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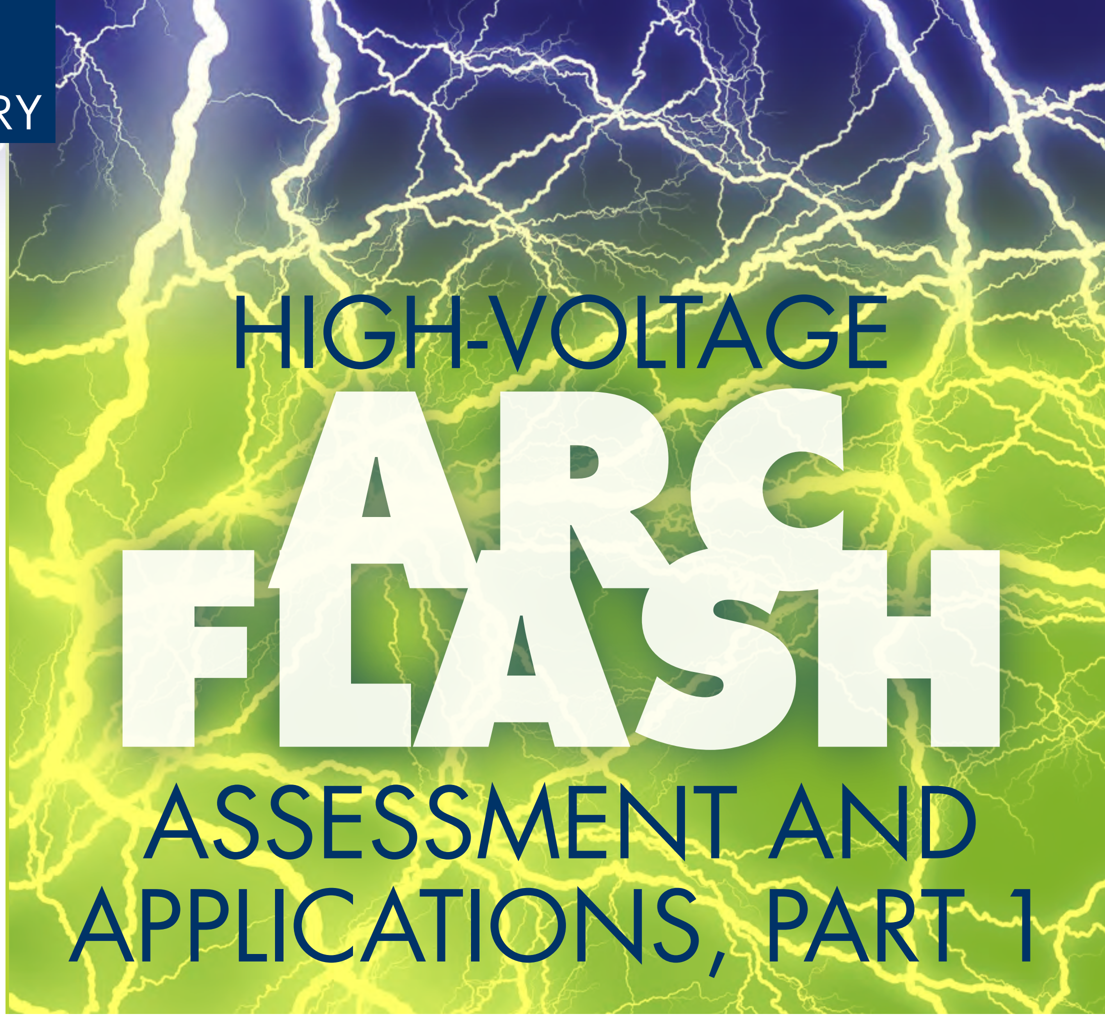

HIGH-VOLTAGE ARC FLASH ASSESSMENT AND APPLICATIONS, PART 1

BY ALBERT MARROQUIN, PE, ETAP; ABDUR REHMAN, PE, *Puget Sound Energy;*
and ALI MADANI, *AllumiaX Engineering*

Protecting utility workers and other working personnel who are exposed to line-to-line voltages above 15kV at live electricity installations is critical. For this reason and to ensure compliance with OSHA regulations, arc flash hazards must be evaluated and studied for every facility with an electrical installation. An arc flash produces extremely high temperatures, intense heat flux and radiation, high sound dB levels, and arc flash blast pressure waves. The intense heat and radiation can ignite clothing and cause severe burns.

Various methods have been proposed to calculate high-voltage arc-flash (HVAF) thermal incident energy levels, including IEEE 1584-2002, the Lee method, and Duke's HFC Calculator. This article focuses on methods derived from Electric Power Research Institute (EPRI) testing as well as methods based on research by V.V. Terzija and H.J. Konglin. These methods serve as the basis for arc flash calculations in the examples, and we explain in detail how they relate to OSHA and NESC regulatory requirements.

Several key driving factors are responsible for the incident energy caused by a high-voltage arc flash. These include conductor gap, short circuit current, arcing voltage, and exposure duration (arcing time) among others. The effect of each parameter in the calculation is explained to help the reader apply the methods.

In overhead transmission and distribution lines, the gap between conductor and ground is the most likely place for an arc fault. This article focuses on open-air, line-to-ground arc faults; however, three-phase arc faults in enclosed equipment (15 kV to 36 kV) are also discussed because of the proliferation of renewable energy collector systems. We explore the differences between the methods to help clear misconceptions about the regulations and the available methodology for performing HVAF incident energy calculations.

REGULATORY REQUIREMENTS

Arc flash has been identified by OSHA's regulatory bodies as a serious hazard requiring prompt mitigation action. OSHA Article 1910.335 states: "*to warn and protect employees from hazards which could cause injury due to electric shock, burns, or failure of electric equipment parts.*"

In Section 5(a)(1) of the 1970 Occupational Safety and Health Act, OSHA requires employers to ensure a safe work place for all working personnel: "*Employers are required to provide their employees with a place of employment that is free from recognized hazards that are causing or are likely to cause death or serious harm.*"

OSHA 1910.333(a)(1) states:

Live parts to which an employee may be exposed shall be deenergized before the employee works on or near them, unless the employer can demonstrate that deenergizing introduces additional or increased hazards or is infeasible due to equipment design or operational limitations. Live parts that operate at less than 50 volts to ground need not be deenergized if there will be no increased exposure to electrical burns or to explosion due to electric arcs.

The NEC's NFPA 70E emphasizes the need for identification of arc flash hazards and the required mitigation measures. To paraphrase NFPA 70E-2018, Article 130.5, Arc Flash Risk Assessment: An arc flash risk assessment shall be performed and shall: (1) Determine if an arc flash hazard exists. The risk assessment shall determine: (a) appropriate safety-related work practice, (b) the arc flash boundary, (c) the PPE to be used within the arc flash boundary. (2) Be updated when a major modification or renovation takes place. It shall be reviewed periodically, at intervals not to exceed 5 years, to account for changes in the electrical distribution system that could affect the results of the arc flash risk assessment. (3) Take into consideration the design of the overcurrent protective device and its opening time, including its condition of maintenance.

This article emphasizes the utility industry electrical safety requirements found in OSHA 29 CFR 1910, Subpart R (1910.269). While the utility industry may own and operate many facilities that fall within the scope of NFPA 70E, and thus can follow the guidelines provided there for incident energy calculations, the majority of transmission and distribution systems fall outside this context.

