IEEE 13-Node Incident Energy Analysis Using Online Platform

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Abstract— **The thermal hazard is considered the most significant hazard from an arc flash event. The protection against this type of hazard is associated with the assessment of incident energy, a study that aims to analyze the possibility of occurrence of an electric arc, the incident energy produced by it and the necessary protections so that the work in electricity is safe. An incident energy analysis is performed to the 634 bus of IEEE 13 Node system using the ATP Draw software to simulate a three-phase shot-circuit and an online platform that runs the IEEE Std 1584-2018 model is employed to obtain the incident energy levels and arc-flash boundary values for different durations of arcing event. As a closing, the personal protective equipment required for the different time scenarios are analyzed, according to the two approaches proposed in NFPA 70E-2021.**

Keywords— Electric Arc; IEEE Std 1584-2018; Incident Energy; NFPA 70E-2021, Personal Protective Equipment.

I. INTRODUCTION

Certain electrical hazards have been known since the advent of electricity's use in the late of 19th century. For the most people, shock and electrocution hazard are the most known. However, most hospital admissions due to electrical accidents are from arc-flash burns, not from shocks [1].

According to [2], 212,820 burn cases were registered in United States between 2008 and 2017. 6,299 (3,1%) cases have been caused by electrical circumstances. A major part of these incidents (59%) was accidental and work-related. This type of injury occurs mostly in male adults, as they tend to be the group that works in industrial settings and on home repairs.

The thermal hazard is generally accepted as the most significant hazard from arc flash, as documented cases of arc flash injuries are predominantly burn injuries [3]. Other hazards related to arc flash events are blast pressure wave, hearing loss, harmful electromagnetic emissions, release of highly toxic gases and shrapnel [4].

Although overall complication rates in electrical injuries are relatively low compared to flame burns, some of the most devastating complications seen after burn injury can occur in this group, such as pneumonia, sepsis, and wound infection [2]. Thereby, to protect the worker against this hazard, personal protective equipment (PPE) is required [5].

The definition of recommended levels of protection is one of the results of an arc flash hazard assessment, a type of study which aims to estimate the incident energy, the arc-flash boundary and to determine the best flame resistant (FR) clothing system that matches with possible exposures at working area.

There are several models to estimate incident energy and arc-flash boundary presented in literature, the best-known being Lee's theoretical method [6], Doughty, Neal and Floyd's model for enclosure arcs [7] and the IEEE Guide for Performing Arc-Flash Hazard Calculations (IEEE Std 1584) [8,9]. Due to the greater range of the model, as well as its constant updating, the IEEE Std 1584 model is the most widespread.

In this paper, the authors present an incident energy estimation using an online platform that employs 2018 version of IEEE Std 1584 to an IEEE 13 Node Test Feeder 4.16 kV open-air bus, to estimate incident energy level and PPEs required are purposed to each situation. The short-circuit study was applied using ATP Draw.

II. DEFINITIONS

Analysing an arc-flash hazard assessment requires to know basic concepts involved in this type of study. Concepts such as arc-flash hazard, incident energy and arc-flash boundary are defined in IEEE Std 1584.

Electric arcing is the term applied to the passage of electric currents through the air. Once air is not a conductor, the current flows the vapor of arc terminal material, usually a conductor metal or carbon [6]. As a characteristic of an arcing event there is the "flash", defined as a sudden brief burst of bright light, so the arc flash is a serious light hazard, known to cause temporary blindness [10]. In terms of the IEEE Std 1584, arc-flash hazard can be defined as a dangerous condition associated with an electric arc likely to cause possible injury [8,9]. To define protection equipment to people working in likely arc-flash scenarios, it is necessary to perform an arc-flash assessment, which outputs are the incident energy and the arc flash boundary.

The incident energy is the amount of thermal energy impressed on a surface, a certain distance from the source, generated during an electric arc event [8,9]. Once incident energy is calculated at working distance, it is used as parameter

https://doi.org/10.53316/sepoc2021.057

to definition of PPE category. The secure working distance is that where incident energy is equal to 5.0 J/cm² or 1.2 cal/cm² and it is called arc-flash boundary [8,9] or still flash-protection boundary [8]. This is considered safe because, in case of an arcing event, the person working in that point receives a level of incident energy to cause a second-degree burn, that is, a curable burn.

III. IEEE STD 1584

The IEEE Std 1584 is a guide elaborated by IEEE Industry Applications Society's Petroleum and Chemical Industry Committee (IAS/PCIC) whose purpose is to provide a model to perform arc flash hazard calculations. Model's applications include electrical equipment and conductors for three-phase alternating current (AC) voltages from 208 V to 15 kV, while calculations for single-phase AC systems and direct current (DC) systems are not covered by the model.

