Medium-Voltage Arc Flash in Open Air and Padmounted Equipment

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***Abstract*—Arc flash is an important consideration for personnel safety. This paper shows test results for overhead arc flash scenarios and arc flash in a padmounted switch. Both scenarios result in more incident energy than expected. For overhead arc scenarios, longer arc lengths are considered when analyzing arc flash. For the padmounted switch, an equation is developed to help coordinate protective clothing with minimum approach distances and upstream protective relaying.**

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

I. INTRODUCTION

Arc flash analysis and protection on distribution circuits is still evolving. More test data, better understanding of arc physics, and more industry experience with arc flash events will help utilities protect workers. In this paper, we discuss results of arc flash tests in overhead scenarios and in a padmounted switch.

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 or energy breakopen threshold (Ebt) rating, based on ASTM test standards [1]. 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 (ATPV) or a 50% probability of fabric breakopen (Ebt). The goal of an arc flash analysis is to ensure that workers have ATPV or Ebt protection sufficient to handle the incident energy that might be expected in a given work scenario.

An arc flash study is like a protective relaying study where the protective devices must clear faults before a worker would be burned based on the rating of the clothing system. To estimate incident energies on overhead distribution lines, most utilities follow the assumptions and approach used in the 2007 NESC [2] which is based on the commercial ARCPRO program [3]. For switchgear and other arc-in-a-box situations, the IEEE 1584 method [4] is often used.

II. ARC FLASH ON OVERHEAD DISTRIBUTION LINES

Previous tests [5, 6] have shown that the assumptions in the NESC for arc lengths of two, four, and six inches (5, 10, and 15 cm) for 15, 25, and 35-kV systems are unrealistically short. Even if an arc starts with a short length, the arc will quickly grow, normally to more than ten inches (25 cm), including the event in Fig. 1. Estimates from utility monitoring of faults also suggests use of longer arc lengths [5, 6].

Additional testing documented here shows several scenarios where incident energies are much higher than those calculated using the NESC arc-length assumptions.

Early industry testing of open-air arcs has been staged in conditions that are unlikely to represent real conditions. Most testing has focused on establishing a known arc path. The open-air testing done by Kinectrics to validate the ARCPRO modeling program was based on a single arc between electrodes where the return path was arranged as a cage to limit magnetic fields and limit arc movement [7]. While this arrangement leads to predictable arc lengths and consistent measurements, it is unrealistic in that it does not consider several important factors. The ARCPRO model does not consider arc movement which can make the distance between the arc and the worker different from initial assumptions. Second, the present model does not consider convection or conduction and relies primarily on heat transfer from

Fig. 1. Example arc across a bushing after being initiated with a metal tool across the bushing.

Manuscript received December 10, 2010. This work was supported by the Electric Power Research Institute (EPRI) under work order 067148.

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radiation. Third, most published open-air testing has been with durations less than 0.2 sec, and under some relaying conditions, arcs on distribution systems can last longer than that. Longer duration arcs allow for even more arc movement and allow for development of larger arc plasma balls making convective heat transfer a bigger issue.

A. *Test Setup*

Testing was performed at EPRI's Lenox, Massachusetts testing facility. The fault source was created from a 4160-V circuit fed by a 23-kV circuit. This voltage is high enough to sustain arcs long enough to be representative of most overhead distribution construction spacings to 35 kV. The 2500-kVA transformer has a 5.9% impedance. The available fault current for three-phase faults is about 3500 A.

For measuring incident energies and heat rates, copper slug calorimeters were installed. These are thin copper plates with a thermocouple attached. The temperature change measured by the thermocouples before and after the arc flash event is used to estimate the incident energy to the copper plate. Calorimeters were built and calibrated according to ASTM specifications [1, 8].

B. *Bushing Tests*

Initiating a fault with a tool across a transformer bushing was a common fault scenario we investigated. An aluminum pipe was used to bridge the bushing as shown in Fig. 2. The circuit was energized by closing a circuit breaker into the fault. The transformer contained no oil, and the core and coil assembly had also been removed. The bushings installed were generally seven to eight inches (18 – 20 cm) long.