Similar to the arc flash requirements at industrial and commercial facilities, utilities follow NESC (ANSI/IEEE C2-2017) for guidance on equipment that falls outside the scope of NFPA 70E. Section 410A3 states:

Effective as of January 1, 2009, the employer shall ensure that an assessment is performed to determine potential exposure to an electric arc for employees who work on or near energized parts or equipment. If the assessment determines that a potential employee exposure greater than 2 cal/cm^2 exists, the employer shall require employees to wear clothing or a clothing system that has an effective arc rating not less than the anticipated level of arc energy.

The standard further states:

When an arc flash analysis is performed, it shall include a calculation of the estimated arc energy based on available fault current, the duration of the arc (cycles), and the distance from the arc to the employee.

To summarize, regulatory requirements state that a safe workplace must be provided in industrial and commercial applications (governed by NFPA-70E) and in utility transmission and distribution applications (governed by NESC). However, although some standards list specific HVAF methods as examples that produce reasonable results, they are certainly not a requirement.

For example, OSHA 1910.269 Appendix E, Section III, Table 2 and Table 3 provide examples of specific methods that can be used to reasonably calculate HVAF incident energy. However, OSHA has clarified by means of an official letter of interpretation that, "OSHA never intended that the calculation methods currently listed in the Appendix would be the only methods employers could use to comply with the standard." In fact, Note 1 to 29 CFR 1910.269(1)(8)(ii) specifically provides that *"[a]n employer may choose a method of calculating incident heat energy not included in appendix E"* as long as the method used *"reasonably predicts the incident energy to which the employee would be exposed."* This information, which is quoted directly from an interpretation letter from the U.S. Department of Labor, Occupational Safety and Health Administration, is the main reason to explore alternative methods that could provide reasonable incident energy estimations from electric arcs.

METHODOLOGY

Research and standards developed in previous decades focused mainly on how to calculate arc flash incident energy for enclosed, three-phase, low- and medium-voltage systems (0.208 to 15.0 kVLL). Far less detailed information has been published or highlighted regarding thermal energy produced by long conductor gaps, which are more prevalent in high-voltage systems. To validate the methods available at the time (and also because of the requirement placed on utilities in 2009), EPRI requested a comprehensive set of tests and experiments. This led to the development of the empirical equations that could be used to validate existing methods.

The experimentally derived equations (1) to (5) from EPRI TR-1022632 provide a method to calculate incident energy and can be effectively used to determine the heat flux and incident energy for open-air, line-to-ground arc faults in overhead power distribution and transmission systems. The first equation defines the voltage gradient, which is a function of the gap and arc current.

Equation (1) must be solved in conjunction with equation (2) using basic iterative routines.

$$Eave = 0.0000112 \times G^{-8} + 1.19 + (0.0069 \times G^{-1.239} - 0.0126) \times Iarc \quad (1)$$

Where:
$Eave$ Average voltage gradient (kV / m)
G Length of the gap between conductors (m)
$Iarc$ Arc current in (kA rms)

The arc voltage (rms) can be determined using equation (2) with the voltage gradient and length of the gap between conductors.

$$Varc = \frac{Eave \times G}{1.1255} = 0.8885 \times Eave \times G \quad (2)$$

Where:
$Varc$ Arc voltage (Volts rms)

The arc power is easily determined once an iterative process has determined the values of the arc current and voltage.

$$P_{arc} = \frac{(0.0000112 \times G^{-8} + 1.19 + (0.0069 \times G^{-1.239} - 0.0126) \times Iarc) \times G}{1.1255} \times I_{arc} \quad (3)$$

Where:
P_{arc} Arc power (MW)

The energy flux equation (4) accounts for the effect of the gap and arc current on the heat transfer at a particular working distance.

$$\Phi = 6.7 \text{ x } Eave \text{ x } Iarc \text{ x } G^{0.58} x D^{-1.58G^{-0.152}} \quad (4)$$

Where:
Φ Thermal energy flux (cal/(s*cm²)
D Working distance (feet)
s Seconds

The incident energy equation (5) can be corrected based on statistical analysis of the energy measurements.

$$W = \Phi \text{ x } \mathrm{T} \times (1 + n \times \sigma) \quad (5)$$

Where:
W Thermal incident energy (cal/cm²)
T Arc exposure duration (seconds)
n Statistical multiplying factor
σ Standard deviation

Similar to the method from EPRI TR-1022632, other international research efforts have led to the development of alternate representations of the long-gap arcs in open air. Similar equations based on the research by Terzija and Konglin can be used to determine the arc voltage gradient, arc current, arc resistance, arc power, and energy as described by equation (6) through equation (11).

$$R_{arc} = \frac{2 \times \sqrt{2} \times U_a}{\pi \times I_{arc}} \quad (6)$$

Where:
R_{arc} Arc resistance (Ohms)
U_a Arc voltage magnitude (Volts)
I_{arc} Arc current (Amps)

$$U_a = E_a \times L \quad (7)$$

Where:
E_a Arc voltage gradient (Volts/meter)
L Gap length (meters)

Substituting equation (7) into equation (6):

$$R_{arc} = \frac{2 \times \sqrt{2} \times E_a \times L}{\pi \times I_{arc}} \quad (8)$$

Use equation (9) to determine U_a:

$$U_a = B + \frac{5000}{I_{arc}} \quad (9)$$

Where:
B Voltage gradient (volts/meter)
I_{arc} Arc current (amps)

The arc power and energy are found using equation (10) and equation (11):

$$P_{arc} = V_{arc} \times I_{arc} \qquad (10)$$

$$E_{arc} = V_{arc} \times I_{arc} \times T_{arc} \qquad (11)$$

Where:
T_{arc} Arc exposure duration (seconds)

The incident energy can be determined using equation (7) and equation (8) developed based on R. Wilkins for various combinations of a and k (which are a function of the box size and electrode orientation), and x (which is a function gap and arc current magnitude):

$$E = \frac{E_{arc}}{4 \times \pi \times d^{x}} \qquad (12)$$

For arcs in open air, equation 12 is applied because the arc freely expands compared to arcs that are confined to enclosed equipment.

For arcs within enclosed equipment (i.e., switchgear) the box size is taken into account in order to determine the Wilkins reflectivity factors a and k. These values are used to account for the reflectivity effect of the enclosure.

$$E = k \times \frac{E_{arc}}{a^{2} + d^{x}} \qquad (13)$$

Where:
E Incident energy (Joules/cm²)
E_{arc} Arc energy (Joules)
d Working distance (mm)
a Wilkins "a" reflectivity coefficient
k Wilkins "k" reflectivity coefficient
x Distance exponent coefficient

Parameters a, k, and x are determined based on a matrix of combinations of gap between conductors, which are optimized based on evaluation of the results.

The basic premise of the two methods — which from this point forward are referred to as the EPRI and Terzija/Konglin methods — is that HV arcs in open air can be represented mathematically using rms equivalents of the arc voltage and current. These rms-equivalent current and voltage gradients can be derived using spectrum analysis of the measured waveforms of open-air, single-phase arcs. The harmonic spectrum obtained from fast Fourier transform (FFT) can be used to create rms waveforms for the voltage, which can be somewhat equivalent to those of a square waveform. Typical high-voltage waveforms can be approximated as a square wave (Figure 1).

