A COMPARATIVE ANALYSIS OF ARC-FLASH CALCULATIONS: IEEE 1584 AND DGUV-I 203-077

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Abstract – It is widely recognized that IEEE Std. 1584™-2018 is used globally to calculate the prospective incident energy for the selection of arc rated clothing and personal protective equipment. In addition, this standard is used for calculating the arcing fault current and arc flash boundary. The information brochure DGUV-I 203-077 describes an alternative calculation method to IEEE 1584. The DGUV-I 203-077 Guide was developed in Germany for the selection of Arc Rated PPE. DGUV is the German Social Accident Insurance Institution which is the national, compulsory program that insures workers for injuries or illness incurred through their employment. Several countries use this document as a preferred alternative to IEEE Std. 1584™-2018. This paper explores the history of DGUV-I 203-077, why there are two incompatible arc-flash calculation methods and a detailed comparison of DGUV-I 203-077 and IEEE Std. 1584™-2018.

Index Terms — Arc Flash, Box Test, incident energy, arc energy, DGUV, German method, PPE Testing, protection class, APC1, APC2, IEEE Std. 1584™-2018, electrode configurations, arc current, IEC arc flash

I. INTRODUCTION

Since it was first introduced in 2002, the standard IEEE 1584 – *IEEE Guide for Performing Arc-Flash Hazard Calculations* [1], [2] has gained acceptance and is the primary method used to calculate arc-flash (AF) thermal hazard globally. This is a fundamental component of the AF risk assessment. IEEE is an international standards organization comprised of more than 400,000 members with the majority of its members residing outside of the United States [3]. This standard provides a model for calculating the prospective incident energy from an arc flash which is then used to assess the risk severity and to select appropriate arc rated clothing and personal protective equipment (PPE). In addition, equations are provided for calculating the prospective arcing current range and arc-flash boundary.

Although IEEE 1584 is the most widely used method for arc-flash thermal hazard calculations, it is not the only method. A calculation method developed and promoted in Germany is also used for arc-flash studies in several other countries. This method is described in DGUV-I 203-077 [4] (hereinafter referred to as DGUV for brevity), which is an information guide/brochure which bases arc-flash calculations on arc energy rather than incident energy.

To understand why there are two different calculation methods, requires recognizing that two distinctly different test methods for arc rated clothing and PPE exist within the International Electrotechnical Commission (IEC) standards. The first test method is described in IEC 61482-1-1: *Live working – Protective clothing against the thermal hazards of an electric arc – Part 1-1: Test methods – Method 1: Determination of the arc rating (ELIM, ATPV and/or EBT) of clothing materials and of protective clothing using an open arc* [5] which is also colloquially known as the “Open Arc Test”. The second test method is defined in IEC 61482-1-2: *Live working - Protective clothing against the thermal hazards of an electric arc - Part 1-2: Test methods - Method 2: Determination of arc protection class of material and clothing by using a constrained and directed Arc* [6]. This method is also known as the “Box Test”.

These two test methods are significantly different in their approach to PPE testing, however, they both co-exist as separate and mutually exclusive test methods within the IEC standards. Determining the arc rating for PPE based on the open arc test method requires conducting arc-flash calculations using IEEE 1584™-2018 (hereinafter referred to as IEEE 1584 for brevity). Selection of PPE based on the box test method is determined based on using equations and procedures outlined in DGUV Information 203-077. Fig. 1 illustrates PPE selection using these two calculation methodologies.

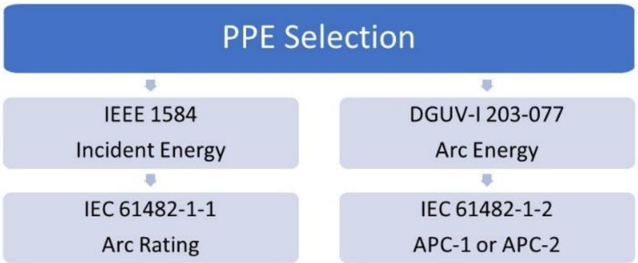

Fig. 1 – Two PPE Test Methods and Calculation Methods

Because there are two different methods for testing PPE and calculating the incident energy or arc energy for the selection of arc rated PPE as shown in Fig. 1, misunderstandings and misinterpretations regarding the calculation methods may exist. This paper provides a review as well as compares and contrasts each of the two methods.

A. ASTM F1959 (Open Arc Test) and IEEE 1584

The test method from IEC 61482-1-1 is similar to the ASTM F1959 Standard Test Method for Determining the Arc Rating of Materials for Clothing [7]. Both the IEC and ASTM methods use two opposing electrodes with an available fault current which has a symmetrical steady state rms component of 8 kA +/- 0.5 kA. To vary the energy, the arc duration can be varied. An open circuit voltage of at least 2,000 volts is used with an X/R ratio that results in a DC component that has a first peak of 2.3 times the symmetrical rms value. Monitor sensors are used adjacent to the test specimen to record the available incident energy as shown in Fig. 2.

Fig. 2 – Open Arc Test Apparatus.