Generally, transformer bushings are not high-risk arc flash scenarios. Overhead transformers generally have external fuses, and these will operate quickly in case of a fault across a bushing. Completely self-protected transformers have an internal fuse, and for utilities that use these without an external fuse, the arc flash hazard at the transformer primary bushing is increased (in addition to decreasing reliability). Other overhead equipment may also have bushings that should be similar in response to the transformer bushing tests. These include voltage regulators and reclosers. These are commonly on the mainline and are subject to the clearing time of the substation circuit breaker or recloser.

Calorimeters were mounted on the perimeter, circling the fault initiation point as shown in Fig. 2 and Fig. 3. Normally six to eight calorimeters were used. A pair of calorimeters was installed on a fiberglass plate supported by a fiberglass tube. Other than the calorimeter plates and the thin instrumentation wires to the calorimeters, nothing electrically conductive was used on the calorimeter supports.

Fig. 1 shows an example of an arc event as viewed through an infrared filter. The arc initially starts between the mock tool and the phase conductor. After the tool is blown clear, the arc lengthens. Fig. 3 shows an overhead view of the transformer. This view is particularly good for viewing arc movement relative to various calorimeter locations. Fig. 4 shows frames from a 300 frame-per-second video recording from overhead. Video records generally show high variability during tests.

Fig. 2. Mock tool across the transformer bushing prior to a test.

Fig. 3. Overhead view prior to test 3.

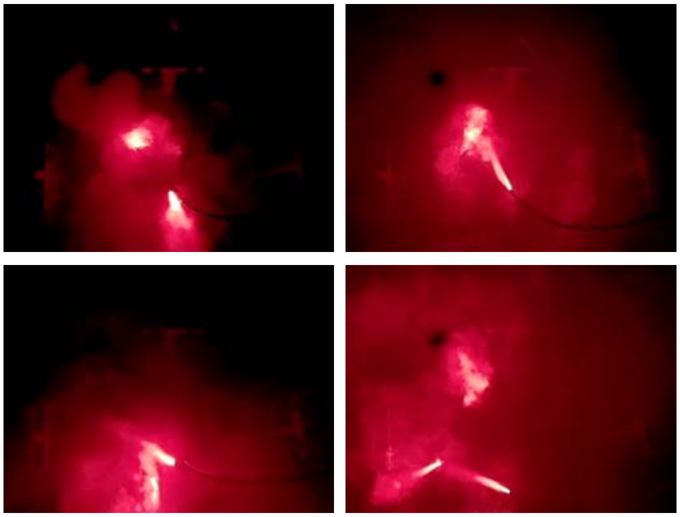


Fig. 4. Video frames from test 3 for an arc flash across a bushing as viewed through an infrared-passing filter.

Fig. 5 shows 300-fps video frames averaged over the duration of test 3, a 3.7-kA, 1.4-sec event. The numbers in Fig. 5 are the incident energies (in cal/cm^2) for test 3 measured by the closest calorimeters. Even though the measurements were 22 inches (56 cm) from the arc initiation point, as the arc moved, the arc could get much closer than that. The averaged frames align well with the differences in incident energies. The hottest regions are the brightest.

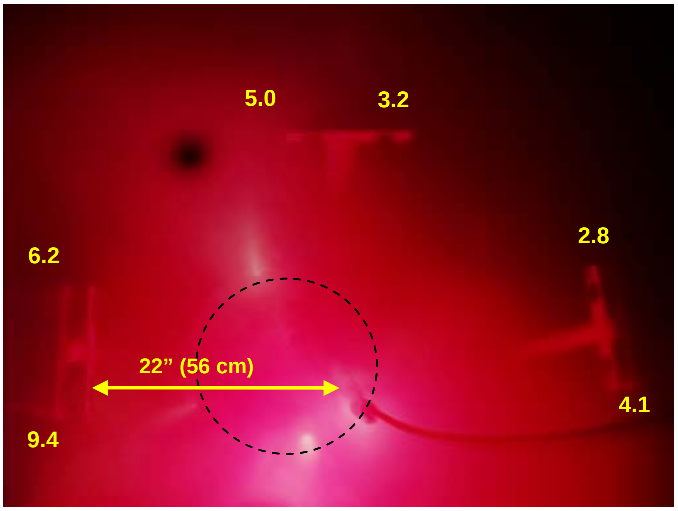


Fig. 5. Average image intensity during test 3 with calorimeter readings (cal/cm^2) indicated.

