures, public policies, education and future research. In this scenario, the central problem of this article is the health risks resulting from exposure to electromagnetic fields from transmission lines. Therefore, it is essential to understand the severity of the problem in order to develop strategies and actions to protect the health of residents living near TLs [5]. The methodology

of this article was structured around a bibliographic review of several case studies, from which the scope of the research, collection and analysis of data from previous research were carried out, resulting in a roadmap for the preparation of a booklet with recommendations for application to the population in risk areas. In short, this work explores potential causes and health effects that the magnetic field of transmission lines can cause to people living in these areas, with the aim of warning about physical health risks, reviewing epidemiological data. The article examines the effects of electromagnetic fields generated by TLs on the health of nearby residents. I. Introduction contextualizes the issue, highlighting irregular occupation of servitude strips and health risks. II. Literature Review covers electromagnetic fields, their impact on human health, and safety regulations, including servitude strips and transmission line components. III. Methodology describes the bibliographic review, data collection, and create informations to develop a booklet. IV. Case Studies analyze the link between proximity to power lines and diseases like leukemia, using statistical methods. V. Results reinforce the need for public policies and awareness. VI. The proposed booklet provides guidance on key topics related to the risks and precautions needed for companies and government agencies to develop security actions and policies in these areas. Finally, VII. Conclusion emphasizes preventive measures and partnerships to mitigate health impacts.

II. Literature Review

Maxwell's equations directly connect the physics of transmission lines to health issues (induced currents) [6]. The two equations - Ampère-Maxwell and Faraday - are the most pertinent and useful for grounding the mechanisms in fundamental theory [7].

A. Electromagnetic Fields and Human Health

EMFs are generated by electric current flow in conductors, comprising electric fields (from voltage) and magnetic fields (from current). These non-ionizing radiations (60 Hz) lack energy to ionize atoms but induce currents within the human body, potentially altering cellular functions [8]. Maxwell's equations elucidate these interactions, linking magnetic fields to charge movement.

The interaction between electric and magnetic fields from power lines is governed by Maxwell's equations, which describe how time-varying currents in conductors generate electromagnetic fields. For transmission lines operating at 60 Hz, the key equations elucidating these phenomena are:

1) Ampère-Maxwell Law:

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} + \mu_0 \varepsilon_0 (\partial \boldsymbol{E}/\partial t) \quad (1)$$

Links magnetic fields (**B**) to the current density (**J**) and time-varying electric fields (**E**) in conductors.

2) Faraday's Law of Induction:

$$\nabla \times \boldsymbol{E} = -(\partial \boldsymbol{B}/\partial t) \quad (2)$$

Explains how alternating magnetic fields from power lines induce circulating electric fields, which can drive currents in biological tissues.

These equations underpin the non-ionizing nature of 60 Hz EMFs: while the energy is insufficient to ionize atoms (**E**-field magnitude >> ionization thresholds), the induced currents ($\mathbf{J}_{induced} = \sigma \mathbf{E}$, where $\sigma \approx 0.5$ S/m for human tissues) may interfere with cellular processes [8].

3) Gauss's Law for Magnetism:

$$\nabla \cdot \boldsymbol{B} = 0 \quad (3)$$

This expresses that there are no magnetic monopoles; magnetic field lines are always closed loops. Around a transmission conductor, the magnetic field circulates around the current-carrying wire. Confirms that field lines from transmission lines form closed loops around conductors.

4) Gauss's Law for Electricity:

$$\nabla \cdot \boldsymbol{E} = \rho/\varepsilon_0 \quad (4)$$

This equation states that electric field divergence is proportional to the local charge density ρ. In the context of transmission lines, high voltages create strong electric fields even in the absence of net charge in the surrounding space.

B. Right-of-Way and Way Safety Zones

The right-of-way facilitates transmission line maintenance and inspection, while safety zones - defined by ABNT NBR 5422 - account for electromagnetic interference, lightning strikes, and short circuits [9]. In Brazil, tht way safety zones easements are designated areas around transmission lines for operation and maintenance, governed by ABNT NBR 5422 standards [10] and Normative Resolution No. 915 of ANEEL [11]. These zones prohibit residential, agricultural, or infrastructural use to mitigate risks from EMFs, electrical discharges, and accidents [9]. TABLE I outlines safety zone widths based on voltage. Prohibited uses include agriculture, construction, and infrastructure projects.

