

The Art and Science of Arc-Flash Studies: Navigating the Nuances of AC and DC Arc Flash

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Abstract – Arc flash and arc blast are critical safety concerns when working with electrical equipment. Standards such as NFPA 70E 2024 and IEEE Std 1584-2018 provide methodologies for evaluating arc-flash hazards, guiding engineers in assessing the risks associated with live work and determining when such work must be prohibited. As systems and calculation tools become more complicated, understanding which model input parameters are most critical in calculations can sometimes be lost. Conducting an arc-flash study is akin to adjusting a panel of dials—some dials have a significant impact on the results, while others are less influential. This paper describes the input parameters, or dials, of different calculation methods and compares the results of different standards under similar circumstances. Ultimately, accurate arc-flash analysis requires both a solid grasp of foundational standards (the science) and the application of engineering judgment (the art) in applying models correctly, particularly in atypical scenarios or when data are incomplete. The final section of the paper focuses on practical mitigation strategies to reduce arc-flash risks, with prohibiting live work as the primary and most effective approach.

Index Terms — Arc flash, arc blast, incident energy, NFPA 70E, IEEE 1584-2018, dead work, electrical safety, arc-flash study

I. INTRODUCTION

IEEE Std 1584-2018, *IEEE Guide for Performing Arc-Flash Hazard Calculations*, defines an arc flash as “an electric arc event with thermal energy dissipated as radiant, convective, and conductive heat” [1]. Arc-flash events may occur during circuit breaker (CB) racking, accidental tool drops, equipment failure, environmental buildup, or other interactions with electrical systems. Arc flash is measured using incident energy (E_i).

Incident energy is measured in calories per square centimeter (cal/cm^2). An incident energy of $1.2 \text{ cal}/\text{cm}^2$ is likely to cause the onset of a second-degree burn. If a butane lighter is held 1 cm away from a person’s finger for 1 s and the finger is in the blue flame, 1 cm^2 area of the finger is exposed to about $1.2 \text{ cal}/\text{cm}^2$. [1]

The arc-flash boundary is the distance from exposed live parts at which a person could receive a second-degree burn if an

electrical flash were to occur. Arc-flash studies are performed to determine E_i levels, required personal protective equipment (PPE), and safe working distances at each location to mitigate risk and prevent injuries. The work of Dr. Ralph Lee established a relationship between time, E_i or temperature, and human tissue cell death, providing a basis for estimating curable skin burn time-temperature relationships [2]. This research increased awareness of arc flash as an electrical hazard, in addition to electric shock.

Arc-flash calculation methods can be either theoretically or empirically derived, and they apply to either ac or dc systems. Each of these methods is defined by bounds wherein the calculations are deemed reasonable. While empirically derived methods may not appear to follow the same equation structure as theoretical models (often being more complex), the primary factors that contribute to arc-flash hazards remain the same.

Numerous arc-flash calculation methods have been developed, with the most recent and comprehensive being IEEE 1584-2018, which is based on extensive testing of voltages between 208 and 15 000 V. However, for systems outside the scope of IEEE 1584, such as direct current (dc) systems, single-phase alternating current (ac), or values that exceed the bounds set for the IEEE 1584-2018 model, alternative methods must be used. These methods include both empirically derived approaches and theoretical models, each with defined bounds and limitations in real-world scenarios. In addition to these E_i calculation methods, NFPA 70E also describes alternative methods for estimating arc-flash risk both in terms of E_i as well as PPE level for ac and dc systems.

In addition to shock and arc flash, arc blast is also a major concern that is not accounted for in E_i calculations. An arc blast is the pressure wave created from an arc-fault event, resulting from expanding gases and vaporized materials that can cause physical harm. For equipment that is not arc-resistant, this blast pressure can build up behind the door and shear the mounting hardware, ejecting the door at the worker. Although there are no commonly accepted methods of calculating this risk, [3] provides an overview of preliminary models and laboratory testing.

This paper examines variations among commonly used arc-flash calculation methods, as well as variations in parameters within each method. Understanding these differences enables engineers to have better judgment when data are unavailable, unreliable, or fall outside the bounds of accepted models.

As arc flash-related incidents continue to cause injury and death in the workplace—due to a lack of training or understanding, incorrect arc-flash calculations, complacency,

noncompliance with PPE, or working distances—it is critical to better understand arc-flash risks and mitigate those hazards. As systems and models become more complex with an increasing number of parameters, it is critical that the most important parameters are understood and applied to arc-flash calculations.

II. OVERVIEW OF AC CALCULATION METHODS

There are many guides for performing arc-flash studies that detail how to gather data, apply IEEE Std 1584-2018 to different system configurations, and organize an arc-flash report [1] [4] [5] [6]. These references give both a high-level overview of arc-flash risk assessment and an in-depth analysis of how to apply this standard to specific scenarios.

Simplified theoretical methods such as the Ralph Lee method for ac systems [2] or the Doan maximum power method for dc systems [7] can help to understand the basic elements of an E_i calculation but may not be as accurate as other more complex methods. Generally, these methods are considered conservative and are best used for preliminary ranges or rough estimates, rather than for final study values. Care must be taken to focus on the criteria that most significantly impact calculation results. Lower-than-realistic calculations can expose workers to E_i higher than PPE ratings, leading to increased injury or death. Higher-than-realistic calculations, or overly conservative assumptions, can put workers at additional risk of heat exhaustion or limited dexterity due to the bulk of the additional required PPE.

In addition to this, many modeling software programs offer multiple calculation methodologies, even though the instruction manuals state that these methods are not accurate for many cases. This can lead engineers to have overconfidence in inaccurate methods or models. The engineer may also attempt to apply more accurate models to cases where those models have not been validated, thus producing inaccurate results.

