# Arc Flash Analysis Approaches for Medium-Voltage Distribution

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***Abstract*—Arc flash is an important consideration for personnel safety. This paper explores available ways to evaluate arc flash severity for primary distribution systems, both in equipment and in open air. Results from staged tests and from utility monitoring data suggest the need to use longer arc lengths than normal as input into open-air arc flash calculations. Results from tests also show how fast arcs can lengthen and evolve to multiple phases, and performance of conductor covers was evaluated.**

***Index Terms*—Arc flash, power distribution, safety, personnel protection.**

## I. Introduction

Arc flash from faults on distribution circuits is a safety issue that can impact work practices, protection requirements for line and substation workers, and relay and other overcurrent protection settings and practices.

In this paper, we discuss approaches to analyzing arc flash on medium-voltage utility distribution equipment. The severity of an arc flash event depends on many factors, including the worker position relative to the fault, the fault duration, the fault current magnitude, and the gap spacing and arc length as it bridges the gap through the air. Fig. 1 shows a staged test for a fault initiated on the left side of the pole. Heat from the arc is released as radiation and that creates a very hot fireball. Burning hot metallic pieces are also expelled from the arcing site.

Arc voltage is an important component of the energy that develops during an arcing fault. The voltage across an arc remains relatively constant over a wide range of currents and arc lengths. The voltage across an arc ranges between 25 and 40 V/in (10 to 16 V/cm) over the current range of 100 A to 80 kA [1, 2]. The arc voltage is somewhat chaotic and varies as the arc length changes. More variation exists at lower currents. As an illustration of the energy in an arc, consider a 3-in (7.6-cm) arc that has a voltage of about 100 V. If the fault current is 10 kA, the power in the arc is $P = V \cdot I = 100\ V \cdot 10\ kA = 1\ MW$.

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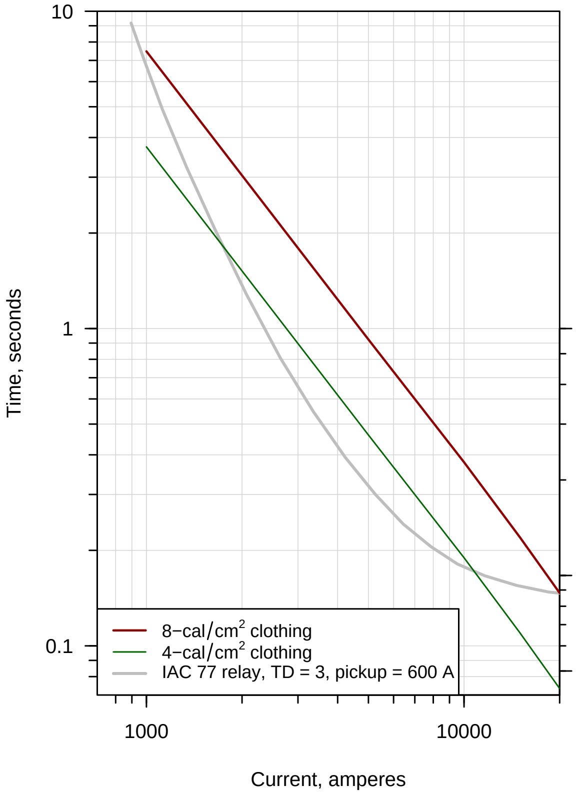
Fig. 1. A staged arc flash test.

The severity of an arc flash event is normally quantified as the incident energy that would reach a worker, normally given in terms of cal/cm$^2$. Flame resistant (FR) clothing systems have an arc thermal performance value (ATPV) rating, based on ASTM test standards [3]. This rating is the incident energy in cal/cm$^2$ on the clothing surface that has a 50% probability of causing a second-degree skin burn. The goal of an arc flash analysis is to ensure that workers have an ATPV protection sufficient to handle the incident energy that might be expected in a given work scenario. Out of 14 responses to an EPRI survey, utility minimum ATPV ratings ranged from 4 to 8.7 cal/cm$^2$ with a median value of 5.4 cal/cm$^2$.

Arc flash protection can be treated as an overcurrent coordination problem. We want the protective device to clear the fault before a fault arc could cause incident energy in excess of the rating of the clothing. Fig. 2 shows an example of coordinating open-air calculation results from ARCPRO for 4 and 8 cal/cm$^2$ clothing against a circuit breaker clearing curve with the given relay settings.

Zahalka and Hoagland [4] provide more information and examples of arc flash analysis and protection. See Haman [5] for a 12-kV case study.




Clothing curves based on ARCPRO results with a 4-in (10-cm) arc length and a 15-in (38-cm) working distance.

Fig. 2. Arc flash time-current coordination example.

As an overcurrent protection problem, two related assumptions are made:

(1) The incident energy increases linearly with time. If you double the duration, the incident energy doubles. All of the modeling approaches make this same assumption.