TABLE I. SAFETY ZONE WIDTHS BASED ON VOLTAGE

Voltage (kV)	Safety Zone Width (m)	Notes
69	12	6 m per side of line axis
138	16	8 m per side of line axis
230	35	17.5 m per side of line axis

Source: [9].

TABLE II, introduce the prohibited uses in main domains.

TABLE II. PROHIBITED USES IN MAIN DOMAINS

Domain	Prohibited Uses
Rural Area	Structures and facilities related to livestock and agricultural activities: electrical and mechanical installations; dams and reservoirs.
Urban Area	Residential and commercial buildings; land subdivision and real estate developments; public squares and parks; Bus stops; Industrial areas; parking lots.
Infrastructure	Roads; Water and sewage networks; communication networks;
Mining	Mining operations; earthworks and excavation

Source: [5].

C. Transmission Lines and Their Components

Transmission lines are critical infrastructure for transporting alternating current (AC) electrical energy over long distances from power generation plants to consumers and industries in urban and rural areas. Their primary

functions include efficient energy transport, minimization of power losses, interconnection of electrical grids, system stability, and ensuring sufficient supply capacity to support economic growth. These lines typically operate at various voltage levels, ranging from 69 kV, 88 kV to 138 kV, and even exceeding 230 kV.

Transmission lines comprise several key components: conductors, support structures, lightning arresters, insulators, and hardware. Each component plays a vital role in the safe and efficient operation of the power transmission system.

1)Conductors:

Conductors are the cables responsible for carrying electrical energy. They can be classified into two main types: solid wires and stranded cables. Solid wires are rigid, single-metallic conductors, while stranded cables are composed of multiple finer wires, which can be arranged in homogeneous or heterogeneous layers. Common types of conductors used in transmission lines include:

- **Aluminum Conductor Steel Reinforced (ACSR) Cables**: These cables consist of na outer layer of aluminum strands surrounding an inner core of steel wires. The aluminum provides excellent electrical conductivity, while the steel core offers high tensile strength, making them sustável for long spans and heavy loads [12].
- **ALPAC Cables**: Like ACSR, ALPAC cables also feature an aluminum conductor with a steel core. However, the steel core in ALPAC cables is smooth, and the individual aluminum strands have a trapezoidal cross-section. This design can optimize packing density and reduce cable diameter for a given cross-sectional area.
- **Expanded Copper and Aluminum-Steel (CAA) Cables**: These cables incorporate a steel core with a copper wire winding, a layer of non-metallic filler material, and an outer aluminum layer. This configuration aims to combine the conductivity of copper with the strength of steel and the lightweight properties of aluminum.

The EMFs are intensified with the increase in current in cables and conductors and the line design must be suitable for the currents calculated for its useful life and must not exceed design values.

2)Insulators:

Insulators are made of vitreous china and tempered glass. They serve to electrically protect power conductors, preventing current from flowing from the conductors to the support, and also mechanically support cables within the structure [12]. Insulators can be pins, posts, discs, fork-eyes, ball-and-sockets, suspension cables, or anchors. Lightning rods protect against atmospheric discharges, directing them to the ground and protecting transmission lines and structures. Without them, insulators would be damaged and arcs could form in conductors and structures [13].

3) Metal Structures:

Metal structures are elements that connect conductors, insulator columns, and the transmission line structure. There are several types of metal structures with different shapes that allow for articulation and connection between transmission line elements [13]. Materials may include lattice towers, tubular poles, and H-frames. Their properties must include mechanical strength to withstand wind, ice, and conductor stress, corrosion resistance, and design for specific terrains and voltage levels.

The EMF is sensitive to the geometry of the structure and changes its behavior. Hence the need to model the magnetic field for a transmission line with assumptions of maximum EMF limits incorporated into the calculation methodology. In section V. Results, the main effects of EMFs on health will be discussed.