Fig. 6 shows heat rates measured at all calorimeters during the bushing tests. This graph illustrates the variability. For a given test, there was often at least a factor of five difference between the highest and lowest reading. Differences were mainly from arc movement and directionality which varied by test. Fault durations were from 0.5 to 2.0 sec as determined by relay settings on the laboratory circuit breaker.

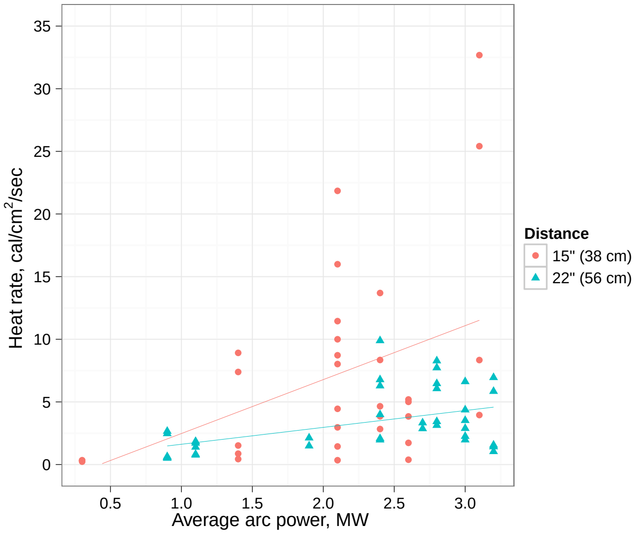


Fig. 6. Bushing test arc power vs. heat rate and distance.

Fig. 7 shows ARCPRO predictions of heat rates using a two-inch (5-cm) arc length. The other inputs to ARCPRO (fault current and duration) are adjusted based on the test data. The solid line in the graph shows the one-to-one line; the area above the line is where measurements exceeded predictions. Over 80% of measurements exceed predictions.

Fig. 8 shows the same comparison but with an arc length in ARCPRO of 15 inches (38 cm). The 15-inch (38-cm) arc length covers 78% of the test results.

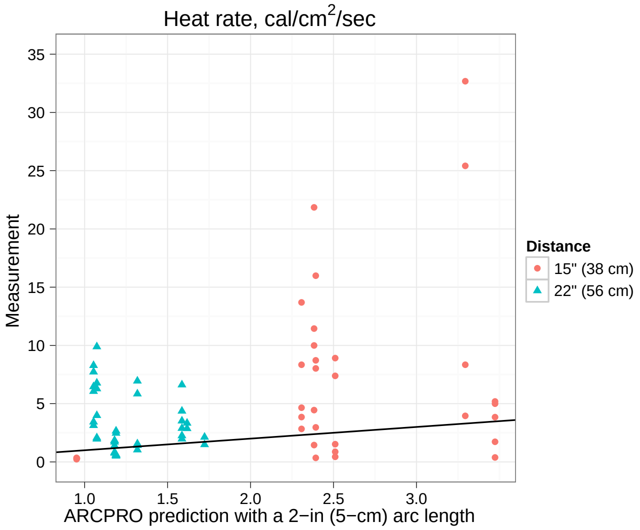


Fig. 7. ARCPRO prediction versus heat-rate measurements.