This open arc test method enables the ability to test many different arc ratings which are continually evolving in the industry. What once began as PPE typically rated for incident energy levels of 4, 8, 25 and 40 cal/cm^2 has expanded to 65, 75 and presently up to 140 cal/cm^2. Note that IEC 61482-2 – Live Working: Protective clothing against the thermal hazards of an electric arc – Part 2: Requirements [8] states that for the open arc test "Due to the limitations of test apparatus at very high energy arcs, no arc rating above 4186 kJ/m^2 (100 cal/cm^2) shall be assigned to garments".

An open arc under controlled laboratory conditions is used to determine the values of ELIM (Incident Energy Limit), ATPV (Arc Thermal Performance Value) or EBT (Energy Break-Open Threshold) of material, garments, or assemblies of garments. ELIM was introduced with the latest edition of IEC 61482-1-1 which is discussed below.

1) *European Union, CE Marking, and ELIM:* The European Committee for Electrotechnical Standardization (CENELEC) headquartered in Brussels, Belgium is comprised of 34 National Standardization Organizations, a network of 200,000 experts, 366 European Partners, and 439 Technical Committees. CENELEC adopts IEC standards for the European Union which means when an IEC standard is published, upon a positive CENELEC vote, it will become a European EN standard.

During the maintenance cycle to develop the second edition of IEC 61482-1-1, it was determined that the use of a 50% probability of the onset of second degree burn as previously used and as used by ASTM F1959 was not acceptable for Europe or CENELEC. Because of this issue, it also meant that arc rated protection could not receive the required CE ("conformité européenne" in French for "European conformity") marking which appears on many products that are traded on the single market in the European Economic Area (EEA). The CE marking is required for many products and is described in further detail in Section II.A. The marking shows that the manufacturer has checked that these products meet European Union (EU) safety, health, or environmental requirements.

To address this issue and satisfy the criteria to achieve a CE marking, the second edition of IEC 61482-1-1 added an additional criterion known as ELIM. ELIM is defined as the numerical value of incident energy attributed to a product (material or equipment), below which the values of all product responses are below the Stoll curve and without breakopen. The ELIM differs from the ATPV in that there is 0% chance of a second-degree burn rather than a 50% probability. The arc rating based on the second edition of IEC 61482-1-1 now includes ELIM in addition to ATPV and EBT.

To determine the appropriate arc rating that is sufficient for the prospective incident energy, IEEE 1584 is used. The second edition of IEEE 1584 – IEEE Guide for Performing Arc-Flash Hazard Calculations^{TM} published in 2018 introduced greatly enhanced accuracy and modeling capabilities for arcing fault current, incident energy, and arc-flash boundary calculations. Knowing the prospective arcing fault current for an arc flash is a critical component when evaluating the fault clearing time used for the arc duration. In addition to capturing the non-linear nature of the arcing fault current vs. bolted fault current, an arcing current variation factor was also introduced that further refines the arcing current calculation. Consideration of the electrode configuration was a major enhancement. The addition of a horizontal electrode configuration can better simulate an eject arc condition. Additional adjustments for different enclosure sizes contribute to an even greater accuracy in arc-flash studies.

B. IEC 61482-1-2 (Box Test) and DGUV Guide

What began as a simple pass/fail test for determining if clothing could contribute to the extent of an injury during an arc flash, has evolved into the IEC 61482-1-2 (box test) standard. The box test method uses an ejected arc from a small plaster box to focus the arc energy towards the test specimen. The tests are conducted at 400 volts with a 0.5 second duration. The box test method is used to classify arc rated protection into one of two classes.

Arc Protection Class (APC) 1 is based on an arc derived from a 4000 amp short-circuit current and Arc Protection Class 2 uses a 7000 amps. This means there are only two PPE ratings with this method: APC 1 and APC 2.

Initially, this was referred to as selecting PPE based on Class 1 and Class 2. However, it was pointed out that PPE and Class were too similar to the NFPA 70E terminology of PPE Category [9] – confusion may result. After careful consideration, the term Arc Protection Class was adopted for use by IEC.

Since the box test method constrains the arc to a small surface area, this does not enable the use of a monitor calorimeter to measure the incident energy as can be seen in Fig. 3. Therefore, no arc rating in terms of energy per unit area such as determined with the open arc test, can be obtained.

Fig. 3 – Box Test Apparatus

Since there are no incident energy measurements, a different approach was taken by using arc energy for the selection. The first edition of this test method was published as part of the International Social Security Association (ISSA) guide [10]. Further refinements were made, and the calculation procedure is now known as DGUV Information 203-077 guide. The estimate of the electric arc energy at the workplace in the event of an arc flash is compared with the protection level (equivalent arc energy) of the PPE.

At the present time, there are two official IEC PPE test standards. However, there are no official IEC arc-flash calculation standards to determine the potential thermal energy released in case of an arc flash for the appropriate selection of PPE.