(2) At lower currents and longer durations, the main impact is due to lower current. Most models have almost a linear relationship between current and incident energy: if the current doubles, the incident energy doubles.

At longer durations, these assumptions are uncertain. As in Fig. 2, incident energies often become more of a concern where fault currents are lower and durations are longer. Arc flash models have been mostly tested with durations less than 0.5 sec. At longer durations, several factors can come into play: the arc can move and/or elongate (increasing energy), the arc may involve additional phases (increasing energy), and the arc may self extinguish (decreasing energy). We evaluated monitoring data and performed tests to better consider these.

When treating arc flash as a protection problem, several questions need to be addressed: Do we use bolted fault current or some reduced value? Do we use line-to-ground fault current, line-to-line, three-phase fault current, or all of the above? Do we assume only a single-phase arc and single-phase fault? If so, in what situations do we do this. Can we assume the fault self clears at some point?

Should a bolted fault be used, or should an arc impedance be used? The 30 to 40 ohm impedance given by the Rural Electrification Association [6] is too large; see also Dagenhart [7] and Burke [8]. The arc in an arc-flash scenario involves relatively low arc resistances. A 3-ft (1-m) arc has a voltage of about 1400 V. If the fault current at that point in the line was 1000 A, then the arc resistance is about 1.4 Ω. A 1-ft (0.3-m) arc with the same fault current has a resistance of 0.47 Ω. Most fault arcs have resistances of 0 to 2 Ω, so that can be used as guidance to find the minimum fault current.

## II. Overview of Analysis Approaches

A number of approaches are available for estimating arc flash. Of the most commonly cited methods, three are based on a single arc in open air: the Lee method [9], Privette's Electric Arc Heat Flux Calculator (also known as the Duke Heat Flux calculator) [10], and the ARCPRO program [11]. The IEEE 1584 method [12] is based on curve-fit regressions to mainly three-phase arc-in-a-box tests.

Ralph Lee first brought arc flash to the attention of the IEEE's Industry Application Society with his 1982 paper [9]. A single, open-air arc is modeled. The arc voltage is assumed to be 70.7% of the system voltage. This is the point of maximum power in the arc, and the voltage drop splits evenly between the system (assumed as all reactive impedance) and the arc. The arc energy is contained within a sphere with a diameter of a few inches (cm) with the diameter of the sphere increasing with the square root of the arc power. For an arc power of 5 MW, the sphere diameter is 1.62 in (4.11 cm). All energy is assumed to be released as radiation.

The Lee method has a number of weaknesses. It has not been corroborated by measurements. It does not account for arc-in-a-box effects, so it is most suited for open-air calculations.

Because the incident energy is tied to system voltage, the incident energy increases dramatically with voltage. Whether in open air or for faults in equipment, the large increase in incident energies with voltage is unreasonable. Arc lengths and arc voltages are primarily a function of gap spacings, not the system driving voltage. This was also pointed out within the IAS community by Stokes and Sweeting [13, 14].

For a 12.47-kV system with a bolted fault current of 5 kA, the Lee method predicts an arc voltage of 8.8 kV. Using a typical voltage gradient of 40 V/in, that translates into an arc length of 18.3 ft (5.6 m). Yet, that same 18-ft (5.5-m), 44-MW arc is supposed to be confined to a sphere with a radius of 5 in (13 cm). At 34.5 kV and 5 kA, a similar analysis predicts a 51-ft (15.5-m) arc fit inside an 8-in (20-cm) diameter sphere. Both scenarios show inconsistent answers, and the arc lengths assumed are well beyond what is reasonable for medium-voltage systems, either in open air or in equipment.

IEEE 1584-2002 [12], was developed by the IEEE Industry Applications Society, a society focusing on industrial and commercial power. IEEE 1584 is the most widely adopted approach to arc flash analysis. The method for estimating arc flash incident energies is based on tests performed at several short-circuit labs. From this test set, regression was used to find equations to best fit the test data. IEEE 1584 assumes a three-phase fault and is mainly geared toward arc-in-a-box evaluations. Above 15 kV, the IEEE 1584 guide and companion spreadsheet default to the Lee method.

The Privette Heat Flux calculator assumes that incident energy drops with the distance squared. It does not account for arc-in-a-box effects. It assumes that all energy is released as radiation. The energy received at a target is a function of what is called a shape function or transfer function. The shape factor used is that between a cylinder (the arc) and a rectangle (the person) at some distance. The shape factor is a complicated equation involving the geometry of the arc and the receiving shape that must be integrated. The system voltage is only used to estimate if the arc will sustain. It assumes about 150 V/in (60 V/cm) is needed to sustain an arc.