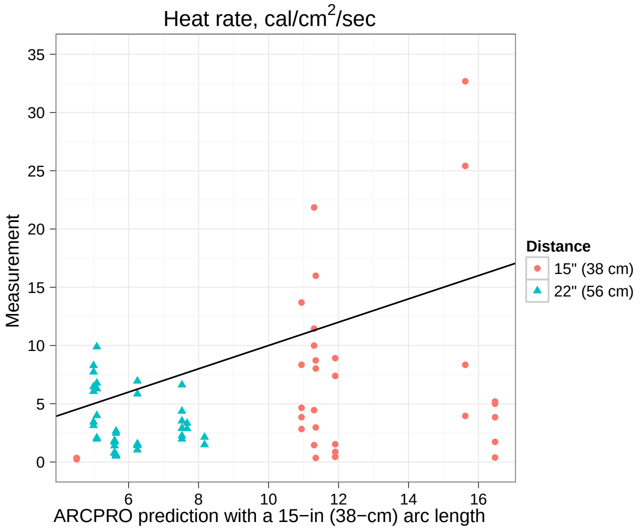


Fig. 8. ARCPRO prediction versus heat-rate measurements assuming a 15-in (38-cm) arc length.

C. Dead-End Tests

A number of arc flash tests were done on a dead-end structure (see Fig. 9). The distance between phase conductors was 24 inches (61 cm). That is tighter than most medium-voltage configurations, but the arc flash response is likely to be similar. If the spacing were wider, the arc could get longer, but there would be lower magnetic fields pushing it out. Faults were initiated by a thin wire wrapped phase to phase to phase. That is an artificial fault initiation, but a similar fault could happen from anything that causes a phase-to-phase fault anywhere on the span. After going phase to phase, the fault will motor to the end of the line at tens of feet per second. This test was intended to measure incident energies from that scenario. Calorimeters were located down-line of the dead-end configuration, up-line of the dead-end (between phases), and above the dead-end structure.

Fig. 9. Three-phase dead-end structure prior to an arc flash test.

Fig. 10 shows an arc event on the dead-end structure. Magnetic forces push the arcs away from the source, into and past the crossarm, and the heat tends to make the arc push upwards.

Fig. 11 shows a side view of one of the dead-end tests. This is from 300-fps video frames averaged over the event duration. Calorimeter readings and key distances are given. This event had a 3-kA fault current and lasted for 1.34 sec.

Fig. 10. Side view of a three-phase fault on a dead-end structure.

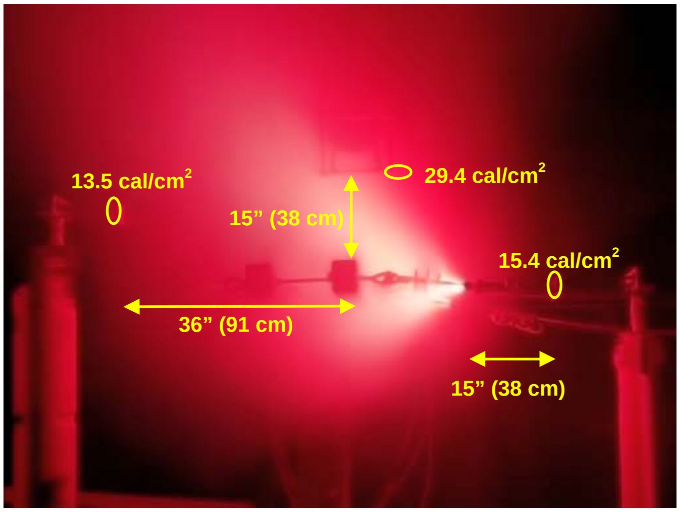


Fig. 11. Side view with video frames averaged.

Fig. 12 shows measured heat rates versus ARCPRO predictions for several of the dead-end tests. Note that the ARCPRO predictions are based on a 15-inch (38-cm) arc length and a single arc. Even with the 15-inch (38-cm) arc length assumption, over 70% of measurements exceeded predictions. These results show that this overhead scenarios—work on dead-end structures—work at hotstick distances (36 to 48 inches/0.9 to 1.2 m) has higher risk than previously thought. Incident energies are much higher than predicted by present modeling methods. This is mainly because (1) arc lengths are much longer than presently assumed, and (2) arc movement is not accounted for. Using a longer arc length in ARCPRO is easy. Accounting for movement is not easy.