The publication of the guide, in 2002, came up against a growing concern about arc-flash related risks. This guide is based upon testing and analysis of the hazard presented by incident energy, so the hazards arising from molten metal splatter, projectiles, pressures impulses, and toxic arc by-products have not been considered in these methods [8]. Amendments were published in 2004, 2011, and 2013, but the literature was still finding failures in the model, especially for medium-voltage system analysis, such as in [11-13]. Finally, in 2018, IAS/PCIP published the latest version, with an improve model to perform arc-flash calculations.

The 2018 version of IEEE Std 1584 is applicable for systems with [9]:

- Voltages in the range of 208 V to 15000 V, three-phase.
- Frequency of 50 Hz or 60 Hz.
- Bolted fault current of 500 A to 106000 A (208 V to 600 V) and 200 A to 65000 A (601 V to 15000 V).
- Gaps between conductors of 6.35 mm to 76.2 mm (208 V to 600 V) and 19.05 mm to 254 mm (601 V to 15000 V).
- Working distances greater than or equal to 305 mm.
- Cubic enclosures test for 600 V (508 mm), 2700 V (660.4 mm) and 14300 V (914.4 mm).
- Enclosure dimension limits of 1244.6 mm (maximum height or width) and 1549 m² (maximum opening area). The minimum width value should be larger than four times the gap between electrodes.
- Electrode configurations: vertical conductors inside a metal box (VCB), vertical conductors terminated in an insulating barrier inside a metal box (VCBB), horizontal conductors inside a metal box (HCB), vertical conductors in open-air (VOA) and horizontal conductors in open-air (HOA).

The application steps of the model are basically four, that is, (i) to determine arcing current, (ii) to determine arcing time, (iii) to determine incident energy and (iv) to determine arc-flash boundary. It is recommended to repeat all the steps applying reduced arcing current. The choice of applicable PPEs is not contemplated by this standard.

In this version, the model is divided in two parts, depending on system open-circuit voltage: there are a model for systems between 600 V and 15000 V and a model for systems between 208 V and 600 V. Both models use a two-step process, in which first intermediate values of arcing current, incident energy and arc-flash boundary are determined and after the final values, by interpolation.

Once in this paper the authors are analysing a 480 V bus, only the model for 208 – 600 V systems will be presented next.

A. Arcing Current

The intermediate value of the arcing current is obtained using (1) [9], where I_{arc_600} is the intermediate arcing current for V_{oc} equal to 600 V, in kA; I_{bf} is the bolted three-phase fault current, also in kA; G is the gap between the electrodes, in mm; log is the base 10 logarithm and k_1 to k_{10} are the coefficients provided by Table 1 of [9].

To find the final value of the arcing current, (2) [9] is used. V_{oc} is the open-circuit voltage, in kV; I_{bf} is the bolted three-phase fault current, in kA; I_{arc} is the final arcing current, at the specified V_{oc}, in kA and I_{arc_600} is the intermediate arcing current for V_{oc} equal to 600 V, in kA, previously obtained.

$$I_{arc\_Voc}=10^{(k_1+k_2\log I_{bf}+k_3\log G)}(k_4I_{bf}^{6}+k_5I_{bf}^{5}+k_6I_{bf}^{4}+k_7I_{bf}^{3}+k_8I_{bf}^{2}+k_9I_{bf}+k_{10}) \tag{1}$$

$$I_{arc}=\frac{1}{\sqrt{\left(\frac{0.6}{V_{oc}}\right)^2\times\left[\frac{1}{(I_{arc\_600})^2}-\left(\frac{0.6^2-V_{oc}^{\,2}}{0.6^2\times I_{bf}^{2}}\right)\right]}} \tag{2}$$

B. Arc Duration

The arc duration is function of the arcing current. In this paper, different fault extinction times were considered, to show the direct relation between the arc duration and the incident energy.

C. Incident Energy and Arc-Flash Boundary

The incident energy is estimated employing (3) and the arc-flash boundary, (4), both presented in [9].

In (3), $E_{\leq 600}$ is the intermediate incident energy when Voc is equal to 600 V, in J/cm²; E is the final incident energy value, also in J/cm²; T is the arc duration, in ms; I_{arc_600} is the intermediate arcing current for 600 V, I_{arc} is the final arcing current and I_{bf} is the bolted three-phase fault current, these three in kA; G is the gap between the electrodes and D is the working distance, both in mm; CF is the correction factor for enclosure size, dimensionless; log is the base 10 logarithm and k_1 to k_{13} are the coefficients provided by Table 3 of [9].