ARCPRO is a commercial program for analyzing arc flash incident energies, developed by Kinectrics. The ARCPRO algorithm is based on the work of Bingwu [15], but it is not completely described in any peer-reviewed paper. The ARCPRO model assumes the following [16]: a vertical free burning arc in air, an arc length much greater than arc diameter, a one arc column, either phase-phase, or phase-ground, no electrode region heat transfer, and an optically thin plasma and gas. Cress [16] reported that ARCPRO was verified with over 300 test points for arc energy and incident energy for currents from 3 to 25 kA, arc durations from 4 to 35 cycles, distances from 8 to 24 in (20 to 60 cm), and with gaps from 1 to 12 in (2.5 to 30 cm).

The 2007 National Electrical Safety Code (NESC) [17] requires an arc flash assessment be performed on systems above 1000 V. They do not provide specifics in general but do offer a table with default assumptions based on an ARCPRO analysis for open-air, single-phase-to-ground faults. The NESC table 410-1 footnotes specify a 15-in (38-cm) separation distance from the arc to the employee for glove work and arc gaps as follows: 1 to 15 kV = 2 in (5 cm), 15.1 to 25 kV = 4 in (10 cm), 25.1 to 36 kV = 6 in (15 cm). Proposed OSHA rules provide a similar table and assumptions [18].

## III. Comparison of Analysis Approaches

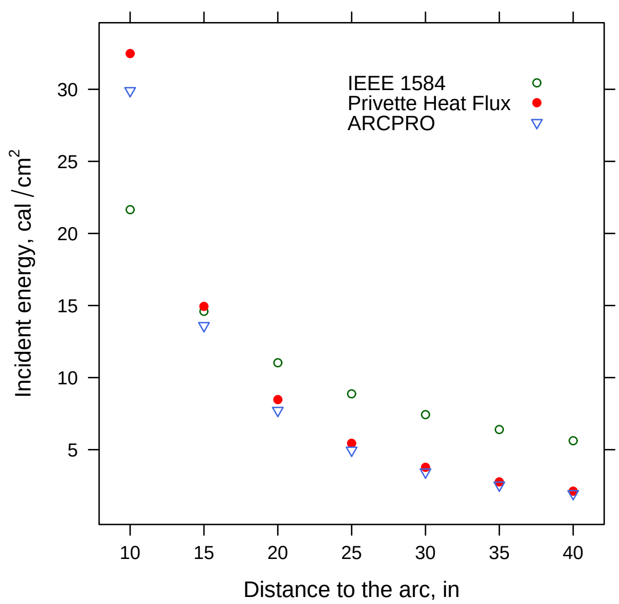
TABLE I compares results for the main arc flash calculation tools for a single-phase open arc at several voltages and for arcs in switchgear for several system voltages. ARCPRO, the Privette Heat Flux program, and the Lee method were all designed for single arcs. For the open-air cases, IEEE 1584 assumes a three-phase fault. The arc gaps for the open, medium-voltage cases were chosen based on the NESC / OSHA table assumptions. The arc gaps for the switchgear cases at 480 V and 12.5 kV were chosen based on the IEEE 1584 defaults; at voltages above that, estimates were used.

TABLE I
Arc Flash Calculation Comparisons

| System voltage (V) | Arc gap (in) | Incident energy, cal/cm$^2$ ARCPRO | Privette Heat Flux | Lee Method | IEEE 1584 |
|---|---|---|---|---|---|
| Open, single-phase arc, line-to-ground voltages given | | | | | |
| 277 | 1 | 2.86 | 1.81 | 1.9 | 3.2 |
| 7200 | 2 | 4.61 | 3.60 | 49.5 | 5.3 |
| 14400 | 4 | 7.34 | 7.11 | 99.1 | 171.9 |
| 19940 | 6 | 9.51 | 10.45 | 137.2 | 237.2 |
| Switchgear, single line-to-line arc or three-phase arc, line-to-line voltages given | | | | | |
| 480 | 1.2 | 3.25 | 2.17 | 3.3 | 6.4 |
| 12500 | 6 | 9.51 | 10.45 | 86.0 | 9.2 |
| 25000 | 9 | 12.10 | 15.00 | 171.9 | 171.9 |
| 34500 | 12 | 15.80 | 18.94 | 237.2 | 237.2 |

Distance to arc = 18 in (46 cm), I = 10 kA, duration = 0.5 sec
1 in = 2.54 cm

Fig. 3 compares incident-energy predictions for three of the tools as a function of distance for a 12.5-kV switchgear fault. ARCPRO and Privette Heat Flux use a single phase-to-phase arc with an arc gap of six inches, the default for switchgear in IEEE 1584. Neither ARCPRO nor the Privette model include a multiplier factor to account for multiphase arcs or arc-in-a-box effects. For distances in the range of 15 to 18 in (38 to 46 cm), it appears that no such multiplier is necessary for these assumptions. At a 36-in (0.9 m) working distance (the IEEE 1584 typical distance for medium-voltage switchgear), a multiplier of 2.5 is necessary to make ARCPRO values equal to IEEE 1584 values.