According to Terzija/Konglin, the voltage gradient can be approximated using a square waveform; however, according to EPRI, the voltage gradient experiences variation, and thus a square waveform model cannot possibly model all combinations of arc current and gap between conductors. An example of this is shown in Figure 2, where the instantaneous voltage waveform does not quite resemble a square wave but has continuous decay from the point where

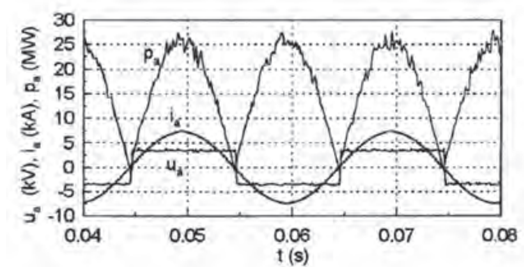

Figure 1: *V_{arc} (U_a), I_{arc} (i_a), and P_{arc} (P_a) Waveforms*

SOURCE: V.V. TERZIJA; H.J. KONGLIN, "LONG ARC IN FREE AIR: LABORATORY TESTING, MODELING, SIMULATION AND MODEL-PARAMETERS ESTIMATION"

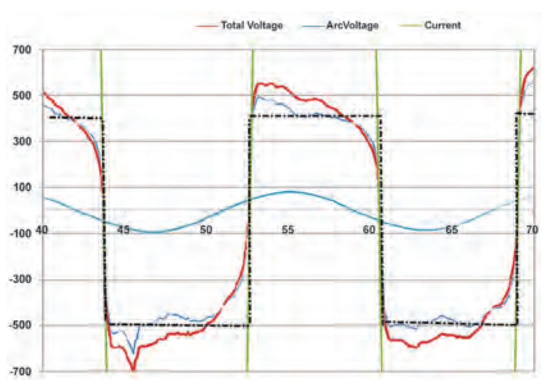

Figure 2: *Total V (red), V_{arc} (blue), and I_{arc} (green) Waveforms*

the arc ignites until the point where the arc extinguishes because of zero crossing.

Figure 2 includes the arc voltage waveform. A square waveform was superimposed on the arc voltage waveform to show that the actual waveform is similar to a square waveform but varies significantly depending on the gap and current. The EPRI method in equation (1) through equation (5) includes the effect of various gaps and arc currents. The same effect can be added to equation (7) for the Terzija/Konglin method to be sensitive to different gap lengths.

The models presented apply to single-phase, open-air arc faults, which statistically have the highest probability of occurring in high-voltage power systems. However, three-phase arcing faults also occur in enclosed equipment operating at voltages higher than 15 kV (outside the range of IEEE 1584 2002 or 2018) for which incident energy calculations need to be performed. There is no standard to address the calculations of three-phase arcs above 15 kV, but two methods have emerged as potential solutions.

The first method is to adapt calculation methods like the ones from EPRI and Terzija/Konglin to conservatively simulate three-phase enclosed arcs. The second proposed method based on T. A. Short utilizes an extension of the IEEE 1584-2002 method equations to determine the incident energy in enclosed three-phase equipment. To convert the single-phase arc to a multi-phase arc, a multiplier of 1.75 to 2.5 is proposed. The dimensions of the enclosure, the electrode configuration, and the working distance are all factors that affect the conversion factor.

CALCULATION METHOD COMPARISONS

The methods described above are only two of several methods that can be used to establish a reasonable estimation of the incident energy generated by a single-phase arc in open air. OSHA 1910.269 Appendix E, Section III, Table 2 and Table 3 provide additional examples of reasonable methods to determine the incident energy levels from flames and electric arcs required for the selection of PPE. Appendix E does not intend to make direct recommendations or imply that the listed methods are to be used exclusively to determine the incident energy. The intent of these tables is to provide examples of methods that can yield reasonable results.

The word “reasonable” was added to these tables in response to a statement in IEEE 1584-2002, which lists the Lee method as acceptable to determine the arc-flash incident energy for systems with voltages higher than 15 kV. Ironically, the reference to the Lee method was removed from the latest edition of IEEE 1584-2018 because the inclusion of this text in Appendix E generated confusion — it was misinterpreted as a requirement. In fact, alternative methods based on actual test results were used to refine some of the results listed in Appendix E and may be included in future revisions of the OSHA regulations.

To prove that several available methods yield similar and reasonable results, comprehensive comparative analysis was performed to observe how the incident energy results of each method vary across parameter sweeps that comprise different gaps, voltages, short-circuit currents, and working distances. This section only provides a small sample of the thousands of comparisons completed for six different methods (including one that cannot be disclosed since it is not a publicly available application and thus has been omitted from the comparisons). A good starting reference for a comparative analysis is to follow the calculations done to generate the data in Table 410-2 and Table 410-3 of NESC C2-2017. Figure 3 compares the five methods:

- EPRI
- Terzija/Konglin
- Theoretically-derived Lee (included for illustration purposes)
- Duke Heat Flux Calculator
- ArcPro V3.0.

The voltage range is 1.0 kV to 46 kV, the working distance is 15 in, and gaps vary according to the footnotes in Table 410-2. The short-circuit current is 5.0 kA for all calculations. The arc exposure duration is varied to show a normalized 4 cal/cm² exposure and is taken from the table. The electrode material is stainless steel (thus, the electrode erosion effect is not considered).

The comparison shows that between 1.1 to 46 kV, the variation between results is approximately 1.6 cal/cm² or less (from highest to lowest). The horizontal line represents the normalized target energy value of 4 calories. The Lee method produces a hyperbolic result nearly 20 times higher, in most cases, and proves to be unreasonable for all applications above 15 kV.

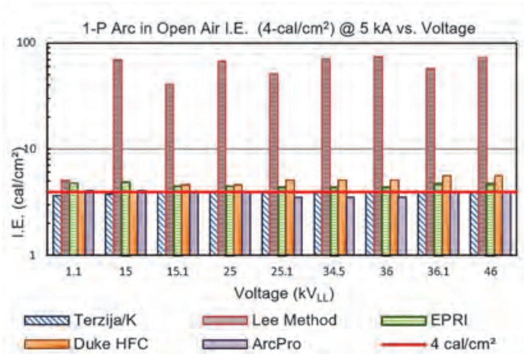

Figure 3: *Comparison of Five 1-P Arc I.E. Methods – 4 cal*

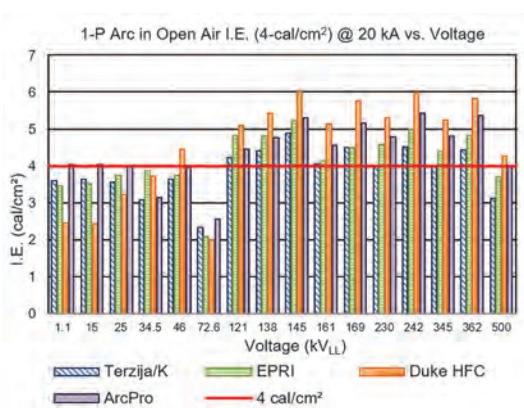

Figure 4: *Comparison of Four 1-P Arc I.E. Methods – 4 cal*

Figure 4 shows further comparisons for longer gaps and higher short-circuit currents. This comparison was made based on the parameters selected to generate NESC C2-2017, Table 410-3. The voltage varies between 1.0 to 500 kV, the working distances and gaps between conductors are determined based on the minimum approach distance, and the voltage of the equipment uses the details provided in the footnotes of Table 410-3. Equation (14) and equation (15) were used to establish some of the working distances and gaps between conductors:

$$Gap_{LG} = \frac{\frac{V_{LL}}{\sqrt{3}}}{10} \times 25.4 \quad (14)$$

$$WD_{LG} = MinAppDist - 2 \times \frac{Gap_{LG}}{1000} \times 39.3 \quad (15)$$

Where:

Gap_{LG}	Gap between conductors (mm)
WD_{LG}	Working distance for line-to-ground (in)
$MinAppDist$	Minimum approach distance w/out tools (ft)
V_{LL}	Voltage Line-to-Line (kV)

In Figure 4, only four methods are compared, since it is impractical to include the Lee method. The data trend shows that the results of all four methods decrease or increase depending on the changes in gap and working distance required for higher voltages. The results of all four methods are higher than the 4-calorie reference value between 121 and 362 kV. The highest incident energy difference between methods is approximately 1.16 cal/cm² or less.