The main areas where calculation methods differ are on arcing current levels compared to bolted-fault current levels, as well as how the arc energy is dissipated out toward the worker. Each of these methods follows the general rule of (1), which is adapted from the Lee equation, seen in (2), [2] and the Doan equation, seen in (3) [7]. These can be helpful to understand the common elements used in arc-flash calculations for ac and dc systems. More complex, nonlinear formulas are better able to model the effect of arc flash at higher voltages, where gap, arc resistance, and arc current play a much larger role than voltage, as discussed in Section II.D.

$$E = K \cdot P_{arc} \cdot \frac{T}{D^x} \quad (1)$$

where

K, X	correction factors
P_{arc}	power radiated from the arc (method of calculation varies based on method used)
T	arc time (s)
D	distance from the arc (cm)

An understanding of the basic elements of arc-flash energy calculations is essential for understanding more complicated and accurate methods, such as the interpolation methods used by IEEE 1584-2018, as well as iterative methods, nonlinear calculation methods, or statistical regression analysis. While these methods can calculate more accurate results than the simplified equation shown in (1), they require more data about

the system configuration, which is often difficult, if not impossible, to obtain. As a result, these more complex models can become less accurate due to misapplication of the intended use of the model or unsound assumptions about model data inputs. It is important to understand the contributing factors of an arc-flash calculation model to know which types of assumptions cause errors that would result in a significant error in the arc-flash calculations.

For example, studies performed by the authors show that it is far more important for a model to use accurate arcing current values and correctly modeled overcurrent protective devices (OCPDs) than it is to get the exact gap between electrodes or enclosure dimensions. However, this may not be true for low-voltage (LV) systems, where the gap and voltage can significantly affect the arc current and resulting E_i . Even with perfect data, arc-flash calculations are intended to present worst-case values, and when compared to actual events, will produce varied results. In addition to these differences, arc-flash E_i calculations can vary at locations where multiple sources are feeding a single location, as this can affect both the arcing current as well as the arc duration. In some cases, these interactions can cause nonlinear behavior in these variables over the duration of the arc event. Voltage level and arc length can also play a role in how long the arc can persist even if no protection device clears the fault.

The empirical E_i equations in IEEE 1584-2018 are the preferred method for E_i calculation in three-phase ac systems between 0.208 and 15 kV. The Lee method is not recommended for use; however, it is included in this paper to illustrate the types of inaccuracies in method selection that warrant attention. In addition to these methods, NFPA 70E also offers Table 130.7(C)(15)(a) [8], often referred to as the table method. This method has very little correlation to IEEE 1584-2018 and can be dangerously erroneous [9].

A. Lee Method

The Lee method in (2), which was adapted from [2], is the most referenced theoretically derived arc-flash E_i calculation method for ac systems. Power system software may still refer to this method when parameters, such as voltage, exceed the bounds of IEEE standards but it has been found to be highly conservative, especially for cases above 1000 V.

$$E_{Lee} = 2.124 \cdot 10^6 \cdot V_{sys} \cdot I_{bf} \cdot \frac{T}{D^2} \quad (2)$$

where

E_{Lee}	E_i (J/cm ²)
V_{sys}	system voltage (kV)
T	arcing time (s)
D	distance from possible arc point to person (mm)
I_{bf}	bolted-fault current (kA)

B. IEEE 1584-2002

The IEEE 1584-2002 standard improved on the Lee method by providing an empirically derived model with correction factors for voltage, open-air versus box configurations, and variable arcing current. This model is applicable for three-phase ac systems operating at 208 V–15 kV, but the standard has since been superseded by the 2018 version.

C. IEEE 1584-2018

Compared to the 2002 edition of the standard, the 2018 standard considers additional configurations and test results and introduces

a two-step process in which intermediate values of average arc current, E , and arc-flash boundary are interpolated to determine final values. Correction factors for enclosure (box) size and arc current variation are applied to adjust the results. [1]

This model is applicable for three-phase line-to-line voltages of 208 V–15 kV, 50–60 Hz ac systems, for commonly sized enclosures at working distances greater than or equal to 304.8 mm (12 in). The electrode gap and bolted-fault current ranges are split by voltage range. For 208–600 V, the range is 500 A–106 kA with electrode gaps of 6.35–76.2 mm (0.25–3 in). For 601 V–15 kV, the range is 200 A–65 kA with electrode gaps of 19.05–254 mm (0.75–10 in). At lower voltage levels, arc sustainability becomes less certain; accordingly, “sustainable arcs are possible but less likely in three-phase systems operating at 240 V nominal or less with an available short-circuit current less than 2000 A” [1].

In addition to introducing more complex equations, this model introduces additional electrode configurations, which can have a large impact on the simulation results, as described in Section III.D. For reference, those configurations are:

- HCB: Horizontal electrodes in a metal enclosure
- VCB: Vertical electrodes terminated in an insulating barrier inside a metal enclosure
- VCB: Vertical electrodes in a metal enclosure
- HOA: Horizontal electrodes in open air
- VOA: Vertical electrodes in open air

The IEEE 1584-2018 method uses polynomial fit equations that do not attempt to behave logically outside the intended range of the model. Fig. 1 compares the 2018 version and the Lee method, showing the variation in E_i for the different electrode configurations while keeping other factors consistent.