II. EUROPEAN ARC FLASH PERSPECTIVE

The European Council Directive 89/656/EEC Use of Personal Protective Equipment [11] covers the minimum health and safety requirements for the use by workers of PPE at the workplace. Laws in EU countries on the use of PPE in the workplace are all based upon this directive. (Note that the United Kingdom’s PPE regulations, which were reviewed in 2022 are still largely based on Directive 89/656/EEC post leaving the EU). Priority must be given to collective safety measures. PPE can only be used where the existing risks cannot be sufficiently limited by technical means or collective protection or work organization procedures. The employer must also provide the appropriate equipment free of charge and ensure that it is in good working order and hygienic condition [12].

PPE can only be prescribed after the employer has analyzed and assessed the risks which cannot be avoided by other means. For arc flash this means an employer must consider other means of achieving safety prior to considering the use of PPE, such as the elimination of hazard, engineering controls and safe systems of work.

In addition to the above is the Regulation (EU) 2016/425 of the European Parliament and of the Council of 9 March 2016 on Personal Protective Equipment, repealing Council Directive 89/686/EEC [13]. The regulation lays down requirements for the design and manufacture of PPE, which is to be made available on the market, to ensure protection of the health and safety of users and establish rules on the free movement of PPE in the European Union.

A. CE Marking

EU Employers must ensure that any PPE they buy bears a Conformité Européene (CE) mark and complies with Regulation (EU) 2016/425 on personal protective equipment. Not to be confused with the Use of Personal Protective Equipment Directive (89/656/EEC), the regulation lays down requirements for the design and manufacture of PPE, which is to be made available on the market, in order to ensure protection of the health and safety of users and establish rules on the free movement of PPE in the European Union. It requires manufacturers to CE mark their products to show compliance. If an employer uses PPE for providing protection against arc-flash hazards, they should ask for confirmation from the supplier that the PPE certification satisfies the requirements of the PPE Directive.

Following Brexit (the withdrawal of the United Kingdom from the European Union), things are different in the United Kingdom. The UKCA (UK Conformity Assessed) marking is a new UK product marking that is used for goods being placed on the market in Great Britain (England, Wales, and Scotland). It covers most goods which previously required the CE marking. The UKCA mark will not be recognized for products being placed on the EU market.

Even though Northern Ireland is part of the United Kingdom, this is a little more complex. The UKCA marking alone cannot be used for goods placed on the Northern Ireland market, which will require the CE marking or UKNI (United Kingdom Northern Ireland) marking. This is because Northern Ireland shares a land border with the Republic of Ireland, and there is a separate Northern Ireland Protocol which, for as long as it is in force, will align with all relevant EU rules relating to the placing of manufactured goods on the market.

B. Arc-Flash Calculation Methods in Europe

There is good standing for the IEEE 1584 hazard calculations, and they provide an auditable and validated method of severity prediction. From discussions with electrical safety consultants in Europe, it appears to be the main method of arc-flash analysis outside Germany. The Institution of Engineering and Technology (IET), a London based professional engineering organization which has 155,000 members in 148 countries [14], has recently published the fact file called Arc Flash Risk Management. It describes IEEE 1584 as the flagship standard thus: “Predicting the severity of the arc hazard has been made more reliable in recent years through the publication of IEEE 1584 Guide for Performing Arc-Flash Hazard Calculations. It is an auditable standard and widely accepted in the global electrical engineering community.” [15]. On the other hand, the DGUV guide is widely used in Germany and a few other countries, although not globally recognized in the same way as IEEE 1584.

A unique relationship exists between EU legislation and the harmonized standards that are produced by the European Standards Organizations. The regulators which include the EU Parliament, Council of the European union and European Commission define the public safety goals or what the policy will be. Against these goals the European Standards Organizations, which are private and independent including CENELEC, determine how to reach the goals set by the legislation. This is through harmonized European standards which provide the presumption of conformity as described previously. The legislators and the standard makers are therefore very closely aligned and to ignore this fact could be detrimental to future influence and access to the European market.

C. The Relationship Between the European Union and the International Electrotechnical Commission (IEC)

The key to cooperation between the European Union and the International Electrotechnical Commission (IEC) is CENELEC (European Committee for Electrotechnical Standardization or in French “Comité Européen de Normalisation Électrotechnique”). CENELEC is responsible for the technical standardization of electrical engineering for the European Union and many countries outside the EU. It is a requirement that members of CENELEC also need to be members of IEC.

Due to the Frankfurt Agreement, signed in 2016 by the IEC and CENELEC, there is close alignment between these two organizations such that 80% of all CENELEC standards are also IEC standards. With a few exceptions CENELEC will offer all new work to IEC for development. They strive for global standardization first by “mirroring” standards with an aim of creating identical documents. This is to implement EN IEC standards in and throughout Europe. The purpose of the Frankfurt Agreement is to recognize the primacy of international standardization over national or regional standardization through the World Trade Organization Code of Conduct and thus reduce non-tariff barriers to trade. It also reduces work through duplication and accelerates the preparation process for new publications.

To conform with IEC standards gives a presumption of conformity (PoC) with EU law through CE marking and therefore access to a European Market of 600 million consumers using global standards. This follows that standards that are not aligned will not get access to this market.