The trends are similar for other incident energy reference values and other combinations of gaps and short-circuit currents. NESC C2-2017 Table 410.3 includes higher incident energy reference values. Figure 5 shows a comparative analysis of the results for 20 kA of available short-circuit current with an 8-calorie reference frame. Similar to the trend established in Figure 4, the incident energy results of the longer gap results tend to be generally higher than the reference. The highest incident energy difference between methods is 2.2 cal/cm² or less.

As mentioned previously, three-phase enclosed arcs are of high interest, particularly between 15 and 36 kV. Figure 6 shows the comparative analysis of four methods when applied to this condition. Typical dimensions for medium-voltage switchgear were used for the comparison. The height, width, and depth are 1143 mm, 762 mm, and 762 mm, respectively, for voltage levels above 15 kV. For 5 kV equipment, 914 mm was used for all three dimensions. A working distance of 36 in was used for all comparison samples. The arc exposure duration was 200 ms for all samples. The short-circuit current is 10 kA. The gap between conductors varied between 4 and 12 in (4 in at 5 kV, 6 in at 15 kV, 9 in at 25 kV, and 12 in at 35 kV).

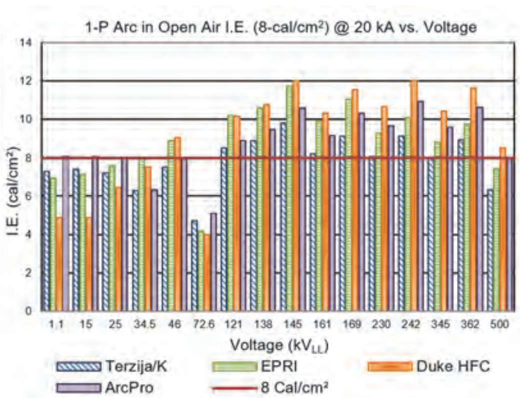

Figure 5: *Comparison of Four 1-P Arc I.E. Methods – 8 cal*

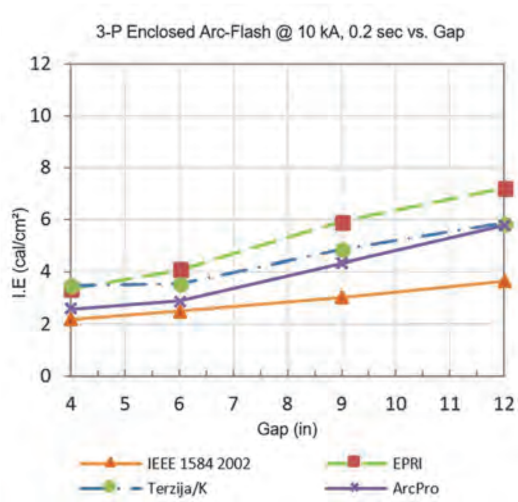

Figure 6: *3-P Enclosed I.E. Comparisons for Four Methods*

The EPRI, Terzija/Konglin, and ArcPro single-phase arc to multi-phase arc results were adjusted using a 2.0 multiplier factor. The incident energy obtained from ArcPro appears to have been converted using a constant 1.75 multiplier to go from three-phase arc in open air to three-phase enclosed conditions. The EPRI and Terzija/Konglin methods were converted to enclosed conditions using reflectivity factors developed based on R. Wilkin and other proprietary sources of information that cannot be referenced.

The variation in incident energy calculations is much higher for three-phase enclosed arcs and can be as high as 50 percent from high to low based on the Figure 6 comparisons. The variation comes from the dimensions of the enclosure, the orientation of electrodes, the distance between the electrodes and the back wall, the distance between the electrodes and the bottom surface of the enclosure, and the working distance. To account for some of these additional sources of variation, the reflectivity factors applied to the EPRI and Terzija/Konglin methods were designed to produce more conservative results.

The new IEEE 1584-2018 standard introduced a new enclosure-size correction factor, but at first sight, the new IEEE 1584-2018 equations do not appear capable of being extended for application on voltages above 15 kV (unlike their predecessors). It appears that the arc current equations collapse, producing unrealistic results at input voltages higher than 22 kV. However, if the input voltage is held at a max of 22 kV, it may be possible to extend the comparative analysis to include this new method as shown in Figure 7. Note that the results of the IEEE 1584-2018 method were obtained using the following assumptions:

- Horizontal conductor in a box (HCB)
- Dimensions of 914 mm x 914 mm x 914 mm for 5 kV
- Dimensions of 1143 mm x 762 mm x 762 mm for 15 kV and higher
- Gaps of 4 in at 5 kV, 6 in at 15 kV, 9 in at 22 kV, and 12 in at 22 kV (No arc current solution is feasible at input voltages greater than 22 kV.)

This final comparison shows that variations in electrode orientation in medium-voltage equipment have a significant effect that may not be captured well with single-phase arc models that are adapted to three-phase enclosed conditions. Figure 7 also shows that additional conservative factors may be adequate to conservatively estimate the incident energy because of many parameter variations that can introduce significant effect in the thermal incident energy transfer.

The comparative analysis performed to determine which method was capable of providing reasonable incident energy results was extensive. Another sample of this effort can be observed in Figure 8, which was recreated based on the comparative analysis performed in Ammerman, Gammon, Sen, and Nelson. Figure 8 originally included only the results of the Duke Heat Flux Calculator, ArcPro V2.0, and IEEE 1584-2002 results for a three-phase, open-air fault. The chart presented here includes the two additional methods applied under identical input parameters. The gap between conductors is 6 in, which is important for this comparison since it shows that even under short-length gaps, all four models can yield very close results. Furthermore, the x-axis represents the available fault current, which varies from 5 kA to approximately 45 kA (very high for high-voltage applications). The working distance used in the comparison was 30 in and the arc exposure duration (arc time) was set at 0.2 seconds.

The correlation between the EPRI method and ArcPro V2.0 results is no more than 1.0 cal/cm² for the 45 kA result. It can also be observed that the lowest value is that of the Terzija/Konglin method. This could be expected, since this method was developed to represent long gap lengths. No conversion factor is used in any of the single-phase arc methods to convert the result to a multi-phase arc.

CONCLUSION

The main purpose for Part 1 of this article was to explore and compare various methods to calculate the incident energy from HV and MV electric arcs. Analyzing the results presented in Figure 3, Figure 4, and Figure 5 demonstrates that several methods can be used to calculate the incident energy generated by open-air, line-to-ground arc faults for systems within the range of NESC tables 410-2 and 410-3.

In Part 2 of this article, key driving factors that directly affect the arc flash incident energy will be discussed in detail along with PPE considerations for different scenarios. A real-life case study will be analyzed to drive home the importance of high-voltage arc flash studies for utility applications.