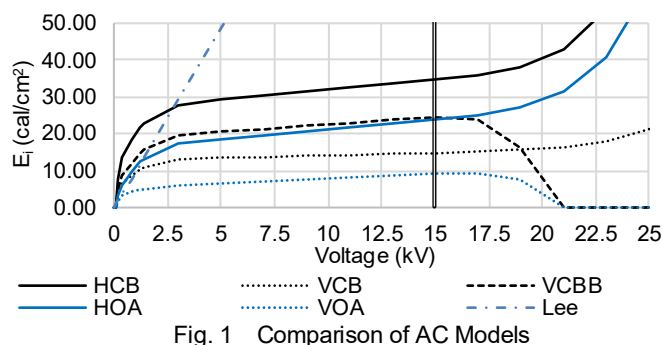


Fig. 1 Comparison of AC Models

Fig. 1 also shows how the IEEE calculations diverge when exceeding the 15 kV voltage boundaries defined in the standard as well as how overly conservative the Lee method can be for higher voltages. With E_i calculation variation of 2–5 times between electrode configurations, this is a critical parameter when applying IEEE 1584-2018. This and other IEEE 1584

calculations were performed using the IEEE DataPort calculator [10], with standardized assumptions of a 480 V VCB, 20 kA bolted-fault current, 200 ms arc time, a 45.7 cm (18 in) working distance, 50.8 cm x 50.8 cm (20 in x 20 in) enclosure dimensions, and a 5 cm (2 in) electrode gap, unless otherwise specified.

D. High-Voltage (HV) Applications

Some arc-flash software packages have the option to apply the Lee method for voltages above 15 kV; however, as illustrated in Fig. 1, this approach will produce highly conservative results. Rather than continuing to apply the Lee method for these cases, it would be more prudent to follow the calculations and guidelines of [11], which are specifically targeted at higher-voltage arc-flash calculations. Reference [11] also provides a comparison of the “EPRI, Terzija/K, theoretically derived Lee (included for illustrative purposes), the Duke Heat Flux Calculator, and ArcPro V3.0” models.

III. AC MODEL PARAMETER VARIATIONS

It is often not possible to perfectly model a system due to inaccurate or limited data, time constraints, modeling software limitations, or errors in the calculation method used. While IEEE and many others have developed the science of arc-flash calculations, it is the responsibility of the engineer to know how to apply these methods in real-world conditions where data are limited and a simple checkbox in a software cannot fully account for system conditions. There are some general rules that apply to all types of arc-flash events regardless of which standard or method is used.

A. Fault Current and Clearing Times

Using fault values based on transient or subtransient reactance values can lead to overly conservative calculations. It is recommended to use the value that most closely corresponds to the operation times of the OCPD and the potential of the system. This can be challenging as fault current is not linear with time. Using a stiff subtransient fault value and the maximum time of two seconds at a location next to a generator, where current magnitude often drops more quickly with time, will result in overconservative E_i calculations.

E_i is directly related to the amount of current and arc time as shown in (1). Arcing current does not have a linear relationship to the bolted-fault current, as shown in Fig. 2. The arcing current will be lower than the bolted-fault current due to the arc creating fault resistance. Because an OCPD may operate more slowly at lower currents, the time before the fault clears will be longer for these lower-fault cases.

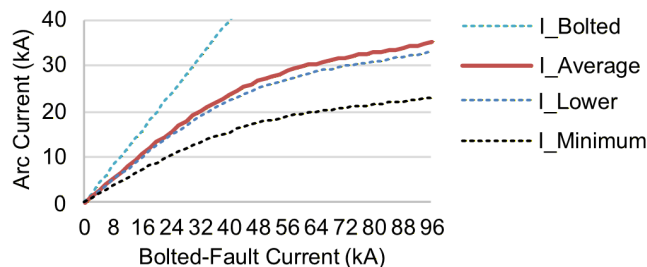


Fig. 2 Arc Current Versus Bolted-Fault Current

This can result in what is often referred to as the arc-flash paradox: lower-fault values can result in larger E_i due to slower protection operation times. This paradox is a serious concern and is most obvious when a protection device transitions from instantaneous overcurrent to a time-overcurrent operation, causing a much larger tripping time with only a slightly reduced fault current. This behavior can lead to higher E_i for faults at the end of a cable compared with those closer to the source, as well as in cases where reduced arc current is caused by larger electrode gaps. Similarly, in islanded systems, minimum-generation cases can have larger E_i than maximum-generation cases. It is critical to understand how the models and software account for these variations. Fig. 3 illustrates this paradox using a typical U3 curve with an instantaneous element; however, the actual relationship will depend on the curve type, pickups, and time-dial settings. It is recommended to evaluate the OCPD operation times and E_i at the maximum and minimum arc-current values and to use the most conservative option. Many arc-flash calculation software applications allow comparison of these values. Overstated current or understated gap values can lead to results that underestimate the risk, especially for LV equipment.

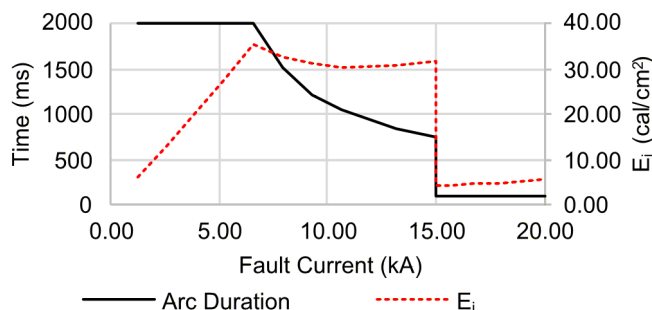


Fig. 3 Arc-Flash Paradox

The selection of the protection device used to determine arc-flash time is also important. If the protection device or CB is in the same location as the arc (i.e., not isolated), it cannot be included in the arc-time calculation, as the CB could be consumed or fail to clear the fault [1]. Software applications have an option to exclude the main CB for these cases when the clearing time must depend on the closest active upstream OCPD. To accurately calculate the arcing time, the analysis must account for coordination intervals, relay operating time for differential or arc detection, communication or lockout relay delays to trip the upstream device, and CB interrupting times.

If an arc-flash point sensor is connected to a relay in the same CB enclosure, there must be a signal sent to the upstream CB to clear the fault. Faults on the source side of the CB while racking in can cause an arc, but opening the faulted CB will not clear the fault. The upstream device that is physically isolated from the fault location would be relied on to clear the fault. Transformer differential trip times can be used for low-side CB faults only if the CB is within the differential zone and the trip clears the high-side breakers. Similar considerations must be made for LV switchgear, motor control centers, or other panels where a protection device may be consumed in an arc event, in which case the upstream breaker trip time must be used.