III. OVERVIEW OF DGUV and IEEE 1584 METHODS

This section provides a detailed comparison of the methodologies described in DGUV-I 203-077 2021 and IEEE Std. 1584™-2018. The required input and output parameters for the arc-flash thermal hazard calculations are systematically compared. The main differences between the two methodologies are presented in this section to allow the reader to make an independent assessment of the appropriate method based on the application requirements. This section discusses the two methods (Worst-case and precise) available in the DGUV guideline and compares them to IEEE 1584.

A. Short-Circuit Standards Requirements

The bolted fault current is a required input to apply IEEE 1584. This current is typically determined using standards such as ANSI C37.010 [16], IEEE Std 551 [17], IEEE Std 3002.3 [18], IEEE Std 242 (IEEE Buff Book) [19], IEEE Std 399 (IEEE Brown Book) [20], and other applicable standards such as Standard IEC 60909-0 2016 [21][22]. The methodology of these standards predicates the use of equivalent subtransient, transient, and steady-state impedance networks of the power system to determine the short-circuit current. IEEE 1584 leaves short-circuit calculations out of the scope of the standard. On the other hand, the DGUV guide is designed exclusively based on Standard IEC 60909-0 [21][22]. According to this standard, maximum and minimum short-circuit currents are to be considered. The maximum short-circuit current (Ik”max), which generally determines the capacity or rating of the electrical equipment, is used for the determination of the final arc energy results in DGUV. The minimum short-circuit current (Ik”min) is used in the DGUV methodology for the determination of the arcing current and exposure time as detailed in Section III.H. For the calculation of the minimum short-circuit current according to [21], inverters, photovoltaic, and wind power station units, typically modeled as constant current sources, are neglected. Therefore, potential current sources which can energize the arc are ignored. Neglecting the contribution of inverter-based resources (IBR) for longer duration faults can lead to incorrect arc-flash thermal energy estimation, especially considering the recent advancements and deployment of IBR with control systems capable of navigating through fault conditions to contribute towards system stability. Another problem with specifying Ik”min to determine the arcing current is that it may not be the lowest current to determine the arc duration (Steady-state short-circuit current Ik is typically lower than Ik”min). In general, short-circuit standards (both ANSI and IEC) were not created to consider arc-flash thermal energy calculations, but instead for system short-circuit protection.

B. Model Voltage Range

IEEE 1584 clearly identifies the voltage range for the empirical equations. The voltage range of the model is 208 Volts to 15 kV, three-phase (line-to-line). This range was established based on over 1800 laboratory test results for five electrode configurations (ECs). On the other hand, DGUV voltage range information is not well defined and may be overstated since the guide does not include any differentiation between the methodologies or equations to determine the energy for medium and high-voltage applications. According to DGUV, the methodology listed in the guide is applicable to work locations with voltages greater than 50 Volts (for both ac and dc) and less than 110 kV for ac systems and 1500 Volts for dc systems.

Based on the laboratory test validated work described in [23] for arc-flash analysis in high-voltage systems, the arc physical behavior can be significantly different when compared to lower voltage arcs mainly due to the longer gap between conductors observed at higher voltage levels. Multiple methodologies are described in [23] for the calculation of thermal energy released in high-voltage AF, however, the thermal energy transfer equations described in DGUV are not applicable for high-voltage applications (in particular above 15 kV). To find the energy in medium and high-voltage systems, the normalized arc power (k_P) must account for the geometry of the arc plasma across longer gaps and the DGUV model does not account for the gap. According to DGUV, the precise method listed within the guide is only applicable for low-voltage systems based on research work detailed in [24].

1) *LV Arc Sustainability*: IEEE 1584 and DGUV recognize the variability of low-voltage electric arcs. According to IEEE 1584, arcs are less likely to sustain in three-phase systems at 240 Volts or less with a bolted fault current less than 2 kA. According to DGUV, thermal hazards due to arc flash are not anticipated when working on equipment rated up to 400 Volts with a total available short-circuit current less than 1 kA. For systems meeting that design criteria, a potential electric arc would “burn unstably and extinguish immediately”.

C. Bolted Fault Current Range

IEEE 1584 clearly defines the short-circuit current range, which varies depending upon the system voltage. For voltages between 208 Volts and 600 Volts, the bolted fault current range is between 0.5 kA and 106 kA. For prefault voltage levels between 601 Volts to 15 kV, the bolted fault current range is 0.2 kA to 65 kA. DGUV-I 203-077 does not define a specific range of prospective short-circuit currents for the applicability of its model. As can be seen in Fig. 4 and based on the test results obtained by IEEE 1584, the relationship between the bolted and arcing short-circuit current is non-linear over a range of prospective short-circuit currents, especially for higher short-circuit currents (> 50 kA), where it can be seen that DGUV methods overpredict the arc current. Therefore, not defining a valid range of bolted fault current for a method can lead to incorrect results outside its valid range (higher arc currents can underpredict the arc duration).