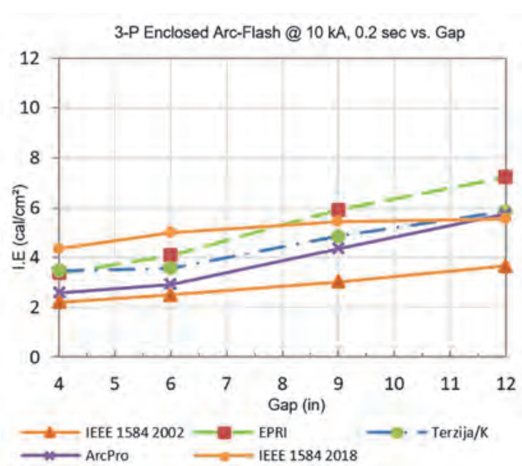

Figure 7: *3-P Enclosed I.E. Comparison including IEEE 1584-2018*

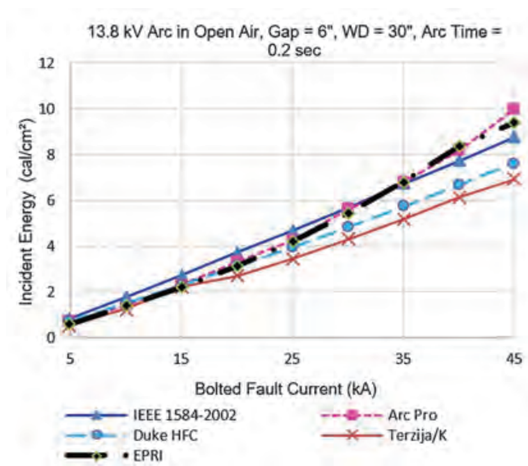

Figure 8: *3-P Open-Air I.E. Comparisons*

SOURCE: R. F. AMMERMAN, T. GAMMON, P. K. SEN, AND J. P. NELSON

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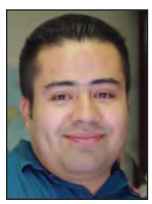

Albert Marroquin, BSEE, PE, IEEE Senior Member, *is Vice President, Validation & Verification, and Senior Principal Electrical Engineer at ETAP. A registered Professional Engineer in the state of California, he is the main designer and product manager for ETAP's ac and dc arc flash products, a working group member of IEEE 1584 and IEEE 1458, and an active attendee at NFPA 70E seminars and meetings.*

Abdur Rehman, BSEE, MSEE, PE*, is the Relay Operations Supervisor at Puget Sound Energy, where he leads a team of relay technicians who maintain, troubleshoot, and commission protection systems throughout PSE territory. Abdur brings a wealth of high-voltage experience in protection engineering and has performed various power system studies, high-profile incident investigations, troubleshooting, and RCAs.*

Ali Madani, BSEE*, is the lead Power Systems Engineer at AllumiaX Engineering. Ali has performed various power systems studies including modelling, short circuit, coordination, and arc flash studies for a variety of low- and medium-voltage facilities.*

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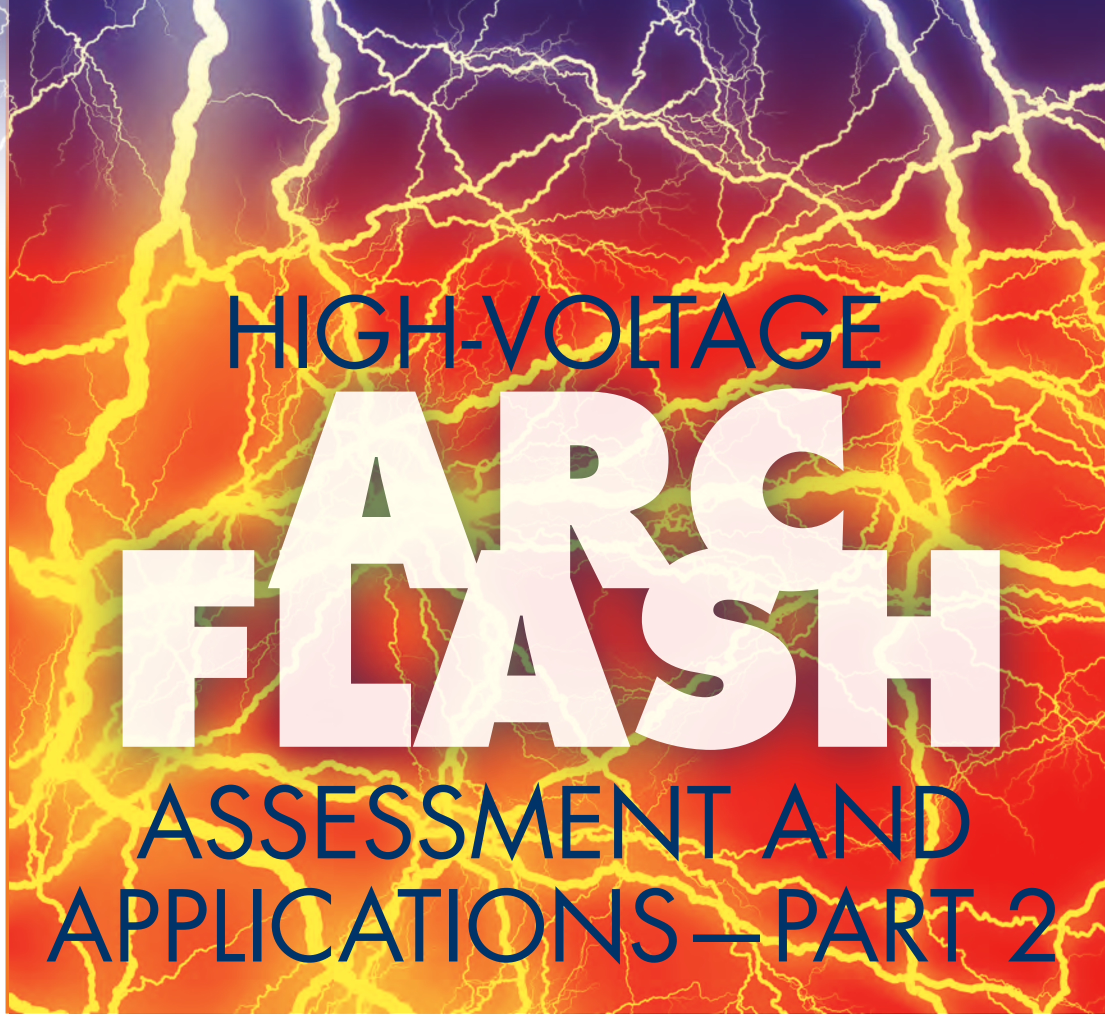

HIGH-VOLTAGE ARC FLASH ASSESSMENT AND APPLICATIONS — PART 2

BY ALBERT MARROQUIN, PE, *ETAP;* ABDUR REHMAN, PE, *Puget Sound Energy;* and ALI MADANI, *AllumiaX Engineering*

Part 1 of this article, which was the cover story in the previous issue of *NETA World*, explored the need for high-voltage arc flash (HVAF) assessment to protect utility workers who are exposed to voltages above 15kV. It also compared various methods to calculate the incident energy from HV and MV electric arcs. Analyzing the results demonstrated that several methods can be used to calculate the incident energy generated by open-air, line-to-ground arc faults for systems within the range of NESC Table 410.2 and Table 410.3.

Part 2 discusses key driving factors that directly affect arc flash incident energy, along with PPE considerations for various scenarios. A real-life case study drives home the importance of high-voltage arc flash studies for utility applications.