Another important factor to consider regarding time and current is for low-side transformer faults. The upstream device is often set to be less sensitive due to coordination and transformer

inrush requirements. Any location with high current and long tripping times will result in high E_i . Any work on the low side of a transformer with a secondary voltage above 480 V that is not within a differential protection zone will likely be dangerous.

Generally, a two-second maximum clearing time guideline is applied to all time calculations, as it is assumed that workers would be able to move away from the arc within that time frame, if the arc blast does not knock them away before then. This generally applied rule should be evaluated for cases of limited mobility or constricted areas, such as confined spaces, work from platforms, or any other space that may constrain the worker from moving away within the two-second time. This maximum time and the effect on E_i are shown in Fig. 3.

B. Voltage, Electrode Gap, and Arc Persistence

In addition to OCPD tripping times, voltage and electrode gaps contribute to both the arcing current and resistance, as well as the time of the arc. Systems with a combination of higher voltages, high fault current, VCBB configuration, and smaller electrode gaps are more likely to sustain an arc for longer periods of time. Testing has found 480 V to be “at some physical threshold of arc sustainability, most likely linked to the degree of vaporization of the copper electrodes” [12]. For these cases, the arc will usually persist long enough to rely on OCPD tripping times rather than the arc self-extinguishing.

Arc-flash E_i generally increases as the arc gap increases due to larger arc exposure, an effect that is most impactful in LV equipment. As the arc length increases, the arc resistance will increase, causing the arc current to decrease; this could also slow down OCPD times. As it is dangerous to measure live electrode gaps and equipment outages can be difficult to obtain, using the larger of the estimated electrode gaps will produce a more conservative result [6]. This is limited at a point by the persistence of arcs at lower voltages or larger-than-usual electrode gaps when there is not enough voltage and current to sustain an arc over a given arc length, as shown in Fig. 4 and Fig. 8 (for dc equivalent). The minimum arc length will be equal to the electrode gap, but magnetic or other forces can cause the arc to elongate [13]. For cases where the electrode gap is larger than the range of the standard, IEEE 1584 cannot be applied directly.

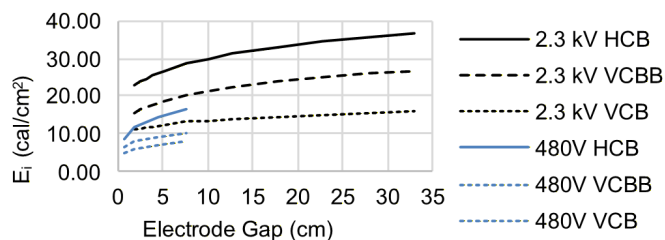


Fig. 4 Arc Gap Versus E_i

C. Working Distances

Working distance plays a critical role in how much E_i a worker may be exposed to. Often a distance of 45.72 cm (18 in) is used for LV equipment, as this is the typical distance between the electrodes and the body of a worker. For medium-voltage (MV) equipment, larger working distances are used on the assumption that workers will be using longer tools, such as a hot stick, when

working on this equipment. The IEEE 1584-2018 model only provides results for working distances greater than or equal to 30.48 cm (12 in). Any part of the body that is closer to the arc point than the posted working distance will be subjected to exponentially larger E_i exposure. There has not been a significant amount of research as to the E_i within the 12-inch limit but estimates from the IEEE 1584 model for these lower ranges (although outside of the range of this model) are shown in Fig. 5. It is critical that when applying working distances, these are posted and understood, as well as ensuring that there are policies and practices in place that prevent these working distances from being breached by the face and chest of the worker.

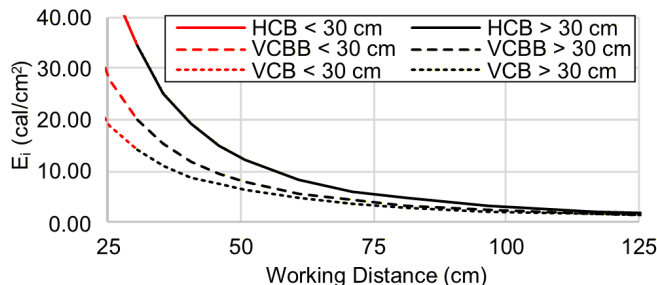


Fig. 5 Working Distance Versus E_i

D. Electrode Configuration

One of the main changes to the new IEEE 1584-2018 standard was the addition of electrode configurations as identified in Fig. 1. For a more detailed discussion and comparison of these configurations, including their relative E_i levels, see [5] and [14]. See [6] for more detail on how these configurations appear in actual equipment, including images showing how a single location can contain multiple configurations. Reference [6] also goes into more detail on common configurations and when the use of each type is most practical, providing detail in comparing the E_i of each one.

In general, arcs tend to follow the path of the conductors toward their end or a barrier blocking their trajectory. Conductors in a box will have larger E_i than those in open air, as the hot gas and plasma will be directed at the person when coming from an enclosed space as opposed to being able to radiate out in all directions. Horizontal configurations, such as CB stabs, will direct the arc outward at the worker. For conductors in a box, the VCB configuration has the lowest E_i , followed by VCBB, with HCB producing the highest E_i and is the most conservative option.

Panels or LV equipment with molded case CBs are usually a VCB or VCBB configuration, as the horizontal electrodes are covered. For CBs that can be racked out, this can lead to exposed stabs when covers are not in place, resulting in an HCB configuration. Any location where a worker is exposed to horizontal electrodes, such as busbars, stabs, or other protrusions should be considered an HCB configuration. Often, a conducting tool may temporarily change this configuration but will likely be ejected away from the arc and not contribute to E_i results over time. Small gauge wire or electrical parts may also evaporate in the arc and change the configuration, resulting in varied actual results when compared to calculations.