Voltage = 12.5 kV, arc gap = 6 in (15 cm), I = 10 kA, duration = 0.5 sec
1 in = 2.54 cm

Fig. 3. Comparisons of arc flash analyses.

It is difficult to compare tools, as each tool can have different assumptions. Different arc gap spacings, system voltages, and fault currents will change relative performances. Variations in parameters are as follows:

*Duration* – All of the tools vary linearly with fault duration, meaning if the duration doubles, the incident energy from an arc doubles. In actual practice, longer duration arcs may be more severe due to arc elongation and movement.

*Fault current magnitude* – The Privette Heat Flux and Lee approaches both assume that the incident energy increases linearly with magnitude. Both ARCPRO and 1584 show increasing energy somewhat more than linearly (multiplying current by 10 increases energy by about a factor of 11.5).

*Arc gap* – In the Privette Heat Flux program, incident energy increases almost linearly with arc length. ARCPRO is close to that, depending on geometries. Both the Privette and ARCPRO tools have arc length as inputs, and IEEE 1584 uses arc gap internally. These are often treated as the same, but the arc length can be longer than the arc gap. IEEE 1584 equations predict a shallow exponential relationship. Moving from a one inch to a two inch (2.5 to 5 cm) arc gap adds about 9% to the incident energy, and for gaps up to 10 in (25 cm), it continues linearly. Note that the arc gap is not a direct input in the 1584 spreadsheet as it uses default gaps for different equipment. The Lee method does not consider the arc length; it assumes the length that creates maximum arc energy.

*Distance to the arc* – ARCPRO, the Privette Heat Flux, the Lee method, and 1584 for open air all predict incident energy varies inversely with distance squared. For faults in equipment, IEEE 1584 has differing coefficients of distance with incident energy varying in the range of $1/d$ to $1/d^{1.5}$.

*System voltage* – ARCPRO and 1584 use the system voltage to determine the arcing current (important at secondary voltages). ARCPRO and the Privette Heat Flux use the system voltage to determine if the arc will sustain. Only the Lee method predicts significant direct effects of system voltage on incident energy.

*Arc movement and plasma effects* – None of the methods account for arc movement. Only IEEE 1584 accounts for plasma effects (and that accuracy has been questioned [13, 19]).

## IV. Medium-Voltage Arc-in-a-Box Calculations

For failures in three-phase equipment like circuit breakers or switches, IEEE 1584 is widely used. It is based on tests that reproduce arcs in equipment. These arc-in-a-box tests included plasma effects. For medium-voltage switchgear, IEEE 1584 provides a typical working distance of 36 in (91 cm).

Fig. 4 compares the predicted incident energies compared to the maximum measured incident energies for the medium-voltage tests in the IEEE 1584 test set. The two different groupings represent data from tests from different test labs.

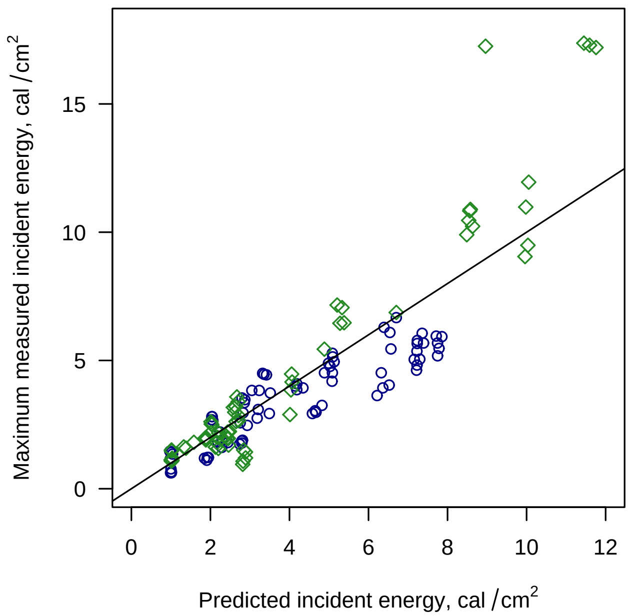


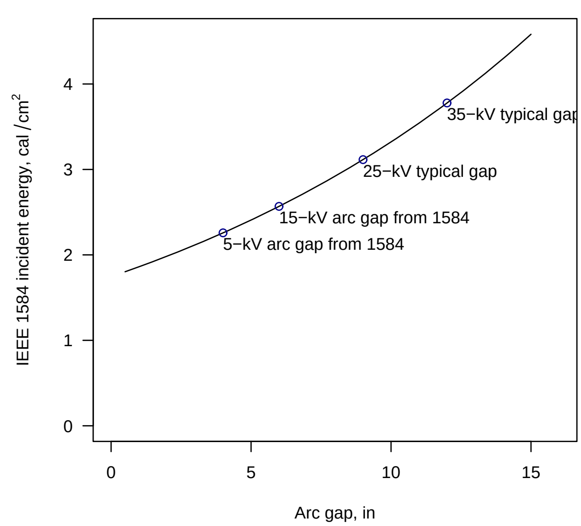

Fig. 4. Predicted versus measured incident energy for the IEEE 1584 dataset.