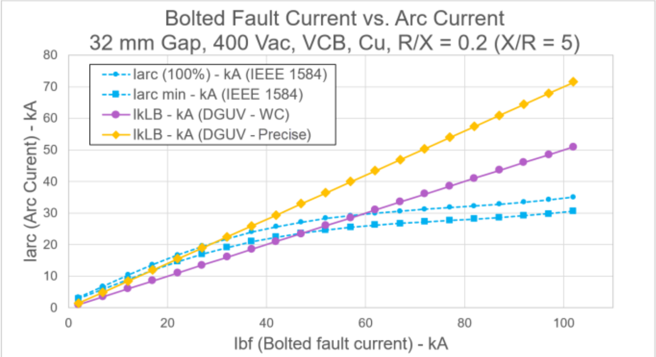

Fig. 4 – Comparison of Bolted Fault Current vs Arcing Current

D. Effect Of Power System X/R Ratio

The relationship between the equivalent system reactance to the resistance plays an important role in the determination of the asymmetrical short-circuit currents in case of an arc fault. The potential asymmetry (DC component) caused by the fault inception angle and the X/R ratio can lead to different response times for the protective devices and ultimately impact the energy results. DGUV accounts for the X/R ratio directly in the determination of the arcing-current limiting factor (k_B) and the normalized arc power (k_P), which ultimately reflect in the arc energy results. In DGUV, the X/R is an actual input parameter to the model unlike IEEE 1584, which includes it indirectly only in the incident energy model.

E. Gap Between Conductors Range

IEEE 1584 specifies a range for the gap between the conductors. For system voltages between 208 Volts and 600 Volts, the gap range is between 6.35 mm and 76.2 mm (0.25 in to 3 in). For higher voltage levels (601 Volts to 15 kV), the gap between conductors scope ranges from 19.05 mm to 254 mm (0.75 in to 10 in). DGUV-I 203-077 does not provide a valid application range for the gap between the conductors. In fact, the electrode gap parameter only has an effect in the precise calculations [24]. The worst-case method completely ignores the gap between the conductors. Gaps in equipment vary widely and their effect on the calculation should not be neglected as previously mentioned in Section III.B.

F. Working Distance Range

The distance between the potential arc source and the face and torso of the worker is defined as the working distance. Energy results calculated through both IEEE 1584 and DGUV are heavily dependent on this parameter.

In terms of working distance range, both standards agree that an upper limit for the working distance might not be applicable. IEEE 1584 establishes the minimum working distance for the model as 12 inches (304.8 mm), and similarly DGUV states that this distance will generally not fall below 300 mm, and that this value can be used as a reference, particularly in low voltage systems.

G. Effect of Electrode Configuration

The arrangement or orientation of electrodes in equipment impacts the physical behavior of the arc. Based on the testing performed during the IEEE 1584 model development, the following common electrode configurations (ECs) may be found in equipment:

- VCB: Vertical conductors in a box.
- VCBB: Vertical conductors in a box terminated with an insulating barrier.
- HCB: Horizontal conductors in a box.
- VOA: Vertical conductors in open air.
- HOA: Horizontal conductors in open air.

DGUV-I 203-077 guide made no mention of ECs or promoted their use until their 2021 edition, where additional details were added for equipment with electrodes positioned and aligned directly towards the electrical worker (i.e., HCB). According to the information found in Appendix 3 of [4], the worst-case method should be used when analyzing this type of work locations. However, DGUV does not account for the lower magnitude of the HCB arc currents.

H. Arcing Current

The prospective arcing current range (typically determined using the maximum and minimum bolted fault current range) is used to obtain the trip time of the protective device which deenergizes the fault. Arcing current determination according to IEEE 1584 Section 6.3 states that a range of arcing current is necessary to estimate the arc duration. The lower range of the bolted fault current can be as low as the steady-state current. Section 4 of the standard provides equations to calculate the arcing current (including arcing current variation). On the other hand, DGUV only considers the minimum initial symmetrical short-circuit current ($I_k"_{min}$) along with the current-limiting factor (k_B) for the calculation of the arcing current as shown in equation (1):

$$I_{arc} = k_B * I^{"}_{k_{min}} \tag{1}$$

The current factor k_B can be a fixed value (worst-case method) or be dependent upon the arc voltage characteristics (precise method). For low-voltage systems using the worst-case method, k_B is to be set to 0.5. IEEE 1584 predicts that the arcing current can be much lower than 50% of the bolted fault current for some electrode configurations. According to [9], the arc current can be as low as 38% of the bolted fault current. Furthermore, the magnitude of $I_k"_{min}$ can be much larger than the steady-state bolted fault current, (referred to as I_{kmin} in [21]), and both of these conditions lead to underestimation of the arc duration.

I. Arc Exposure Duration

As detailed in Section III.H, both standards require the comparison between the arcing current and the time-current characteristic curves (TCC) of the protective devices for the determination of the arc duration. Additionally, the concept of a potential maximum arc exposure time or otherwise known as the two-second rule is also discussed in DGUV. According to DGUV-I 203-077, one second of exposure time can be used to estimate the energy when clearing time cannot be determined from the Overcurrent Protective Devices (OCPDs). Both standards highlight the fact that these recommendations are only applicable for work locations where the electrical worker can physically move away quickly from potential arc source. A person performing a task in a bucket truck or tight cable trenches, or canals may need more time to move away from the hazard.