The conversion of the incident energy from J/cm² to cal/cm², which is the most common unit for selectin PPEs, is done by dividing the value in J/cm² by 4.184.

From (3) to (4), the other variables that show are $AFB_{\leq 600}$, that is the arc-flash boundary for Voc equal to 600 V, and AFB, the final value of arc-flash boundary, both in mm.

$$E = E_{\leq 600} = \frac{12{,}552}{50} T \times 10^{\left(\begin{array}{c} k_1 + k_2 \log G + \frac{k_3 I_{arc\_600}}{k_4 I_{bf}^7 + k_5 I_{bf}^6 + k_6 I_{bf}^5 + k_7 I_{bf}^4 + k_8 I_{bf}^3 + k_9 I_{bf}^2 + k_{10} I_{bf}} \\ + k_{11} \log I_{bf} + k_{12} \log D + k_{13} \log I_{arc} + \log \frac{1}{CF} \end{array} \right)} \tag{3}$$

$$AFB = AFB_{\leq 600} = 10^{\left(\frac{\begin{array}{c} k_1 + k_2 \log G + \frac{k_3 I_{arc\_600}}{k_4 I_{bf}^7 + k_5 I_{bf}^6 + k_6 I_{bf}^5 + k_7 I_{bf}^4 + k_8 I_{bf}^3 + k_9 I_{bf}^2 + k_{10} I_{bf}} + k_{11} \log I_{bf} \\ + k_{13} \log I_{arc} + \log \frac{1}{CF} - \log \frac{20}{T} \end{array}}{-k_{12}} \right)} \tag{4}$$

D. Reduced Arcing Current

The reduced arcing current is obtained employing (5) [9], where I_{arcmin} is the reduced arcing current, in kA, and I_{arc} is the final arcing current, also in kA.

The arcing current correction factor, $VarC_f$, is provided by (6) [9], which is a function of the open-circuit voltage, V_{oc}, in kV, and the coefficients k_1 to k_7, provided by Table 2 of [9].

$$I_{arc\,min} = I_{arc} \times (1 - 0{,}5 \times VarC_f) \tag{5}$$

$$VarC_f = k_1 V_{oc}^6 + k_2 V_{oc}^5 + k_3 V_{oc}^4 + k_4 V_{oc}^3 + k_5 V_{oc}^2 + k_6 V_{oc} + k_7 \tag{6}$$

IV. NFPA 70E

The NFPA 70E is a standard developed by National Fire Protection Association that presents requirements for safe work practices to protect personnel by reducing exposure to major electrical hazards. In Brazil, the ABNT NBR 16384, published in 2020, can be considered an equivalent standard, since it also proposes four levels of thermal protection.

Its guidance about the use and selection of PPE is widely considered. Since the 2018 edition and still in 2021 edition [14], it purposes two ways to select the applicable PPE, to know: (i) incident energy analysis method and (ii) arc flash PPE category method.

The incident energy analysis method considers that the level of exposure to incident energy must be based on the working distance of the worker's face and chest areas from the possible source of arc for the specific task to be performed, being the clothing and other PPE used by the worker according to this incident energy value. The clothing and other PPE required are divided in two groups, one for incident energy exposures equal to 1.2 cal/cm² up to and including 12 cal/cm² and other to incident energy exposures greater than 12 cal/cm².

To the arc flash PPE category method, four categories of arc flash PPE are purposed, as presented in Table I.

TABLE I. ARC-FLASH PPE CATEGORIES [14].

PPE CAT	**Minimum arc rating (cal/cm²)**
1	4
2	8
3	25
4	40

V. METHODOLOGY

An incident energy analysis can be performed to any system where there is human intervention. In this paper, the authors opted by a known system, the IEEE 13 Node Test Feeder, because this system operates into the IEEE Std 1584-2018 voltage range of application. Decided the point which will be analyzed, a short circuit simulation must be performed, to provide the bolted fault current value. After that, the incident energy estimation model is applied and, with the results obtained, the necessary PPE is indicated.

A. *IEEE 13 Node Test Feeder*

The IEEE 13 Node Test Feeder is a small circuit model used to test common features of distribution analysis software, operating at 4.16 kV, and is part a group of systems created in 1992 that were designed to evaluate and benchmark algorithms in solving unbalanced three-phase radial systems [15]. The system is presented in Figure 1.