Traditionally, all existing HVAF simulation programs (e.g., ARCPRO, Duke HFC) require a manual, time-consuming process to calculate incident energy because they do not contain network and protective device information. This article illustrates the importance of performing a HVAF assessment for utility applications and highlights the benefits of using a tool capable of limiting human error factors from data transfer across different platforms by performing incident energy calculations along with network short-circuit currents (phase and sequence) and protective device operating time.

PROTECTION SYSTEM CHARACTERISTICS

The three most important driving factors that directly affect arc-flash energy are the short-circuit current, the gap between conductors, and the duration of the arc. Incident energy increases with higher short-circuit currents. However, due to the operation of protective devices (PD), higher short-circuit currents can result in lower incident energy because of faster PD operation. Similarly, the gap between conductors dominates the geometry of the arc column plasma and the voltage gradient, and the incident energy is significantly affected by the effect of this factor (EPRI TR-1022632). Accurate estimation of incident energy thus depends on the relationship between all three parameters. This section describes the operating characteristics of HV and MV protection systems assuming that accurate arc fault currents have been determined.

HV Transmission Line Protection and Clearing Time

HV protection systems are standardized and designed to operate at high speeds due to the nature and importance of the system and the devastating implications of sustained arc faults. In fact, government regulations and organizations such as the Federal Energy Regulatory Commission (FERC) ensure that energy services are economically efficient, safe, reliable, and secure. Utility protection engineers use a combination of protection schemes particularly for the bulk electric system. Step-distance protection that detects and operates for phase faults (3PH & LL) and directional ground overcurrent protection that typically detects and operates for ground faults (1LG, 2LG) are the most common protection elements for HV transmission systems. Protective relays detect faults and send trip signals to HV circuit breakers rather quickly. High incident energy levels most commonly arise due to slow fault clearing times and should be given paramount importance in a HVAF evaluation. High-resistance arc faults (purely resistive in nature) show a constant

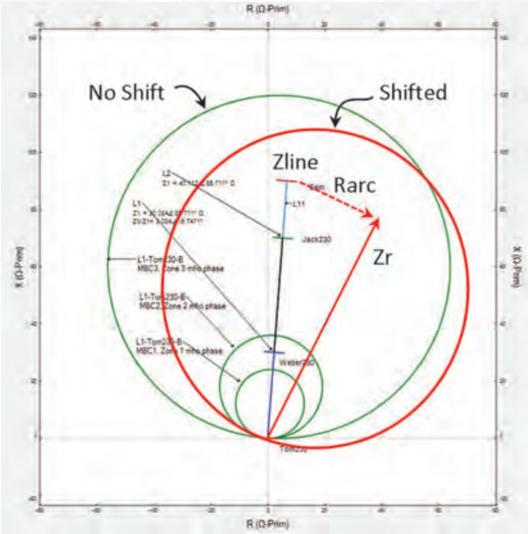

Figure 1: *Distance Relay Mho Zone Shift for Arc Resistance*

voltage drop proportional to the gap, and arc resistance will vary inversely with the current flowing through the arc. Distance protection components may need to be adjusted or shifted to account for resistive arc faults. Figure 1 depicts how a mho setting shifts the line impedance angle to gain greater arc resistance coverage while still maintaining coverage of the line.

High-impedance ground faults also produce lower short circuit current (because of additional ground path resistance) and typically operate slower in a directional ground overcurrent protection scheme. Protective relays commonly operate with a 0.30-second delay for ground overcurrent protection. Other examples of delayed fault clearing include breaker failure, stuck breaker, or relay failure conditions.

The concept of sequential tripping for ground fault protection is an important part of transmission line protection. During a close-in ground fault condition, the close-in terminal would detect the fault in the instantaneous region (50G), and the remote terminal would detect the fault in the time region (51G). However, as soon as a close-in terminal breaker opens, the fault current reroutes, and more

Figure 2: *Linemen Working on a Short-Gap Distribution Line*

current flows through the remote terminal. This causes the time element to speed up into the instantaneous region.

High-voltage systems tend to have faster arc fault clearing times because distance relay protection is expected to operate fast. Distance relay (21-element) zones of protection include a main zone and backup-up zones. Typically, the first zone of protection is defined as Zone 1 (close-in). Arc faults in HV transmission systems are expected to produce fault currents and impedance zone detection within Zone 1 of the distance relay protection. Zone 1 protection typically has no delay and only detection time plus breaker opening time are considered to determine arc duration. Zone 2 and Zone 3 typically operate in 20–50 ms (1.5–3 cycles) and with 100–250 ms (6–15 cycles) delays. The delays are included to provide backup protection, coordination, and selectivity.

One way to determine a conservative arc fault exposure time (assuming a worst-case scenario) is to assume Zone 1 failure and instead use the Zone 2 time-delay operation. This adds a 20–50 ms delay to the incident energy estimation and brings total HV system arc fault clearing time for incident energy calculations to 70–120 ms (20–50 ms delay + 50–80 ms for breaker opening time). Zone 3 protection operation for arc fault conditions is rarely used for incident energy calculations.

It is common for HV protection engineers at the author's utility company to assume 2-cycle delay for microprocessor detection time in the case of instantaneous protection. For Zone 2 protection, 18-cycle delay is programmed. It is also common to assume 5-cycle clearing time for HV breaker opening time.

A tool used to perform high-voltage arc-flash incident energy calculations should allow simulation of distance protection components to minimize the human error factor of engineers who traditionally have been performing this analysis using manual older technology.

Pole Construction and Gap between Conductors

The length of the gap between conductors, which is directly related to incident energy, is also a factor. Typical line performance and design criteria clearly show that line-to-ground and line-to-line gaps between conductors vary significantly mainly because of the design voltage of the power system. Longer arc lengths produce larger heat energy sources. In high-voltage transmission lines, the arc length is longer, and the shape of the arc plasma column is very different from the more spherical shape arc encountered in low-voltage (short gap) equipment. HV arc plasma clouds may take on a cylindrical shape. An 110kV line could have a gap between phase and ground conductors as long as 1,100 mm, whereas a typical gap between phase conductors in MV switchgear is 152–305 mm (Figure 2 and Figure 5). The shorter gap plasma cloud can be approximated as spherical for incident energy modeling purposes.

Furthermore, longer gaps provide the arc more room to elongate and spread out in all directions. Arc elongation, a phenomenon described in Terzija and Konglin's "Long Arc in Free Air: Laboratory Testing, Modeling, Simulation and Model-Parameters Estimation," is not to be confused with the actual length between conductors. Arc movement along conductors caused by magnetic field forces is another factor that is not included in the methods proposed in this article; only the effect of longer arc length is considered in the models. Arc movement and arc elongation may cause the arc column and plasma to move away from the electrical worker; however, it can also cause the working distance to be reduced. This should be considered when selecting the working distance that will be used to determine the incident energy.

The authors use conductor gaps for a transmission line that vary with each type. For a 115kV overhead line (Figure 3, Figure 4, Figure 5), the gaps range from 2ft.-6in. for a compact, horizontal post line to as large as 11ft.-3in. for an H-frame type tower. On the other hand, the conductor gaps for high-voltage 34.5kV switchgear are shorter when compared to an overhead line. This is due to the lower voltage level, which permits shorter gaps without jeopardizing personnel safety.