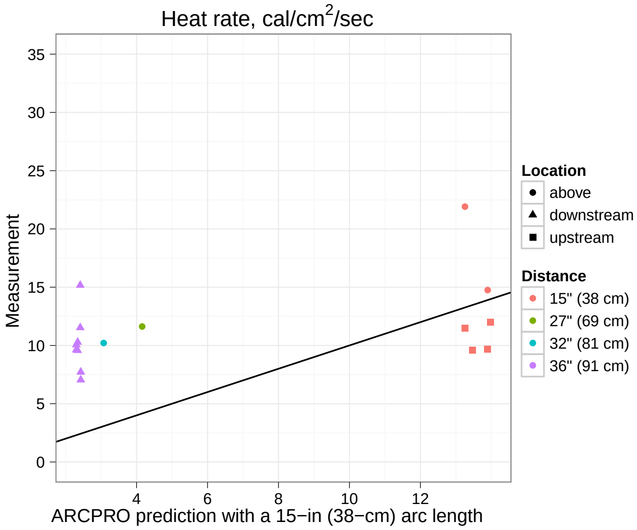


Fig. 12. ARCPRO prediction versus heat-rate measurements for dead-end faults.

If longer arc lengths are used in ARCPRO, predictions match better with measurements. What are the impacts to protection and clothing systems needed? Fig. 13 shows that clearing times would need to be substantially reduced for an 8-cal/cm^2 clothing system if the arc length were increased from two to fifteen inches (5 to 38 cm). These curves use a 15-inch (38-cm) working distance as assumed in the NESC for live glove work.

Some of the implications of assuming an arc length of 15 inches (38 cm) or longer and a clothing curve that requires faster tripping are:

Fast trip – To meet the lower clothing curve on many circuits, a fast trip of some sort would be required. This is common as the hot-line-tag feature of a recloser, but it is less common for substation relays. Adding the feature to substation relays will likely require digital relays, and possibly SCADA control of the relay settings group. A fast trip will also miscoordinate while it is enabled.

High currents – At currents above 10 kA, the clearing time of some devices may not be fast enough to provide protection.

Down-line devices – With existing assumptions used by most utilities, open-air work beyond down-line feeder devices such as fuses and reclosers would normally be a non-issue.

With a lower curve like the 15-inch (38-cm) curve in Fig. 13, large fuses (140 and 200 A) and some reclosers may need review.

More feeders affected – With a lower curve, more feeders will have issues. This will require more operational work (hotsticking where gloving was used previously or circuit reconfigurations to lower fault currents or speed up tripping) and overcurrent protection work to address the additional feeders impacted by a lower curve.

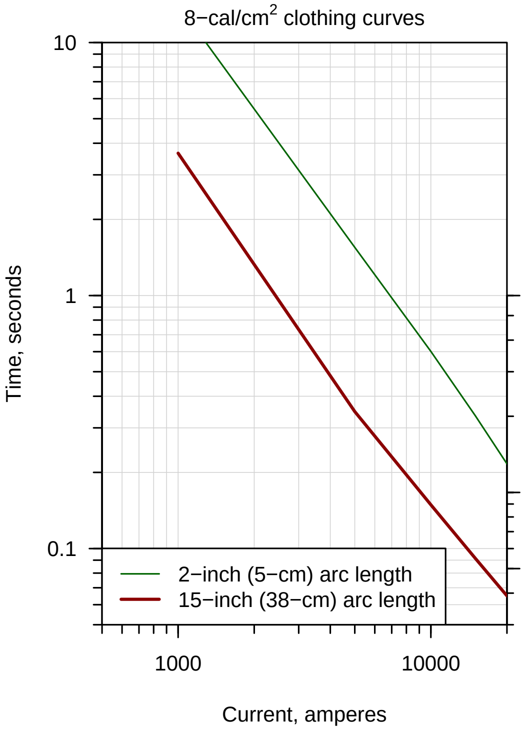


Fig. 13. Comparison of clothing curves based on ARCPRO predictions with different arc lengths.

Even though the testing clearly supports the incident energy levels measured at a working distance of 15 inches (38 cm), are the results overly conservative if a longer arc length is used? To address this, the industry will have to address the following questions:

- Is arc flash protection designed to protect against all burns, to limit burns enough to keep exposed workers alive, or somewhere in between?
- Do arc-flash accident rates and severity on open-air work justify the additional reductions in potential incident energy and the reduced clearing times needed?
- Is the 15-inch (38-cm) working distance reasonable? What is the right arc length to use?
- How does one handle multi-phase faults and especially severe cases like the scenario of the dead-end fault tests?