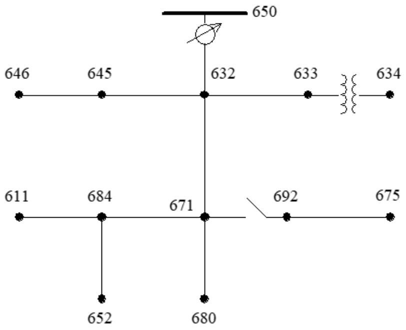

Fig. 1. IEEE 13 Node Test Feeder [15].

B. *ATP Draw*

The ATP Draw is a graphical mouse-driven pre-processor to the ATP version of Electromagnetic Transients Program (EMTP) on the MS-Windows platform [16]. In this paper, it is used to simulate a bolted three-phase fault in a 480 V bus (bus 634), once this level of voltage is covered by IEEE Std 1584. The choice of the type of short-circuit is purely based on the model adopted, which only applies to three-phase faults.

It is worth mentioning that other software can be used for the short circuit simulation. The option for ATPDraw was based mainly on the fact that it is a free software.

C. *Online Platform*

An online platform was used to calculate incident energy and arc-flash boundary, according to the IEEE Std 1584-2018 model. This platform uses the Java language, and it was developed within the scope of a research and developed project in which the authors currently work.

The goal of this platform is to provide an easy and intuitive tool, accessible from anywhere, that allow the user to employ the IEEE Std 1584-2018 model quickly.

The layout of the online platform is presented in Figure 2.

Energia Incidente

Informe os parâmetros a seguir para o cálculo de energia incidente conforme IEEE Std 1584 (2018).

Tipo de Eletrodo: VCB
Tensão (V): 11000
Corrente de Falta Trifásica Franca (kA): 43,265
Distância entre Eletrodos (mm): 152
Distância entre Eletrodo e Calorímetro (mm): 914,4
Duração do Arco (ms): 400
Altura do Compartimento (mm): 2000
Largura do Compartimento (mm): 500
Profundidade do Compartimento (mm):

Fig. 2. Incident energy calculation online platform.

VI. RESULTS

A. *Short Circuit Simulation*

To obtain the available bolted fault current, a short-circuit simulation was performed for bus 634 of IEEE 13 Node system, using the software ATP Draw.

This software presents the current value by phase, to know: 16.048 kA in phase A, 15.770 kA in phase B, and 15.678 kA in phase C, as shown in Figure 3.

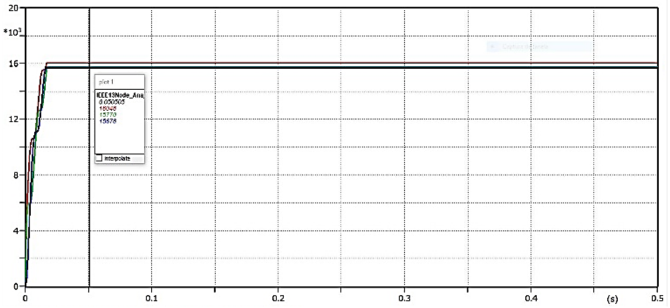

Fig. 3. ATP Draw short circuit simulation results.

The value obtained through the short-circuit simulation in one of the input variables that is used to perform the arc-flash hazard calculations.

B. *IEEE Std 1584 Application Parameters*

The applicable parameters are presented in Table II.

TABLE II. CASE STUDY PARAMETERS

Parameter	**Value**
Voc	0.480 kV
Ibf	16.048 kA
G	200 mm
D	330 mm
Electrode configuration	HOA

The incident energy and the arc-flash boundary are proportional to arc duration, that is, the longer the arc flash event lasts, the greater the incident energy will be. For this reason, reducing the arc duration is one of the most widely used strategies to mitigate incident energy levels. In this work, the arc duration varies from 100 to 500 milliseconds (ms), with a step of 100 ms. A scenario with the arc duration equal to 50 ms is also presented.

C. *Online Platform*

Considering the parameters presented in Table II and employing the online platform, arcing current is equal to 5.3812 kA. For this level of arcing current and for the several arc extinction times considered, the incident energy levels, and arc-flash boundary values are presented in Table III.

Already the values of incident energy and arc-flash boundary considering the reduced arcing current equal to 4.6358 kA are presented in Table IV.

Although the reduced arcing current has this name, it will not always generate lower incident energy levels and shorter arc-flash boundary than that obtained employing the arcing current, because both the incident energy and the arc-flash boundary are also dependent of other several factors.

TABLE III. INCIDENT ENERGY LEVELS AND ARC FLASH BOUNDARY VALUES FOR ARCING CURRENT 5.38 KA AND SEVERAL ARC DURATIONS.