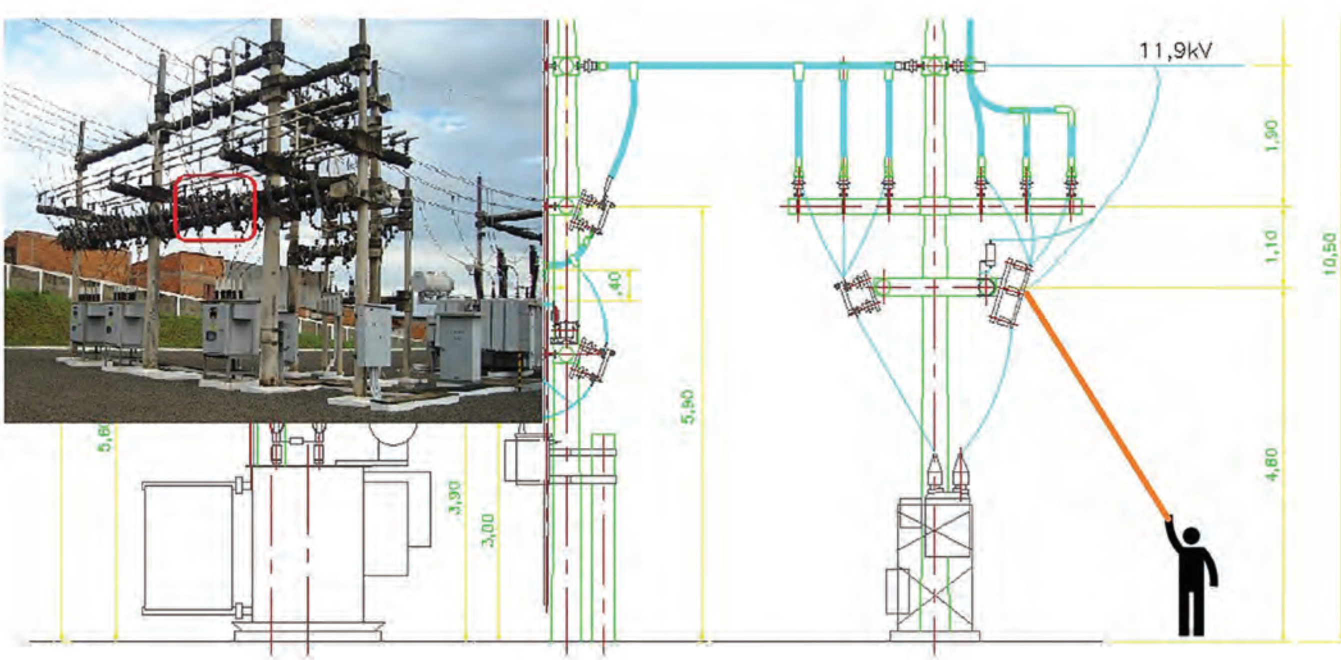

Figure 3: *Outdoor Substation*

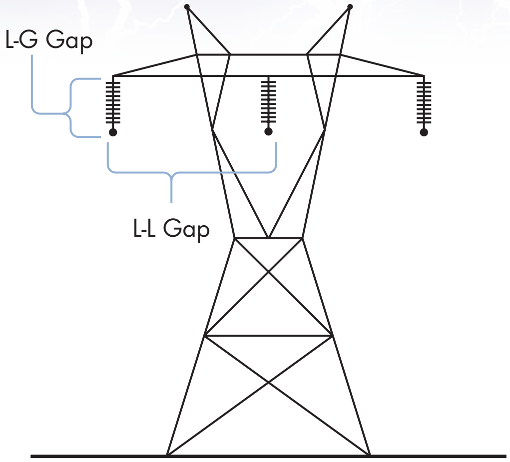

Figure 4: *Transmission Lines*

CASE STUDY: CALCULATING HV AND MV ARC FLASH INCIDENT ENERGY

To demonstrate HV incident energy calculations, a utility application consisting of high-voltage equipment has been prepared as an example of an HVAF assessment using simulation software that implements the EPRI and Terzija/Konglin methods. Two examples are provided:

1. HV 115 kV open air transmission line (Figure 6)
2. MV 34.5 kV switchgear for a renewable energy collector system (Figure 7)

Figure 5: *Distribution Lines*

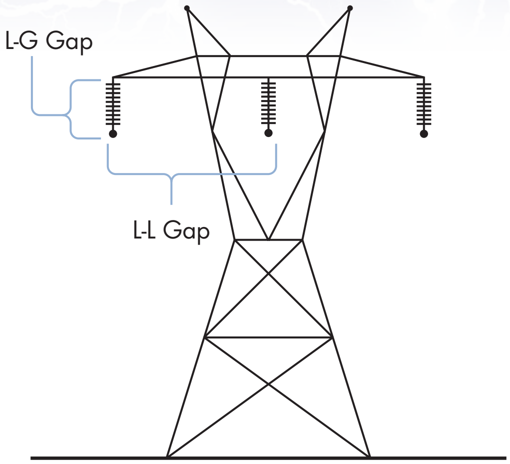

Figure 6: *120 kV Transmission Line Design*

SOURCE: WESTINGHOUSE ELECTRIC CORP. "ELECTRICAL TRANSMISSION AND DISTRIBUTION REFERENCE BOOK"

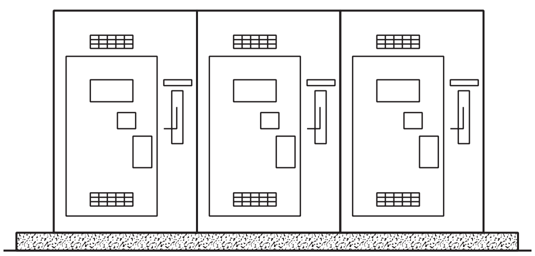

Figure 7: *34.5 kV Outdoor Switchgear*

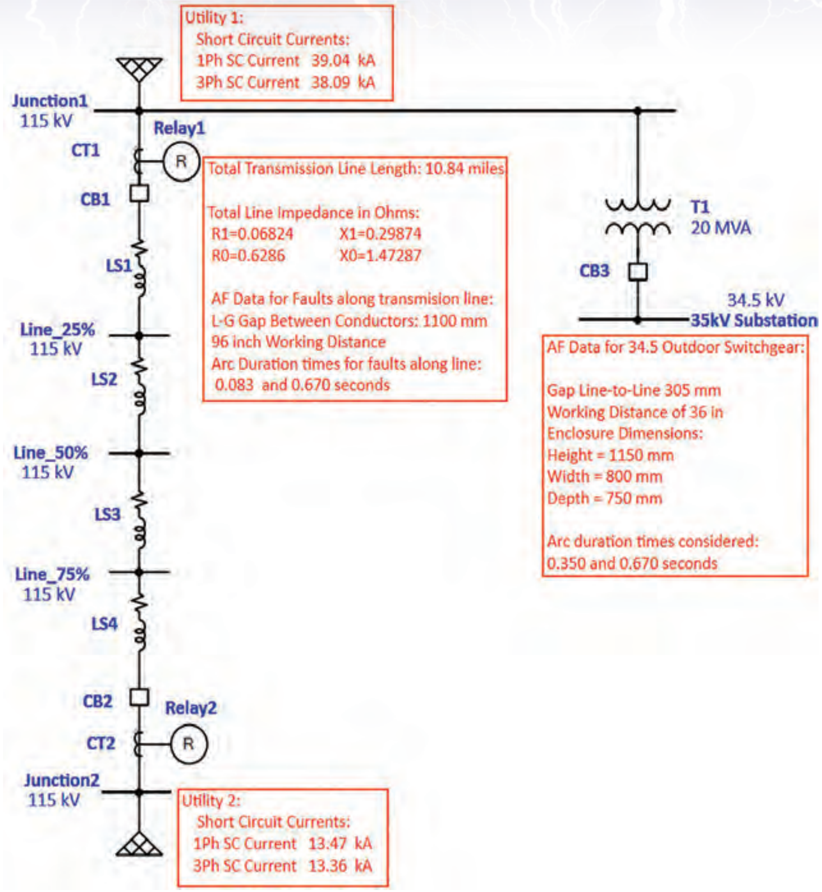

Figure 8: *115 kV Transmission System One-Line Diagram*

The incident energy of the 115kV transmission line is calculated at five different locations (i.e., 0%, 25%, 50%, 75%, and 100% taps (Figure 8). The incident energy analysis is performed using typical overcurrent relay fault clearing times. The electrical properties including resistance, reactance, short-circuit current, and other input data are also shown in Figure 8. The dimensions of the equipment, gap between conductors, and working distance are included in the figure legends.