III. Methods

This study employed a mixed-methods approach, including a literature review, scoping, data collection from previous studies, and proposed risk reduction and control actions through informational materials and public awareness. The existing literature review focused on the health effects of EMFs in communities near power lines. Data from three case studies were analyzed to assess the association between EMF exposure and health outcomes.

These studies included: (1) a 1979 investigation of childhood leukemia near power lines [14]; (2) a 1999–2015 study in Uberlândia, Brazil, examining all types of leukemia [15]; and (3) a 2001–2005 study in São Paulo, Brazil, analyzing leukemia, brain cancer, and amyotrophic lateral sclerosis in adults over 40 [16]. The work was based on statistical methods, including logistic regression and odds ratios (OR) with 95% confidence intervals (CI), used to assess risks. A proposed booklet was created with topics needed to provide residents with clear guidance on risks and safety measures in these areas.

IV. Case Studies

Three independent case studies were considered to investigate the potential association between exposure to electromagnetic fields from power transmission lines and the incidence of leukemia. The first study focused on pediatric populations and aimed to explore a possible link between childhood leukemia and residential proximity to high-voltage transmission lines. Data were collected and analyzed to assess correlations between spatial location and disease incidence.

The second investigation, also using a case-control design, examined all types of leukemia in residents of Uberlândia, Brazil, between 1999 and 2015. Data were obtained from the Unified Health System (SUS) and hospital mortality records. Geographic proximity between residential addresses and transmission infrastructure was determined using cartographic databases and Google Earth imagery. A statistical framework was applied for data tabulation and risk assessment.

The third study, conducted in the city and state of São Paulo, analyzed adult mortality records between 2001 and 2005. This case-control study specifically assessed the spatial correlation between adult leukemia cases and residential proximity to high-voltage transmission lines. Statistical analyses were performed using unconditional logistic regression models, confidence intervals (CIs), and odds ratios (ORs) to quantify the strength and precision of the observed associations.

A. 1979 Study (Denver, USA)

A pioneering case-control study investigated childhood leukemia near transmission lines but found no conclusive evidence [14].

In 1979, an epistemological study investigating leukemia cases in children living near power transmission lines was conducted by Ed Leeper and Nancy Wertheimer, but without any proven evidence.

The pioneering case-control study in history was conducted in Denver, USA, involving 155 deaths and 155 controls, using a wire-code classification method that considered the proximity of homes to power lines, wire thickness, and transformer locations. It involved Hospital Case-Control (HCC) and Population-Based Case-Control (PBCC) classifications, the former involving selection of hospital cases and the latter of control cases from the general population.

Subsequently, over 100 studies have failed to confirm the associations or results of the first study.

B. 1999–2015 Study (Uberlândia, Brazil)

This study reported a significant association between leukemia risk and proximity to transmission lines, with an OR of 1.73 (95% CI: 1.56–1.66) for residences within 50 meters [15].

In Uberlândia, a study was conducted to analyze the influence of all types of leukemia on the development of residents living near power lines from 1999 to 2015.

This study was conducted using hospital data and the hospital statistics department. Cases were grouped according to the proximity of their homes and age group.

To assess the likelihood of leukemia recurrence in relation to the distance from homes to power lines, multiple logistic regression was used with 95 percent confidence intervals for age and equivocal adjustments.

Age groups were divided into (18-40; 41-60; >60) and gender, as well as the distance from homes to high-voltage lines (up to 50m; 50 to 100m; 100 to 200m; 200 to 300m; over 300m). To determine the cases, addresses from patients' medical records and power lines were used with a cartographic base and the GoogleEarth application.

The study concluded that the risk of leukemia for adults increases with proximity to power transmission lines; the closer the residence, the greater the risk of developing the disease.

C. 2001–2005 Study (São Paulo, Brazil)

Analyzing 9,287 individuals, this study found elevated risks for leukemia, brain cancer, and amyotrophic lateral sclerosis in adults living within 50 meters of high-voltage lines (OR = 1.50, 95% CI: 0.98–2.28) [16].