The Lee method predicts unreasonably high increases in incident energy with increasing system voltage, due to his assumption of an arc resistance that maximizes arc energy.

Spacings in higher-voltage switchgear are not considerably higher than 15-kV systems. Energy is a function of gap spacings and arc "bowing", not system voltage. Fig. 5 shows the variation predicted by IEEE 1584 with gap length. Several gaps are highlighted: at 5 and 15 kV, the 1584 arc gaps of 4 and 6 in (10 and 15 cm) are shown. For 25 and 35 kV, typical spacings of 9 and 12 in (23 and 30 cm) are shown. The difference between 15-kV class results and higher voltages are as follows:

25 kV: for a gap of 9 in (23 cm), results are higher by 21%

35 kV: for a gap of 12 in (30 cm), results are higher by 47%




Assumptions: 10-kA bolted fault current, 0.2-sec duration, arc in switchgear, solidly grounded, and a 36-in (91 cm) working distance.

Fig. 5. IEEE 1584 variation with arc gap.

Another more conservative approach is to simply increase the IEEE 1584 results by a multiplier based on the gap length relative to the 6-in (15-cm) gap assumed for 15-kV systems as follows:

25 kV: for a gap of 9 in (23 cm), multiply results by 1.5

35 kV: for a gap of 12 in (30 cm), multiply results by 2.0

## V. Arc Characteristics Based on Monitoring

Arc length and arc voltage are important arc characteristics impacting medium-voltage, open-air arc flash hazard estimation. To a first approximation, arcs have a constant voltage drop. If we know arc voltage, we know arc length. The arc length is a key input into ARCPRO and the Privet method. In both of these tools, the arc length determines the arc voltage. The Privette calculator assumes a constant arc voltage of 30 V/in (11.8 V/cm). ARCPRO calculates a voltage that increases somewhat with current; based on a 10-in (25-cm) arc, at 5 kA, the arc voltage is 39.5 V/in (15.6 V/cm), and at 10 kA, the arc voltage is 42.6 V/in (16.8). The arc voltage (along with the arc current) determines the arc power.

We have two datasets with power quality monitors on overhead distribution circuits. These record voltages and currents on all three phases. When a monitor captures a deep voltage sag during a fault directly upstream, it is seeing the arc voltage. If the fault is not directly upstream but off of a tap upstream, there can be a sinusoidal component mixed in with the arc voltage. To best estimate the arc voltage, we developed an arc-voltage estimator. The estimator algorithm uses the following approach:

(1) Find the 3rd, 5th, and 7th harmonics.

(2) Divide the 3rd, 5th, and 7th harmonics by 0.3, 0.18, and 0.129 respectively. Each of these is an estimate of the arc voltage if the arc were an ideal square wave.

(3) Take the median of these scaled square-wave estimates.

(4) Find the rms voltage.

(5) Take the minimum of the rms voltage and the median of the square-wave estimates.

This algorithm is applied on a rolling basis, sweeping along the voltage wave. To make automatic identification of arc voltages easier, we concentrated on voltage sags with the following characteristics: single-phase voltage sags, sags to below 40% of nominal, and sags to below 5% or those with 3rd above 20% of the fundamental and 5th harmonic above 10%. EPRI's Distribution Power Quality (DPQ) project was the bases for one fault dataset. In the DPQ study, power quality monitors were installed on distribution primaries at voltages from 4.16 to 34.5 kV [20, 21]. Two hundred seventy seven sites resulted in 5691 monitor-months of data from 1993 to 1995. In most cases three monitors were installed for each randomly selected feeder, one at the substation and two at randomly selected places along the feeder.  We used the downline feeder results for these analyses. A similar dataset was provided by a DPQ participant, referred to as Utility A, who kept their monitors in place after the study ended, and the data covered from 1995 until 2008.