Based on tests, a 15-inch (38-cm) arc length is not the worst case. We chose it for discussion purposes because it covered a large number of test measurements from the bushing tests, and it matched “middle of the road” arc lengths based on other tests and from estimates from utility monitoring data. Arc lengths exceeded 70 inches (1.8 m) in some of our tests (about the maximum length that our 4.1-kV source could sustain). A 15 to 35-kV system can support very long arcs. The main limiting factor is often the distance between conductors. As we’ve seen, the arc length can also change with time; if it starts short, it takes a few cycles to increase in length, but we’ve also seen cases where arc lengths can increase very quickly. Two factors make the 15-inch (38-cm) curve conservative:

Arc lengthening – At fault times of 0.1 to 0.2 sec corresponding to fault currents above 8 kA, arcs are likely to be smaller, and the fireball will not have had time to expand as much.

Worker movement – At fault times above 0.8 sec, worker movement will normally reduce the effective incident energy. Because incident energy depends so strongly on distance, even a small movement can greatly reduce energies.

The 15-inch (38-cm) working distance assumed in the NESC for glove work is also open for discussion. Because arc flash energy exposure drops quickly with distance, we should consider that 15 inches (38 cm) may be on the conservative side. Workers often are within 15 inches (38 cm) of energized conductors, but it is difficult to say how often they are this close to likely fault initiation points. Applying grounds or jumpering conductors are scenarios where a worker may initiate a fault where the working distance probably is something like 15 inches (38 cm). For other scenarios, the distance is harder to define and likely to be longer.

Better data on industry accident rates and detailed records of arc flash accidents could better answer some of these questions. As an industry, it would benefit the industry to collect more detailed data on arc flash incidences to better determine appropriate working distances to use. Before that is done, utilities will have to use judgment on what assumptions to use when doing arc flash assessments on open-air medium-voltage systems.

Overall, we recommend assuming longer arc lengths than are used in the 2007 NESC, but we await more industry feedback as to the most appropriate set of assumptions.

III. ARC FLASH IN A PADMOUNTED SWITCH

Arc flash in medium-voltage switchgear is normally analyzed using the IEEE 1584 approach. Padmounted switchgear operated with a hotstick was thought to have relatively low incident-energy exposure because of longer working distances associated with hotstick work. Test results have found surprisingly high incident energies in a padmounted switch, indicating that we should not ignore this scenario.

We tested three S&C PMH-9 units (see Fig. 14), at PG&E’s San Ramon, CA, test facility. These units are rated at 25 kV. This switch has load-break capability and fusible disconnects. Common work that may have an arc flash risk is opening or closing of these fuse disconnects.

Faults were initiated by jumpering with a #18 copper wire from the phase unirupter to the top of the disconnect arm and then to the door (Fig. 15). The copper wire burns away quickly once the test circuit is energized, leaving an arc initially along the path of the vaporized copper wire. Then, the arc is free to move. An array of nine calorimeters was positioned in front of the switch to measure the incident energy from arc flash events. Two tests were intiated at each of the six phase unirupters allowing at least 12 tests from each PMH-9 test specimen before unit damage was severe enough to alter the arc behavior.

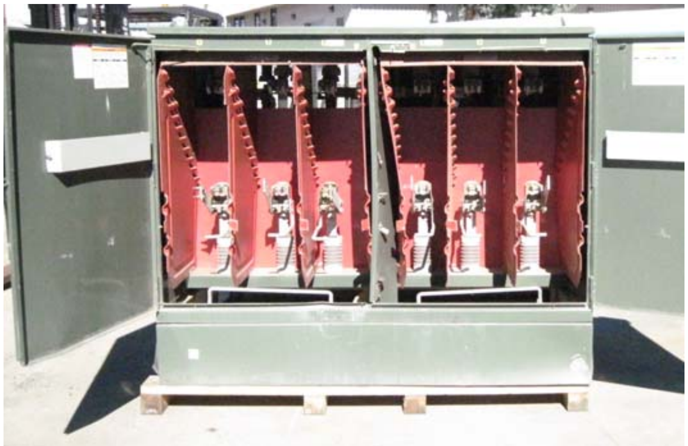


Fig. 14. PMH-9 test unit.