A case-control study was conducted with adults aged 40 and older in the metropolitan region of São Paulo. The study included all cases of leukemia, brain cancer, and amyotrophic lateral sclerosis from 2001 to 2005. Data were provided by the official database of the city of São Paulo and the state of São Paulo. The present study was based on evaluating the connection of magnetic fields from power transmission lines to homes.

The 39 municipalities including the city of São Paulo had an estimated population of 20 million people and a total of 2,571 km of transmission lines. This study was approved by the Ethics Committee of the São Paulo School of Medicine. Unconditional logistic regression was used to calculate the odds ratio (OR) and 95% confidence intervals for the risk of death by relating distances to homes. Geolocation software was used to establish the relationship between distances, and the participation of cases or controls was not required to avoid any bias. With a total of 9,287 individuals, including 4,706 controls and 4,581 cases, 3,212 deaths from leukemia, brain cancer, and amyotrophic lateral sclerosis were determined. Voltages > 200 kV and < 200 kV were considered, as well as groups with distances from residences > 400 m, > 200 to 400 m, > 100 to 200 m, 50 to 100 m, and up to 50 m.

The cases assessed as having the highest risk are those located up to 50 m from the power line. The study's confidence interval (CI) is (OR = 1.47; 95% CI = 0.99-2.18).

V. Results and Discussion

Case-control epidemiological studies offer a rigorous framework for assessing the potential health impacts of EMF exposure by comparing the incidence of disease in exposed populations with that in matched, unexposed control groups. An additional analytic approach involves computing the proportional mortality ratio (PMR), which evaluates disease-specific mortality relative to the broader mortality profile within the study population.

A. Data Analysis

Data analyses from the case studies referenced in this work reveal a consistent pattern suggestive of adverse health outcomes—particularly among individuals residing directly beneath or within 50 meters of high-voltage transmission lines. These findings underscore a potentially elevated risk profile associated with chronic EMF exposure.

Table III shows the main characteristics of the case studies of the work demonstrate too the main characteristics of the case studies researched in the work, listing the type of disease, type of study, statistical method and age group.

TABLE III. Main characteristics of the case studies in the work,

Main characteristics of the case studies	**Case Study 1**	**Case Study 2**	**Case Study 3**
Type of disease	Leukemia	All types of Leukemia	Leukemia, brain cancer, and amyotrophic lateral sclerosis
Study type	Case-control	Case-control	Case-control
Statistical method	Wire-code	Multiple logistic regression	Unconditional logistic regression
Age group	Children and young people up to 19	Adults over 18 years	Adults aged 40 or older

The convergence of accelerated urban sprawl limited public awareness of electromagnetic hazards, inadequate state-level urban planning, and lapses in utility oversight have collectively intensified the risk of unintentional human

exposure to environments plausibly classified as carcinogenic.

In accordance with the precautionary principle, it is imperative to implement a comprehensive suite of interventions—spanning public education, targeted risk communication, governmental regulation, and cross-sector collaboration—that collectively aim to mitigate exposure while preserving the trajectory of sustainable economic development.

B. Electromagnetic Fields and Health Effects

EMFs from transmission lines consist of electric fields generated by voltage and magnetic fields induced by current flow [17]. These non-ionizing radiations, typically at 60 Hz, lack sufficient energy to ionize atoms but may induce currents in the human body, potentially increasing electrical conductivity fourfold [17]. Studies suggest an association between EMF exposure and health risks, particularly leukemia, with a noted risk increase within 50 meters of transmission lines [15], [16].

The established levels for magnetic flux density for frequencies between 1 Hz and 100 kHz for the general public are 200 µT, in accordance with International Commission on Non-Ionizing Radiation Protection (ICNIRP), which establishes limits for human exposure to electric and magnetic fields [17].

Therefore, power utilities must comply with these values by continuously measuring and calculating the magnetic field in transmission lines.

Despite numerous international and national studies and publications, there are still uncertainties regarding the effects of this exposure and the actual damage. Although different case study metrics have been adopted, the scientific community has not been able to achieve the same results.

Another type of uncertainty concerns the residential environment where there are sources of electromagnetic field emissions, such as home appliances, computers, mobile phones, and radio and television stations.