These configurations will have less of an effect on the total E_i as the working distance increases, allowing the arc energy to dissipate more. As the electrode configuration for IEEE 1584-

2018 can have a significant impact on total E_i results, care must be taken to evaluate how workers will interact with the energized locations to determine which configuration to use.

E. Cubicle Dimensions

The final consideration for arc flash has a modest effect on total E_i . "The enclosure size and depth correction factor was implemented [using] incident energy as a function of opening width" [1]. This has the largest E_i at opening areas of 2581 cm² or 50.8 cm x 50.8 cm as shown in Fig. 6, comparing the different configurations as well. As the opening widens, it allows the arc to dissipate more, rather than being projected at the worker, and as it gets smaller, the enclosed space restricts the dispersion of the arc. Panelboards and other LV equipment may be deemed as shallow per IEEE 1584-2018 guidelines and may further reduce the E_i seen. Any arc in a box will force the energy out toward the worker and will require some kind of correction factor of around 1.6–2.2 when compared to open-air applications or open-air models. This also applies to dc methods, as described later.

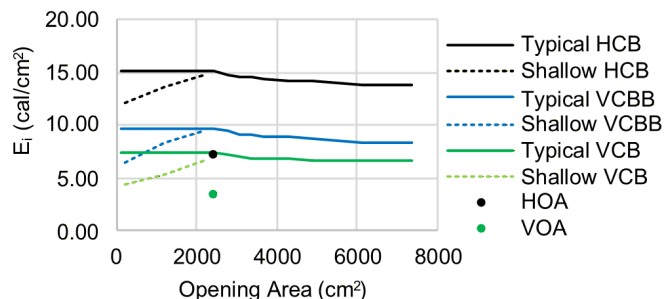


Fig. 6 Box Opening Versus Open Air

IV. DC MODELS

As with ac arc flash, dc arc flash exhibits significant variation in how arc current relates to voltage, current, and electrode gap. In addition, there are many types of dc sources, such as batteries, photovoltaic (PV) arrays, dc-dc converters, and rectifiers. Each of these require special consideration as described in [15] and [16]. These sources affect the fault current, arc duration, and voltage shutdown times. Proximity to these sources and the location of the OCPDs are also major factors to consider.

References [15] and [17] provide more detail about the various dc arc-flash methods and a comparison between them. There has not been as much testing done on dc systems compared to three-phase ac systems, but the most used methods for calculating the dc arc-flash hazard are Doan's maximum power, Paukert, and Stokes and Oppenlander (S&O) methods [18]. In general, dc does not exhibit a zero crossing like ac does; therefore, ac-based models cannot be applied directly to dc systems. For high-current dc systems, such as those fed from batteries, electrode erosion can play a significant role in arc gap if the configuration is such that erosion of the electrodes results in a widened electrode gap.

Doan's maximum power equation, similar to the Lee method for ac systems, assumes total conversion of electrical arc energy at the maximum power transfer point into thermal energy. This energy is modeled as being radiated uniformly outward in a

spherical manner. It does not account for nonlinear arc current, electrode configurations, or electrode gap distance. NFPA 70E has recommended that this equation be multiplied by a safety factor of as much as three to account for arcs in a box versus arcs in open air because arcs in a box are directed at the worker. This model does not have specific bounds as it is theoretical. In a similar manner to the Lee equation mentioned earlier, values are known to be overly conservative when compared to live tests. Specifically, “repeated testing by multiple companies over the years has shown that it overestimates arc-flash energy by a factor of at least 2–10, especially at lower voltages” [18], even without applying the factor of three when compared to arc-in-a-box tests.

While this method is known to be overly conservative, it can be a useful quick calculation to eliminate areas that do not have a significant risk. If a location is found to have a high E_i using the maximum power method, a more detailed engineering analysis using a more accurate calculation model should be performed. The version of the maximum power method for dc arc-flash E_i used by NFPA 70E Annex D [8] is shown in (3), which can be correlated from equation (1).

$$E_{MaxPower} = 0.01 \cdot V_{sys} \cdot 0.5 I_{bf} \cdot \frac{T_{arc}}{D^2} \quad (3)$$

where

$E_{MaxPower}$	E_i (cal/cm ²)
V_{sys}	System voltage (V)
I_{bf}	Bolted-fault current (A)
T_{arc}	Arc time (s)
D	Working distance (cm)

For voltages lower than 465 V, [18] proposes using a modified time estimation that accounts for the lack of arc persistence at lower voltages rather than relying on the two-second rule. However, this approach does not account for arc initiation methods, sources not directly fed from a battery, or variations in electrode gaps and configurations. Because arc-flash calculations must represent a worst-case scenario, simply modifying the theoretical maximum power method may be insufficient for accurate analysis. It is more important to accurately model the system impedances and OCPD trip times associated with both the bolted-fault and arc-current values.

The Paukert and S&O methods are empirically derived formulas “based on arc resistance...It was concluded that their models generally agreed with each other; however, they did have some deviation especially for larger gap distances up to 20 cm” [9]. They both require an initial guess and iterative equation solving to produce results. If the arcing current is too low relative to voltage, these equations do not converge [18]. These three methods were compared to laboratory testing at 130 Vdc, as shown in Fig. 7, which is adapted from Figure 2 of [17].

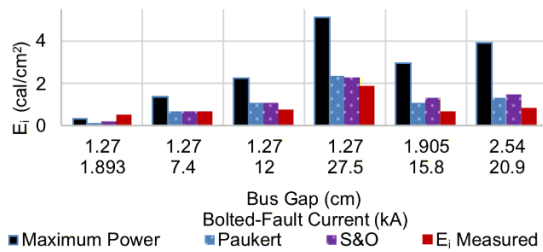


Fig. 7 Laboratory Tests Compared at 130 Vdc [17]

If access to the Paukert or S&O method is available within a power system software, they are the preferred methods because they are currently the most accurate without additional extensive laboratory testing similar to IEEE 1584. All dc arc-flash calculation equations use fixed current values, and similar to ac systems, arc current is not linear with time. Arc-flash E_i is also not linearly related to voltage.