J. Enclosure Dimensions

According to IEEE 1584, enclosure size is one of the main parameters considered for the determination of the incident energy. The table below shows the dimensions for the enclosures tested across the different voltage levels studied by the standard's working group.

Table I – Typical enclosure dimensions for IEEE 1584 tests

Voltage (V)	**Enclosure dimensions (H x W x D)**	
	SI unit (mm)	**Imperial units (in)**
600	508 x 508 x 508	20 x 20 x 20
2,700	660.4 x 660.4 x 660.4	26 x 26 x 26
14,300	914.4 x 914.4 x 914.4	36 x 36 x 36

Based on test data available, the following limits apply to the model:

- The maximum height or width is 1244.6 mm (49 in).
- The maximum opening area is 1.549 m^2 (2401 in^2).
- The enclosure width should be larger than four times the gap between the conductors.

A correction factor for the enclosure size is determined to account for variations in the equipment dimensions and its effect on the incident energy results. Variations in the enclosure dimensions (i.e., height, width, and depth) directly influence the physical behavior of the plasma cloud and amount of thermal energy released in case of an arc flash. Enclosure size correction factor defined in IEEE 1584 takes those parameters into account for the estimation of the incident energy at the specified working distance. As can be seen in Fig. 5, equipment with different enclosure dimensions have significant differences in terms of arc reflectivity (e.g., shallow enclosures would reflect less energy).

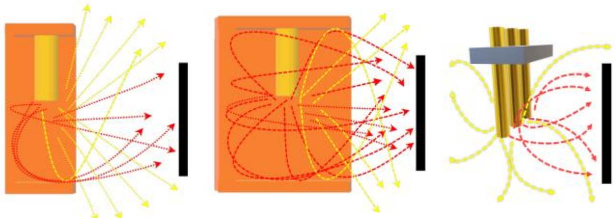
(a) (b) (c)

Fig. 5 – Enclosure effect for the thermal energy calculations in IEEE 1584

Similarly, DGUV also considers the spatial propagation of the energy according to the geometric characteristics (i.e., dimensions) of the equipment enclosure through the transmission factor (k_T). This parameter represents the effect of the enclosure dimensions on the PPE's protection level which is ultimately compared against the arc energy to determine the PPE appropriateness. Reference values of k_T range from 1 to 2.4 for modeling of any type of equipment (from enclosed equipment with low volume to open air, respectively), as can be seen in Fig. 6.

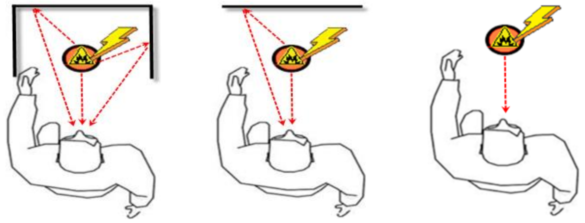
k_T = 1 k_T = 1.5 – 1.9 k_T = 2.4

Fig. 6 – DGUV transmission factor typical values.

K. Energy Determination

The purpose of IEEE 1584 is to provide a guideline for the determination of the incident energy to which employees may be exposed in case of an arc flash while performing operations or maintenance tasks. DGUV-I 203-077, on the other hand, focuses on providing guidance for the selection of PPE based on the determination of the arc energy (WLB) and its comparison against the protection level afforded by the PPE.

Two different methods are mentioned in the guideline: worst-case (WC) and precise calculations. However, it should be noted that the precise method calculation details and equations are not included in the document.

L. Arc-Flash Boundary

DGUV-I 203-077, does not recognize or define an arc-flash boundary (AFB). This is an important parameter to determine interaction with the equipment. IEEE 1584 provides the methodology for the calculation of the AFB at an energy threshold of 1.2 cal/cm^2, which represents the likely onset of a second degree burn.

M. DC Systems

Arc-flash incident energy calculations for dc systems are not part of the scope of IEEE 1584 but recommendations about other references that can be used are provided in Section 4.12. Such references recommend methods that are similar to those listed in NFPA 70E Annex D.5. On the other hand, DGUV provides two calculations methods for dc systems (i.e., worst-case, and iterative). Unlike the ac AF calculation equations, the DGUV dc AF iterative calculation method equations are very similar those mentioned in NFPA 70E 2024 [25][26] and IEEE 1584 with the exception of two constant values. Equation (2) represents the arc voltage calculation according to Stokes and Oppenlander model [26], where "*d*" is the length of the gap between conductors.

$$V_{arc} = (\mathbf{20} + \mathbf{0.534} * d) * {I_{arc}}^{0.12} \tag{2}$$

Similarly, equation (3) is the arc voltage calculation from DGUV guideline.

$$V_{arc} = (\mathbf{34} + \mathbf{0.532} * d) * {I_{arc}}^{0.12} \tag{3}$$

IV. COMPARATIVE ANALYSIS RESULTS

This section provides a summary of comparisons between DGUV, and IEEE 1584 IE results obtained using commercially available power system analysis software. Five locations were selected for this comparison from the DGUV-I 203-077 examples (work locations 1, 2, 3, 6, 7). The comparisons focus on the arc current, arc duration determination, and equivalent incident energy. The Wilkin's IE reflectivity method, which was developed based on IEEE Std. 1584™-2002 tests [27], is employed for the determination of the equivalent incident energy derived from the arc energy of the DGUV method to compare similar output results.