Considering the importance of the energy distribution system and its impact on society and the economy, institutes and agencies recognize the risks to the population's quality of life, health, and well-being and, to this end, create measures and limits, such as Brazilian Law 11.934/2009, for human exposure.

Therefore, there is a need to improve, maintain, and intensify systems to prevent encroachment on rights-of-way.

This monitoring is the responsibility of energy concessionaires, in partnership with government institutions and urban planning policies, educational and awareness materials and campaigns, public-private partnerships for urbanization programs, inspection and continuous monitoring to accurately ensure compliance with safety standards.

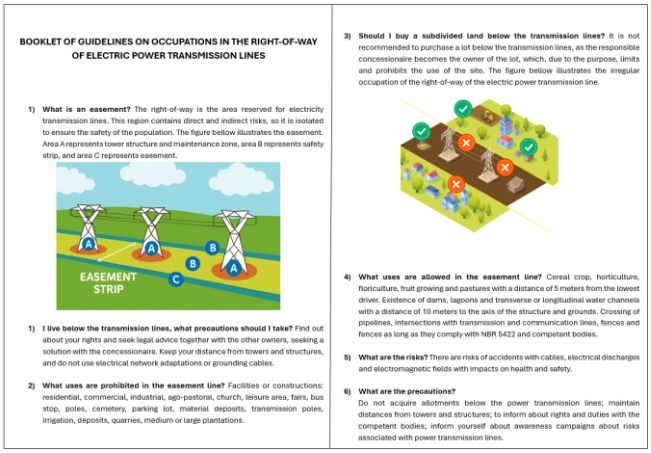
VI. BOOKLET

To bridge the gap between scientific evidence and public action, an educational booklet was developed to inform communities about the health risks associated with EMFs exposure LTs and provide practical risk mitigation strategies. Designed for accessibility, the booklet targets residents, local governments, and utility stakeholders, and is suitable for distribution in digital and printed formats through schools, health institutions, and energy companies.

The main sections for inclusion in guidance material should contain the following items:

- **Definition of Easement and Safety Zones:** Clarifies the legal and technical distinctions between easements and regulatory safety zones.
- **Health Risks of EMF Exposure:** Summarizes scientific findings on diseases associated with EMFs, including leukemia and neurodegenerative diseases, with simplified explanations of the biological mechanisms.
- **Prohibited and Permitted Activities:** Based on ABNT NBR 5422 and ANEEL Resolution 915, the guide provides a visual reference of prohibited land uses, including residential buildings, agricultural infrastructure, and recreational facilities.
- **Recommended Precautionary Measures:** Encourages residents to avoid physical proximity to towers, refrain from unauthorized electrical modifications, and consult municipal authorities or utility companies before making any land use decisions.
- **Guidance for Affected Populations:** Provides contact information for legal assistance, public health services, and communication channels with utility companies to report unauthorized occupations.

FIGURE I. BOOKLET OF GUIDELINES ON EASEMENT STRIPS,



The booklet's dissemination strategy leverages partnerships with municipalities and utilities to integrate it into public health campaigns, ensuring broad reach and impact. By translating complex scientific findings into actionable guidance, it aims to empower communities to mitigate EMF-related health risks effectively.

VII. CONCLUSION

This study underscores the potential health risks associated with EMF exposure from power transmission lines, particularly for residents within 50 meters, where epidemiological evidence suggests increased risks of leukemia, brain cancer, and amyotrophic lateral sclerosis. Maxwell's equations elucidate the physical basis of EMF generation, highlighting the induction of currents in biological tissues as a plausible mechanism for health effects. While uncertainties persist due to conflicting study outcomes and confounding factors, the precautionary principle necessitates proactive measures. The proposed informational booklet serves as a practical tool to raise awareness and guide residents on safety measures, such as avoiding servitude easement occupation. To enhance public health protection, we recommend: 1) stricter enforcement of servitude easement regulations by utilities and regulatory bodies like ANEEL; 2) integration of EMF risk assessments into urban planning policies; 3) public education campaigns to disseminate the booklet; and 4) further research into bioelectromagnetic interactions using advanced computational models. These interventions aim to balance the demands of energy infrastructure expansion with the imperative to safeguard community well-being.

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