Any dc arc-flash study above 1000 V is outside of the bounds of currently established models. Based on ac testing, it may be inferred that dc arc-flash E_i above 1000 V will likely follow a pattern similar to that observed when comparing the IEEE 1584-2018 method to the Lee method for ac systems, as shown in Fig. 1, leading the maximum power equation to become highly conservative. However, the exact nature of this relationship is unknown and would require further testing for specific dc sources, as the contribution of a battery versus a dc-dc converter will have different fault current characteristics [15]. HV dc arc-flash methods similar to those mentioned in Section II.D can be used to investigate long-arc or HV cases.

The S&O or Paukert methods can usually get close for typical cases; however, for electrode gaps larger than 20 cm (7.9 in), high-current electrode erosion, or atypical cases, additional analysis may be required. As these iterative methods are more challenging to implement into standards, such as NFPA 70E, the maximum power equation can still be used for quick, conservative estimations but should not be the sole source calculation requiring workers to wear excessive PPE, as many dc locations under 300 V often have smaller E_i values. Further analysis using more accurate models would result in more reasonable and safer recommendations.

The same rule of electrode gaps and configurations from ac systems applies to dc systems, with larger electrode gaps resulting in higher incident energies. OCPD trip times may also increase due to reduced arc current with larger gaps. A comparison of the E_i for the S&O method at the maximum energy point of electrode gap variation for various voltages, for a 1 s, 20 kA bolted fault at an 46 cm (18 in) working distance is shown in Fig. 8. The maximum power point of the S&O method occurs when the voltage and current are 50 percent of bolted-fault current or open-circuit voltages, respectively. A reduction in electrode gap will lead to larger arc currents but smaller arc voltages, resulting in less overall power.

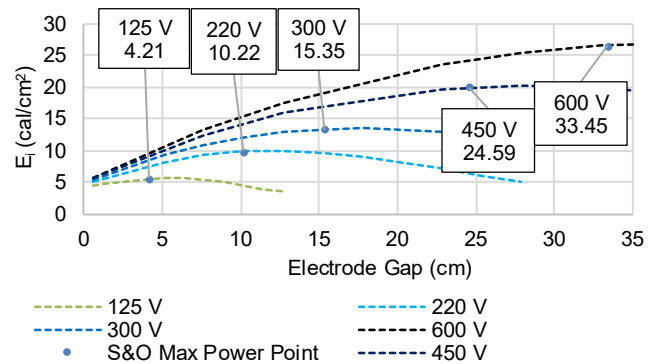


Fig. 8 Electrode Gaps for S&O Compared

As arc lengths increase, it is unknown at what point the arc will self-extinguish. The influence of electrode gap width on arc sustainability is illustrated in [16]. As noted, “The minimum

voltage to maintain an arc depends on the current magnitude, the gap width, and the orientation of electrodes” with horizontal electrodes having the more conservative values [16]. Measured values (solid lines) and calculated values (dotted lines) are shown in Fig. 9 for gap widths 5, 20, 100, and 500 mm (0.20, 0.79, 3.94, and 19.7 in), ordered from bottom to top, respectively. It is important to note that other configurations, such as VCB or aluminum electrodes, can differ from the values shown in Fig. 9.

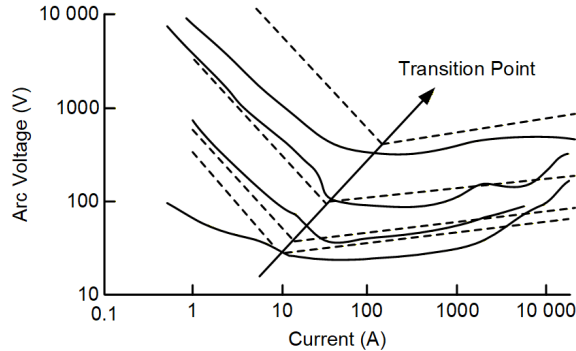


Fig. 9 Minimum DC-Arc Voltages for Horizontal Arcs [19]

References [18] and [20] suggest that the tables and recommendations in NFPA 70E be updated in the next published revision and not rely solely on the conservative maximum power method. In addition to recommending the Paukert and S&O methods, [20] states that “the maximum power method should be replaced with the erosion model” contained in [21], especially for higher current sources, such as a battery energy storage system (BESS) where electrode erosion plays a significant role in arcing events when electrodes are not parallel to each other and electrode erosion would lead to increased electrode gaps. Electrode erosion will elongate the arc but, as shown in Fig. 8, this will eventually lead to reduced power. The larger gap from electrode erosion will ultimately extinguish the arc.

V. WHEN DIRECT APPLICATION OF MODELS DOES NOT APPLY

There are many cases, especially in wind or solar generation, microgrids, and other distributed generation systems, where direct application of an arc-flash model within the defined range of the model may still not provide reasonable results. As most laboratory tests employ a stiff source as well as equipment configurations built for a laboratory environment, these may not always translate correctly to real-world applications. Any system that is connected to an inverter-based resource (IBR), PV array, wind turbine, or small generator will likely not have the typical linear fault current contribution as is used in laboratory testing. This may result in varied E_i and OCPD tripping times.

In addition,

arcing faults in an industrial workplace may be initiated under a wide range of conditions. Arcing, by nature, is a dynamic process, and industrial arcing faults are much more dynamic, random, and turbulent than constrained arcs initiated in a controlled environment (for example, a laboratory setup). [22]

Actual arc-flash E_i can differ greatly from calculated values, even when using the most accurate models. Just because an arc-flash calculation model or method exists, it does not guarantee it will accurately reflect all real-world applications; these methods are either theoretical or based on laboratory testing and cannot account for every type of situation.