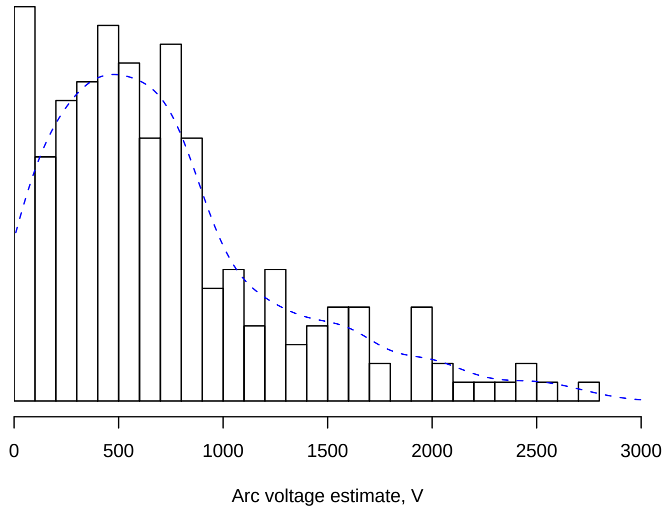



Fig. 6. Histogram of arc voltages in the DPQ study.

We used the subset of 3,465 DPQ events captured as “rms events” where the voltage dropped below 40% of nominal. This made processing the events more manageable. From this set of voltage sags, we applied the criteria given above for likely arc voltages followed by manual removal of events that were not faults (circuit interruptions or monitor errors sometimes satisfied the criteria). This left a dataset of 209 events. The appendix shows the voltage on the faulted phase during each of these events. For these events, we only have a waveshape for the first 0.2 sec of the event, so our arc voltage and arc length estimates are for the first 0.2 sec of the event.

Fig. 7 shows an example arc voltage recorded. For the first 3.5 cycles, the fault looks fully sinusoidal, probably because it is a bolted fault. Then, it transitions to having a more traditional arcing wave signature. Fig. 7 shows the rolling rms voltage superimposed upon the arc voltage estimate.

The 2007 NESC table 410-1 and OSHA 1910 table assume certain arc lengths for different distribution voltage classes: 2 inches for 15-kV class systems, 4 inches for 25-kV systems, and 6 inches for 35-kV systems. The results from utility monitoring are summarized in TABLE II. Equivalent arc lengths are determined based on using a constant arc voltage gradient of 40 V/in (15.7 V/cm).

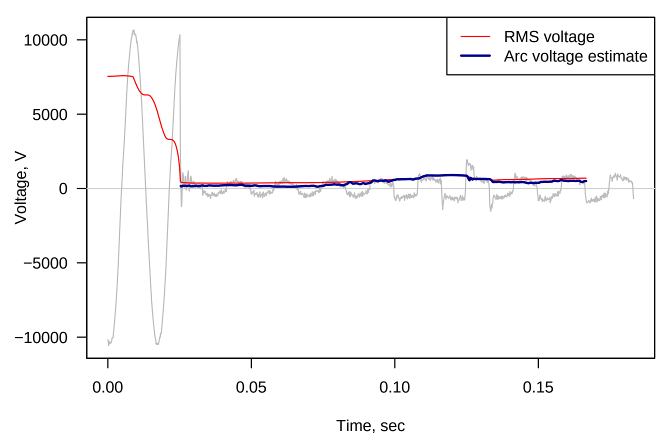



Fig. 7. Example of an increasing arc voltage with the arc-voltage estimation.

We also tried another approach to estimate arc voltages based on substation measurements. This allows a different estimation approach, and it opens up more data for review as more utilities have substation data than have downline feeder data. Radojevic et al. [22-24] initially developed this arc voltage estimation. Their approach relied on the approximation that the arc voltage was a square wave. A modified version of this method was developed to evaluate arc characteristics and also to improve fault locating algorithms [25, 26]. Results from one utility are similar to those found with more direct measurements as shown in TABLE II.

TABLE II
ARC VOLTAGES AND EQUIVALENT ARC LENGTHS FROM VARIOUS MONITORING DATASETS

| Data source | Arc voltage, volts* Median | Arc voltage, volts* 25 – 75% Range | Equivalent arc length, inches (1 in = 2.54 cm) Median | Equivalent arc length, inches (1 in = 2.54 cm) 25 – 75% Range |
|---|---|---|---|---|
| EPRI DPQ | 594 | 301 – 954 | 15 | 7.5 – 24 |
| Utility A | 368 | 222 – 630 | 9 | 5.5 – 16 |
| Utility B | 605 | 235 – 1058 | 15 | 5.8 – 26 |

* The median arc voltage up to the first 0.2 sec of the event.

Notes: The DPQ data and utility A results are from downline feeder measurements; utility B results are estimated from substation measurements.

Other findings on arc voltage and arc length from analysis of the monitoring data include:

*Impact of system voltage* – Data from both the DPQ study and from utility A data suggest that longer arc lengths are appropriate at higher-voltage systems. In the DPQ dataset, the median arc voltage for 15-kV systems was 578 V (n=183) compared to a median of 833 V for 25-kV systems (n=26).

*Fault cause* – The data from utility B where cause code information was available showed longer arc lengths for some fault types, particularly conductors on crossarms.