For the 115kV system, line-to-ground arc faults are examined at different fault clearing times (FCTs). The term "FCT" is used interchangeably with arc exposure duration. FCTs are determined based on typical transmission system protective device settings. For both junctions, the selected fault clearing times are 0.083 sec and 0.670 seconds, respectively. For faults on the transmission line taps (different segments along the line), a fault clearing time of 0.099 seconds is used.

The 35kV substation represents an outdoor collector system switchgear with available short-circuit current of 3.835 kA. For this fault location, three-phase enclosed arc faults are examined with clearing times of 0.350 and 0.670 seconds, respectively.

Multiplying factors are used for each method (refer to individual method OEM reference manuals for details) to convert arc fault incident energy from L-G in open air to three-phase enclosed. The Duke Heat Flux Calculator does not offer direct inputs for correction factors; thus, they were applied manually. The ETAP ArcFault™, EPRI, and Terzija / Konglin methods presented in this paper are also adjusted using methodology described in R. Wilkins.

CASE STUDY RESULTS

Table 1 lists the methods compared in Tables 2–6.

Table 1: *Arc Fault Methods*

Method	Description
ETAP ArcFault – Method 2 (M2)	Electric Power Research Institute Method in ETAP 18.0.0.N
ETAP ArcFault – Method 1 (M1)	Terzija / Konglin Method in ETAP ArcFault v. 18.0.0.N
ArcPro	ArcPro V3.0
Duke HFC	Duke Heat Flux Calculator

ANALYSIS

Analyzing the incident energy results of the four methods reveals several interesting findings and observations. The first general observation is that the results of the line to ground faults in open air are relatively close when the fault current values are within the range of the models. As the results at Junction 2 of Table 2 show, the incident energy difference is approximately 0.5/cm² (the highest delta is between maximum and minimum results). The short-circuit current at this location is 22.147 kA, which is approximately in the middle of the current range of the models (approximately 5 kA to 40 kA). As short-circuit current increases past the upper limits of the model towards a value of 45.29 kA, the incident energy difference can increase significantly. This is evident when observing the results of Junction 1 in table 3.

Another basic observation from the results listed in Table 4 is that along the length of the line, energy flux appears to be directly proportional to the change in short-circuit current. Furthermore, when the arc-fault exposure time is 100 ms or less, incident energy is well below 2.0 cal/cm². Utilities commonly assume a normalized arc fault exposure time along a transmission line segment to calculate the incident energy at different approach distances. The results in

115 kV Transmission Line

Table 2: *L-G Arc Fault (AF) with Fault Clearing Time (FCT) = 0.083 Seconds*

Fault Location	Incident Energy Results (cal/cm² @ 96 in)				
	Ibf (kA)	ArcFault M2	ArcFault M1	ARCPRO	Duke HFC
Junction 1	45.298	1.49	1.43	2.141	1.922
Junction 2	22.147	0.847	0.607	0.888	1.098

Table 3: *L-G AF with FCT = 0.670 Seconds*

Fault Location	Incident Energy Results (cal/cm² @ 96 in)				
	Ibf (kA)	ArcFault M2	ArcFault M1	ARCPRO	Duke HFC
Junction 1	45.298	12	11.56	17.219	15.513
Junction 2	22.147	6.84	4.9	7.169	7.434

Table 4: *L-G AF at Different Line Locations with FCT = 0.099 Seconds*

Fault Location	Incident Energy Results (cal/cm² @ 96 in)				
	Ibf (kA)	ArcFault M2	ArcFault M1	ARCPRO	Duke HFC
Line_25%	23.439	1.060	0.773	1.139	0.976
Line_50%	18.701	0.870	0.600	0.871	0.925
Line_75%	18.45	0.860	0.592	0.851	0.912

34.5 kV Switchgear

Table 5: *3-P AF on Outdoor Switchgear with FCT = 0.350 Seconds*

Fault Location	Incident Energy Results (cal/cm² @ 36 in)				
	Ibf (kA)	ArcFault M2	ArcFault M1	ARCPRO	Duke HFC
34.5 kV Switchgear	3.839	4.640	3.240	3.115	4.882

Table 6: *3-P AF on Outdoor Switchgear with FCT = 0.670 Seconds*

Fault Location	Incident Energy Results (cal/cm² @ 36 in)				
	Ibf (kA)	ArcFault M2	ArcFault M1	ARCPRO	Duke HFC
34.5 kV Switchgear	3.839	8.880	6.210	5.963	9.044

Table 4 assume an approach distance of 96 in. A high-voltage arc flash incident energy study may typically require the results to be presented at three different approach distances. It is also common for the results to be presented in the form of approach distances to different incident energy levels. In other words, at what approach distance is the incident energy exposure 2.0, 4.0, 8.0.… X.X cal/cm²?

One finding is related to the methods used to adjust the incident energy from open-air L-G to three-phase enclosed arc faults. Software manufacturers of high-voltage arc flash methods use different techniques to correct the energy flux. The correction factor to convert from L-G open air to three-phase open air varies between 1.5 and 2.5 p.u. The correction factor to convert from three-phase open air to three-phase enclosed varies between 1.5 and 3.5 p.u. Similar conversion factors were applied to make the comparisons in Table 5 and Table 6.

CONCLUSION

The purpose of this paper was to explore and compare the various methods to calculate the incident energy from HV and MV electric arcs. New technology that considers the entire electrical network, calculates the short-circuit current, and simulates the response of various types of protective devices removes the main disadvantages of older methods requiring labor-intensive, single-solution-at-a-time approaches that are prone to human error factors.

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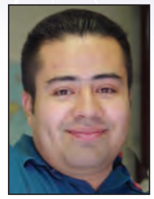

Albert Marroquin, BSEE, PE*, IEEE Senior Member, is Vice President, Validation & Verification, and Senior Principal Electrical Engineer at ETAP. A registered Professional Engineer in the state of California, he is the main designer and product manager for ETAP's AC and DC Arc Flash products, a working group member of IEEE 1584 and IEEE 1458, and an active attendee at NFPA 70E seminars and meetings.*

Abdur Rehman, BSEE, MSEE, PE*, is the Relay Operations Supervisor at Puget Sound Energy, where he leads a team of relay technicians who maintain, troubleshoot, and commission protection systems throughout PSE territory. Abdur brings a wealth of high-voltage experience in protection engineering and has performed various power system studies, high-profile incident investigations, troubleshooting, and RCAs.*

Ali Madani, BSEE*, is the lead Power Systems Engineer at AllumiaX Engineering. Ali has performed various power systems studies including modelling, short-circuit, coordination, and arc-flash studies for a variety of low- and medium-voltage facilities.*