A. Microgrids

Traditional systems are fed from a single source and rely on a single OCPD to clear the fault. Microgrids or other similar systems may have multiple sources each with a varying trip time. For systems with multiple sources and clearing times—such as an ac bus fed from both a transformer as well as an IBR, or a dc bus fed from a battery and a bidirectional inverter— E_i from both sources must be considered. For the examples given, a battery would produce much higher fault currents but be cleared quickly by the fuse and the inverter would continue to supply a smaller fault current for a longer period. It is important that the initial combined current contribution from the battery not be used with tripping times of the inverter.

Many modeling software applications also do not allow for the modeling of looped single-phase systems. This prevents the connection of the grid and an inverter to the same bus on a single-phase system. For these cases, the inverter contribution to the fault and the other contribution must be simulated separately and combined.

1) *IBRs, Converters, and Power Electronic Sources:* Correct modeling and sizing of IBRs are essential to help overcome many of the unknowns about inverter fault current and time behavior. These IBRs are usually set as current-following or voltage-following. These may have a spike in output for a short time but then resume outputting at 1–2 per unit until the controls shut down the unit completely. The exact behavior would depend on the specific device [23] and must be modeled per the manufacturing specifications.

PV arrays also pose a unique challenge as arc current is similar to full-load amperes (FLA), but the voltages can be high enough to sustain an arc. It is unlikely that a fault will draw enough current to clear protection devices unless multiple strings are combined. This often results in an extended electrical fire rather than an arc blast. In laboratory testing, it was found that the maximum power method calculations were 5 to 10 times higher than measured results for PV applications [13]. Testing was done in a 1000 kW PV array and concluded that Paukert and S&O methods resulted in E_i values at a 45.72 cm (18 in) working distance around 5 cal/cm² with test results around 2 cal/cm² and maximum power calculations around 10 cal/cm² [24]. This shows that while the Paukert and S&O methods tend to be more conservative when applied to PV installations, they are still more accurate than the theoretical maximum power method.

Although more testing needs to be done to determine exactly what the limits of arc-flash E_i are in regard to microgrids and IBRs, Das provided extensive calculations in [15] and concluded in [16] that with “many large LV and MV dc systems, which are well designed and protected, it can be safely said that the E_i is limited to no more than 8 cal/cm².” Even for a 2.4 kV dc converter, it was found that E_i values at standard working distances were less than 8 cal/cm². Analysis specific to each application must be conducted to verify this finding.

Due to the increased likelihood of an arc being sustained in dc

systems when compared to ac systems of similar voltage and size this conclusion can be applied to most ac LV and MV IBRs. While a general analysis of these systems should be conducted, the results will likely tend to be less than 8 cal/cm².

2) *Distributed Generators*: Rotating machines used as distributed energy resources typically have time-dependent decrement curves, which cause fault current levels to change as a function of time. These will often degrade to half of the initial current by 100 ms, limiting the contribution to an arc. Whether the generator excitation is maintained or removed will also play a significant role in the output of the generator. Any system that is connected directly to a generation bus will likely be affected by this decrement in current. Note that the arc-flash paradox mentioned earlier and shown in Fig. 3 will still apply and affect the tripping time of the OCPD for these cases. A more detailed investigation of time and current curves as described in [15] would need to be conducted to predict more accurate results.

3) *BESSs*: For high-current dc systems, conductor erosion, electrode configuration, and electrode gap must be accounted for when determining calculations as these play a significant role on the nature of arcs. The arc may elongate during the fault due to the conductor melting or magnetic forces imposed on the arc, thus increasing E_i throughout the duration of the arc to the point where the electrode gap or arc length is larger than the arc can be sustained at, causing the arc to self-extinguish. How much this impacts the arc-flash results depends on whether the electrodes are parallel to each other or butted together [25]. Typically, battery systems are limited to the large electrode gaps at battery terminals. Combiner boxes or other locations where electrodes may be closer together will be more likely to sustain an arc and would likely rely on an OCPD to clear the fault. In addition, fast-acting or current-limiting fuses, as well as dc-dc converters prior to the combiner box, often limit the E_i of arcs. Applying standard maximum power, Paukert, or S&O methods to these systems may not result in accurate analysis.

B. LV and Single-Phase AC

Single-phase ac arcs will pass through a zero crossing every half cycle, leading to an increased chance for the arc to self-extinguish. Lower voltages or single-phase systems may require additional considerations to determine whether total arcing time is limited by protection tripping times or the arc self-extinguishing. Lab testing has found VCB single phase systems less than 424 V to self-extinguish, resulting in reduced arc times and E_i [12]. VCB configuration, smaller electrode gaps, different materials, or other factors may cause an arc to not self-extinguish, even at these lower voltages, thus making a time restriction on this basis unreliable. Typically, it is best to assume that the arc persists until the OCPD can clear the fault.

In addition, single-phase systems have less power than three-phase systems, directly applying IEEE 1584 can result in overly conservative values. Correction factors can often be applied to common arc-flash modeling software to account for these cases. References [12] and [26] provide more detail about applying IEEE three-phase models to single-phase applications with such a correction factor. For single-phase tests with open-circuit voltages greater than 434 V, arc-flash burn injuries to unprotected skin are significantly more likely. Average E_i values ranged up to 5 cal/cm², with arc-flare hot spots yielding localized heat values twice the average measured across the calorimeter array [26].

C. Portable Equipment

There exists a significant amount of portable electrical equipment at or above 480 Vac that is not based on locally generated power at the portable equipment utilization point but rather a source located at varying distances from this equipment. For example, portable load centers and other electric mining equipment move around where needed. Because of the nature of portability, the source impedance can vary significantly and thus the resulting calculated values generally have little meaning. One could contest to calculate E_i based on the worst-case scenario, but those calculations will often exceed 40 cal/cm² due to the slow operating region for the upstream OCPD. The implication of such a scenario is that a simple no-live-work policy would be recommended and therefore no study would be required. These locations would require a built-in absence of voltage testers to allow workers to verify the de-energized state from outside the enclosure.