*Fault duration* – Most arcing faults stayed constant during the first ten cycles captured by these power quality monitors. Some events had arcs that lengthen at up to 12 in/cycle (60 ft/sec or 18 m/sec).

*Faults evolving to multiple phases* – For utility A and B, where we had access to several fault events longer than 0.5 sec, one-third to one-half of these faults evolved to multiple phases. For utility B, the median time to involve another phase was 0.2 sec, but less than 25% of faults evolved to another phase within 0.1 sec.

## VI. OVERHEAD ARC FLASH TEST RESULTS

Exploratory arc-flash tests were done at the EPRI Lenox, MA, facility to establish realistic arc lengths and voltages, find how fast arcs can lengthen and evolve to multiple phases, and evaluate the performance of conductor covers. The setup used a 4160-V supply with a three-phase available fault current of about 3500 A. The main findings of the testing are:

*Arc length and arc voltage* – The arc lengths assumed in the NESC tables are unrealistically short. In most work scenarios that could lead to a fault being initiated, the arc length quickly grows to many inches and sometimes a few feet.

*Movement* – Once initiated, a fault arc can grow and move quickly. Magnetic forces from the fault current dominate the arc movement. The fireball is normally pushed in the same direction as the arc, and the fireball also rises vertically from thermal forces. In a phase-to-phase event, velocities of tens of feet per second (several meters per second) were observed .

*Directionality* – Even in open air, some fault scenarios are directional, meaning the fireball is focused in one direction (like a flamethrower), similar to arc-in-a-box type faults.

*Conductor coverup* – Conductor covers are effective at reducing the likelihood of flashovers to protected conductors from a fault initiated elsewhere.

Even if arcs start across a short gap, the arc length and arc voltage can increase rapidly. This was observed with several tests: a jumper wire shorting phase to phase or phase to ground, a solid pipe bridging conductors, and a mock tool bridging a bushing. In nine similar tests, the median arc voltage over the first 0.1 sec (6 cycles) was 446 V, corresponding to an 11-in (28-cm) arc length.

Fig. 8 shows results from a test with a phase-to-phase jumper tied solidly at one end and through a #12 wire at the other. During the test, the #12 wire acts as a fuse and burns away within a short time, and the arc is free to move. We attached the jumper to a stirrup to minimize damage to the conductor. The main goal of this test is to mimic a case where a worker accidently jumpers an energized phase to a grounded conductor or to another energized phase. The side with the connection through the #12 wire is the side where the arc occurs right when the worker touches the jumper to that conductor.

The video frames on the right in Fig. 8 are from a dark filter that passes infrared and some red light. This allows us to see the hottest part of the arc, the arc channel. Fig. 8 also shows the voltage between phases for the line-to-line fault initiated. In this particular event, the #12 wire took several cycles to burn away because more than one wire was jumpered to the stirrup. Once the connector wire burned away, the voltage and arc length increased to several feet (more than one meter) until the fault self cleared. The 4160-V was unable to sustain an arc that long. For 15 to 35-kV systems, much longer arcs could be possible.