Arc duration (ms)	Incident energy (cal/cm²)	Arc flash boundary (mm)
50	4.6647	652.8522
100	9.3293	924.8818
200	18.6586	1310.2603
300	27.9880	1606.3702
400	37.3173	1856.2178
500	46.6466	2076.4785

TABLE IV. INCIDENT ENERGY LEVELS AND ARC FLASH BOUNDARY VALUES FOR REDUCED ARCING CURRENT 4.64 KA AND SEVERAL ARC DURATIONS.

Arc duration (ms)	Incident energy (cal/cm²)	Arc flash boundary (mm)
50	4.1201	613.3724
100	8.2402	868.9516
200	16.4805	1231.0252
300	24.7207	1509.2285
400	32.9609	1743.9671
500	41.2012	1950.908

Once final values of incident energy and arc-flash boundary are the higher between both cases presented before, the final values of incident energy and arc-flash boundary are presented in Table V.

TABLE V. FINAL INCIDENT ENERGY LEVELS AND ARC FLASH BOUNDARY VALUES FOR SEVERAL ARC DURATIONS.

Arc duration (ms)	Incident energy (cal/cm²)	Arc flash boundary (mm)
50	4.6647	652.8522
100	9.3293	924.8818
200	18.6586	1310.2603
300	27.9880	1606.3702
400	37.3173	1856.2178
500	46.6466	2076.4785

D. *Applicable PPEs*

In Table VI, the applicable PPEs for each situation are presented for both methods purposed by [14]. It is important to note that both methods are valid, but that they cannot be applied simultaneously, because it can cause ambiguity in warning signs that guide the worker.

The selection of PPEs (clothing and others) by the incident energy estimation proposes to employ a fabric that supports the incident energy level of exposure according to the need, that is clothing capacity is customizable. The selection by categories, in turn, facilitates the acquisition of the PPE, but can lead to the use of an oversized garment for a given scenario.

It can be seen in the PPE selection for the scenario where the arc lasts 100 ms. While for the incident energy estimation method the PPE applicable is the one that covers up to 12 cal/cm² and the clothing dimensioned for the incident energy level of 9.2393 cal/cm² or more, but limited to 12 cal/cm², for the selection using the PPE categorization method, the PPE would be category 3, whose garment supports up to 25 cal/cm², which implies a greater weight for the workers.

TABLE VI. FINAL INCIDENT ENERGY LEVELS AND APPLICABLE PPE.

Arc duration (ms)	Incident energy (cal/cm²)	Applicable PPE (IE Method)	Applicable PPE (Category Method)
50	4.6647	1.2 < IE ≤ 12	2
100	9.3293	1.2 < IE ≤ 12	3
200	18.6586	IE > 12	3
300	27.9880	IE > 12	4
400	37.3173	IE > 12	4
500	46.6466	IE > 12	-

In addition, the limitation of PPE categories to 40 cal/cm² does not allow services to be performed above this level of exposure, which leads to the need of employ incident energy mitigation techniques.

Since the incident energy levels are a direct function of the arc duration, most mitigation strategies are dedicated to reducing this time. In addition to this, the worker’s distance from the arc source and the fault current level are also factors that can be managed to reduce the thermal effects of this type of event.

VII. FINAL CONSIDERATIONS

This paper presented an incident energy analysis for bus 634 of the IEEE 13 Node system using an online platform that employs the IEEE Std 1584-2018.

The IEEE Std 1584 model is the most widespread method of estimating incident energy in both industry and academia, and its strong point the fact that it is an empirical mathematical model, whose constants are derived from laboratory tests. Responsible personnel for the arc-flash analysis can purpose mitigation techniques from the knowledge of the proposed model.

However, it has limitations for incident energy analysis in distribution systems. Its application range of IEEE Std 1584 reduces its applicability, once it covers only low-voltage and part of medium-voltage systems, leaving a gap to arc-flash analysis of other classes of medium and high-voltage distribution systems.

Furthermore, the possibility of selecting protective clothing by two different method, as proposed by NFPA 70E, facilitates the management of the clothing and other PPEs.

ACKNOWLEDGMENT

The authors would like to thank the technical and financial support of CPFL Energia to the project “Metodologia e Ferramenta Computacional para Avaliação e Modelagem das Condições de Arco Elétrico em Sistemas Elétricos de Potência no Contexto Brasileiro”, developed under the ANEEL R&D Program PD-00063-3069/2020. This study was also financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brazil (CAPES/PROEX) – Finance Code 001.

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