A. Case Study System Overview

The power system used to compare the results from both standards is described in Annex 5 of [4]. All the location examples are for low-voltage equipment (400 Volts) as part of a thermal hazard analysis for a municipal power distribution system. Fig. 7 shows a high-level diagram of the power system and some of the work locations to be used in this comparative analysis.

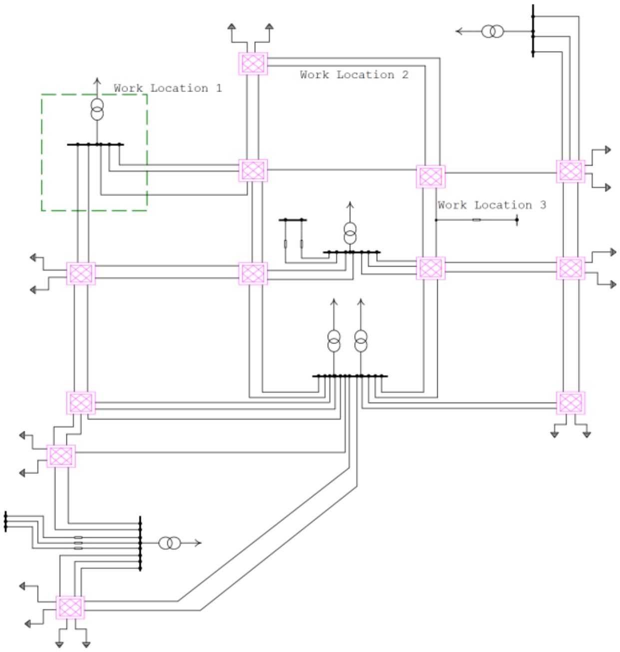

Fig. 7 – One-Line for Municipal Low-Voltage System

B. Work Location Input Parameters

This section provides a summary of the input parameters of the work locations studied. Electrode configurations "VCB" and "HCB" were used for all work locations to obtain a range of incident energy from the IEEE 1584 model. Typical values of a LV switchgear with dimensions of 508mm x 508mm x 508mm (20in x 20in x 20in) were used for the Wilkin's reflectivity factors (a = 400 & k = 0.312). Such dimensions are the closest to the ones used in the Box Test method which is employed to rate the PPE used along with DGUV guidelines. Table II below provides further details on the input parameters for the calculations.

Table II – Input parameters

Locations	Gap (mm)	WD (mm)	kT	R/X
Work Location 1	60	300	1.5	0.27
Work Location 2	45	300	1.9	1.3
Work Location 3	45	300	1	2
Work Location 6	20	300	1.5	0.81
Work Location 7	20	600	1.9	0.12

C. Software Output Result Validation

The application of DGUV calculation methods was validated before comparisons were made to ensure that the software tool applied the methodology correctly. A comparison was performed to validate the software results against the results published in the DGUV guide using a fixed arc duration as specified in the standard. The arc duration from the examples in the DGUV document were used directly as an input to the software to ensure that the arc current and energy models produced the same results.

Fig. 8 and 9, show the software arc energy (WLB) results calculated for both worst-case and precise methods respectively compared against the results published in DGUV. The differences are negligible, which means that the software produced acceptable results for the next level of comparison.