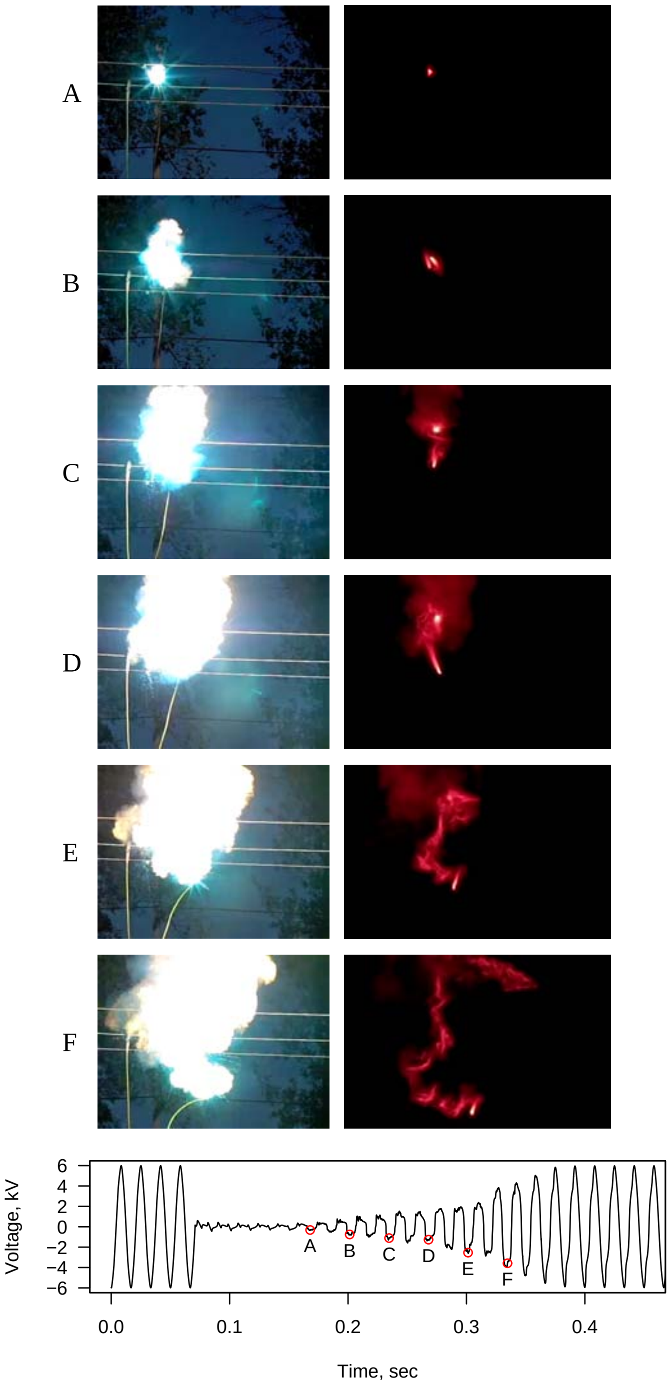



Fig. 8. Video snapshots and voltage waveform for a jumper pulling away.

A number of tests were performed to evaluate the effectiveness of conductor covers at preventing faults from escalating to multiphase faults. This is important if you assume only line-to-ground faults in your arc-flash analysis for glove work. We performed a number of tests where a fault was initiated about two feet (60 cm) under an unfaulted conductor. Of tests without any conductor covers, the unfaulted and unprotected phase flashed over at an average time of 0.1 sec. Fig. 9 shows a filtered image overlayed on a background as the arc attaches to the unprotected phase above. In five tests using line hoses to cover the unfaulted phase, the phase did not flashover in two of the cases (fault duration = 1.3 sec). In the cases where it did flashover, the average time to flashover was 1.0 sec. Based on the videos of the arcs and examination of the line hoses after tests, all flashovers that occurred with cover-up were to exposed parts of conductors. We found no evidence that any events punctured through the coverings or snaked through the seams even though the line hoses were fully engulfed in the plasma fireball from the arc (see Fig. 10 for a test without flashover).

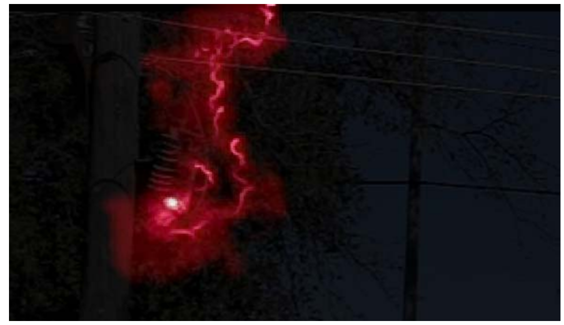


Fig. 9. Arc that attaches an unfaulted phase at 90 msec.

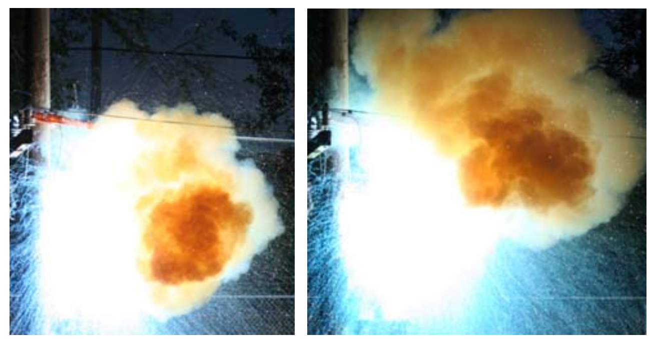


Fig. 10. Arc test with a line hose protecting the unfaulted phase.

## VII. Discussion

For open-air medium-voltage evaluations, the monitoring and test results reported here suggest that longer arc lengths are suitable for inputs to arc flash analyses than the default assumptions in NESC and OSHA. The NESC table gives lengths of 2 to 6 in (5 to 15 cm), and arc lengths of between 10 and 15 in (25 to 38 cm) are more realistic. The analyses tools do need more evaluation and comparison with tests using longer, more realistic arcs.

For switchgear and other equipment, IEEE 1584 is commonly used for analysis. For 25- and 35-kV class voltages, the Lee method makes unrealistic assumptions, so using a multiplier to the 15-kV results in IEEE 1584 is a suitable option.

Further work is warranted in the area of medium-voltage arc flash, particularly arc-in-a-box testing with wider electrode spacings to more confidently extend the IEEE 1584 predictions to 25- and 35-kV systems and open-air testing with calorimeter instrumentation to measure incident energies with longer arc lengths.

### ACKNOWLEDGEMENTS

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