VI. MITIGATING ARC FLASH

The parameters used to calculate ac and dc arc flash are also the same parameters used to mitigate arc flash. While configurations may not always be changed, the most effective mitigation strategies rely on removing the largest contributors to E_i , which can include:

1. De-energizing equipment prior to any work being performed.
2. Limiting or reducing bolted-fault current (considering the arc-flash paradox).
3. Reducing arc duration.
4. Increasing the working distance.
5. Redirecting thermal energy exposure.

There are many ways to reduce current, such as not paralleling transformers, not using oversized transformers, or using current-limiting fuses. The use of variable frequency drives, other IBRs, or power electronic converters can also greatly reduce overall E_i . For BESS applications, using dc-dc converters between the battery strings and the combiner bus rather than fuses can also reduce the arc-flash E_i .

In addition to limiting current, limiting time can be a major factor in reducing arc hazards. An OCPD may have adjustable parameters that can minimize the tripping time, resulting in significantly reduced E_i , typically by adjusting the instantaneous setting to the left of the estimated arcing current. When these circuits feed transformers, typically the OCPD settings are set such that the instantaneous setting is to the right of an arbitrary eight to ten times the FLA value to allow for transformer inrush during energization. The eight to ten times value may be accurate for the first 1/4 cycle in industrial transformers; however, because of this very short duration, most OCPDs cannot react fast enough to trip. More reasonable inrush values for OCPD coordination can be significantly reduced using practical inrush values [27]. Fig. 10 illustrates the tabulated values graphically and contrasts the significant difference between the lower end of the 8 times rule of thumb and the practical values as proposed in this reference.

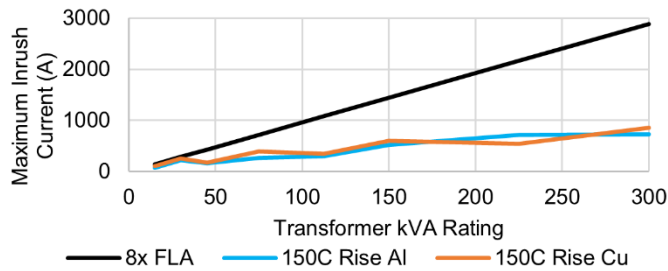


Fig. 10 Practical Transformer Inrush Values

Arc-resistant switchgear can reduce arc hazards for workers when doors are closed, but it does not mitigate the significant stress on electrical equipment. Another suggested arc-flash mitigation technique is active arc-quenching technology [28], but this can impose heavy bolted-fault duty on systems and could lead to more system damage. In addition, this technology can only be used in systems that are built to withstand sustained bolted-fault current and could still damage adjacent equipment with bolted through-fault currents.

Arc-flash hazard mitigation and reduction are always preferred to requiring additional PPE. There are other factors besides E_i that cause risk to workers, such as force of blast, hearing loss, toxic gases, and vision impairment, as well as increased damage to equipment. In addition to this, having fast protection and reducing fault current can protect equipment, even when no one is around [29].

VII. CONCLUSION

Often, arc-flash calculations are seen as a science, yet even the most advanced models produce only estimates at best. Small variations in system configuration or input parameters can create large differences in calculated E_i . Results of arc-flash studies should not be interpreted as exact. Although IEEE 1584-2018 provides robust guidance for ac arc-flash risk assessment, applying it correctly requires understanding both the limitations of the model and the behavior of arcs under different conditions. Lower-fault currents, longer tripping times, or variable generation can significantly impact arc-flash results. Understanding the different operating conditions is critical to getting the most accurate results.

For dc systems, the NFPA 70E recommendation to use the maximum power method often produces overly conservative results especially for dc control voltages. This can lead to excessive PPE requirements and introduce secondary risks, such as heat stress and reduced dexterity. While this method can be used as a quick calculation to assess risk, more empirically tested models and analyses should be used whenever a location presents a meaningful risk.

From the analysis and comparison of models and test data, several key observations emerge:

- Reduced current due to fault resistance or faults at the end of cables can paradoxically increase E_i because of longer OCPD clearing times. This arc-flash paradox underscores the importance of considering time as a factor in assessments, as shown in Fig. 3.
- Even with the most accurate arc-flash calculation methods, system configurations and model parameter inputs can cause great variability in results. Careful

analysis must always be taken, especially when system data and configurations are unknown.

- Theoretical methods, such as the maximum power method for dc systems, may provide a quick check to make sure a location does not pose a significant risk. However, for locations that do pose a significant risk, a more comprehensive analysis must be performed using a more accurate method to avoid imposing excessive PPE requirements.
- Exceeding the limits of test data or models will lead to divergent results. For these cases, it is critical to use methods that have been vetted for the voltage and current capacity of the system.

In some cases, system conditions cannot be verified or are variable, such as portable equipment or varied generation. In these situations, a strict no-live-work policy should be implemented rather than attempting to apply fixed models to varying systems. Ultimately, arc-flash studies are not just about applying equations; they also require engineering judgment in interpreting assumptions. Engineers must understand when conservative values enhance safety and prevent bum injuries and when overly excessive PPE requirements can lead to elevated risk, especially for systems under 200 V.

Fig. 1, Fig. 3, and Fig. 5 illustrate the variation of the calculations based on various configurations, which are often assumed. Actual arc-flash E_i can be ± 2 –5 times the value on labels for actual equipment, even when using the latest empirically derived standards. While arc-flash studies can provide helpful information about the risk or hazard associated with a given system or location, the most effective way to ensure worker safety is to design inherently safe systems and promote a culture that avoids working on live equipment as the primary arc-flash mitigation strategy.

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IX. VITAE

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