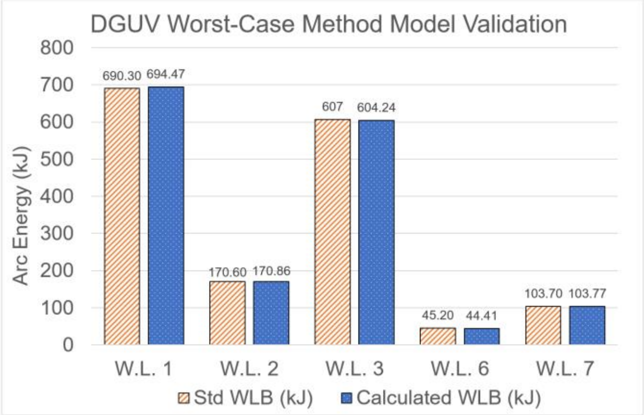

Fig. 8 – Model validation for DGUV Worst-Case

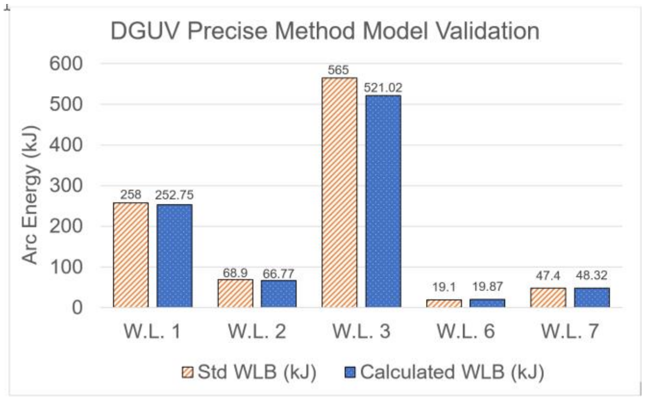

Fig. 9 – Model validation for DGUV Precise calculations

Due to inconsistencies observed in the fault clearing time determination in the examples from DGUV guideline, the comparative analysis in the following sections was performed based on the response time obtained automatically from protective devices with similar time-current characteristics available in the power system analysis software.

D. *Arcing Current Comparison Results*

This section provides a summary of the comparisons between arcing current results from IEEE 1584 and DGUV (Worst-Case and Precise methods). Fig. 10 shows the results from both standards compared to the bolted fault current (Ibf) obtained as a result from the system characteristics and configuration. As can be seen below, the DGUV worst-case method consistently yields lower values of arcing current due to its assumption for LV systems where the arcing-current limiting factor (k_B) is fixed at 0.5. For the precise method, the arcing currents for most of the cases resulted lower than IEEE 1584, except for Work Location 7 (W.L. 7) where the gap and the high X/R caused the arcing current result to be higher.

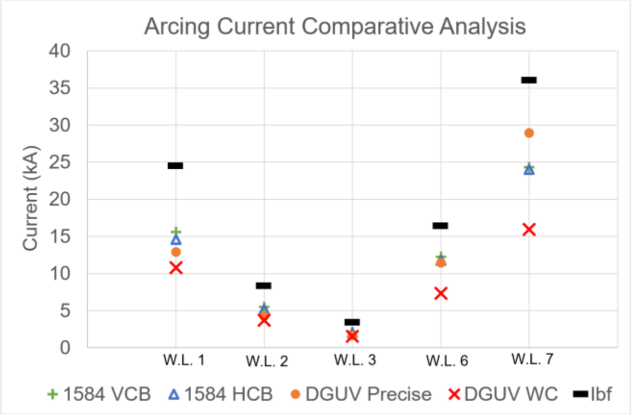

Fig. 10 – Arc Current Comparative Analysis

E. *Incident Energy Comparison Results*

This section provides a summary of the comparisons between the incident energy results from IEEE 1584 and DGUV (Worst-Case and Precise methods) standards. As mentioned, Wilkin's reflectivity method was employed for the determination of the incident energy from the arc energy results obtained for DGUV. Fig. 11 shows the estimated incident energy results for both standards.

Based on the DGUV guidelines, calculations for equipment with electrode configurations such as "HCB" are to be performed based on the WC methodology. Therefore, DGUV WC results are compared against IEEE 1584 HCB. For DGUV precise calculations, no specific electrode configuration is recommended, therefore, VCB was used for the comparison against IEEE 1584.

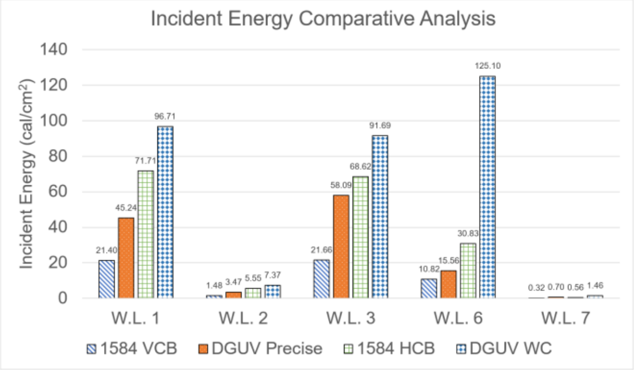

Fig. 11 – Incident Energy Comparative Analysis

Furthermore, Fig. 11 shows that the equivalent incident energy obtained from DGUV WC method results are at least 30% to 200% higher when compared to IEEE 1584 HCB. On the other hand, DGUV precise calculations are between 50% to 100% higher than the IEEE 1584 VCB results. Based on the simulations it can be observed that the incident energy estimated using the DGUV WC method can be significantly higher than the one obtained using IEEE 1584 HCB. However, further analysis is needed to validate this observation which is based only on the small number of examples published in the DGUV guide.

V. CONCLUSIONS

Currently, two PPE test methods coexist as mutually exclusive IEC standards which require two different calculation methods. IEEE 1584 is used for calculating the incident energy when determining the PPE rating based on the open arc test method. DGUV-I 203-077 is used for calculating the arc energy for selecting PPE tested according to the box test method.

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VII. VITAE

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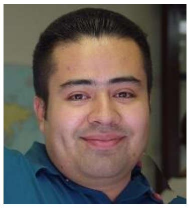

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