This fault initiation mimics the fault scenario where a worker attempts to close in the fuse, but it does not firmly connect. If the fuse pulls away, it can draw a load arc, and if this load arc contacts the enclosure, it will become a line-to-ground fault.

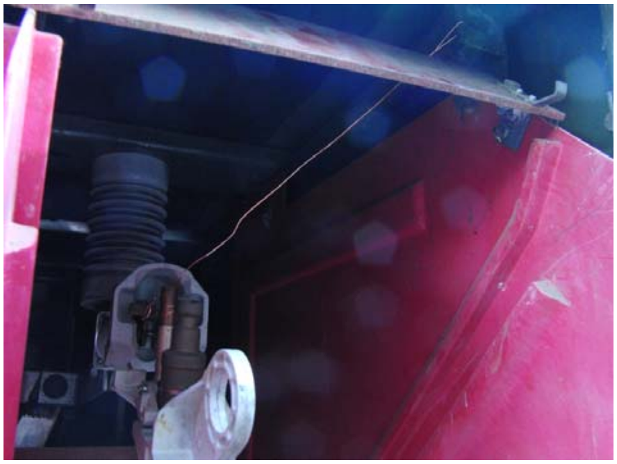


Fig. 15. Example fault initiation.

Fig. 16 shows an example arc flash event on one of the PMH-9 units. The arc propels the fireball out of the front of the enclosure, mainly from the arrangement of the busbars. As shown in Fig. 17, the internal busbars are arranged horizontally, pointing out the front. Horizontal electrode configurations push much more of the arc energy out the front of the enclosure than do vertical electrodes. IEEE 1584 tests were based on vertical electrodes, which explains why we see more incident energy than expected. With the horizontal arrangement, the fault current leaves the busbar straight out of the box then loops back to the enclosure. Fig. 18 shows video frames taken through an infrared-passing filter that show the arc and hot gases being propelled a significant distance away from the electrode where the fault was initiated. In addition to bringing the arc closer to the worker, the forward movement of the arc from horizontal busbars pushes the fireball towards the worker.

Fig. 16. Example event.

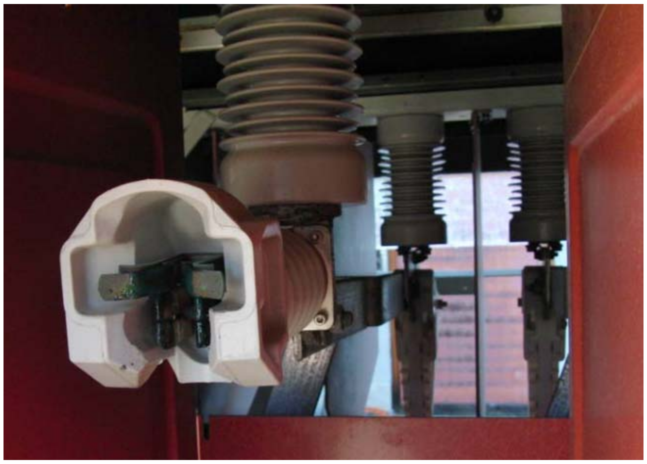


Fig. 17. View along a top bus bar in the PMH-9 test unit.

The first PMH-9 unit flashed over on an adjacent phase 20 cycles into the third test. The bushing from the busbar to the top of the enclosure (the closest bushing in Fig. 17) flashed over from the hot gases generated by the fault in the adjacent section. Repeated tests blanket the bushing with soot, making multiphase flashover more likely. The second PMH-9 unit flashed over near the beginning of the third test. Because both units survived two tests without flashover, the remaining tests were conducted with only a single phase energized.

A number of tests were performed with faults initiated between a top front electrode and the enclosure. Incident energies were measured by nine copper calorimeters on stands spaced eight inches (20 cm) apart; see Eblen and Short [9] for more information on the test setup. Two fault levels, 4.3 and 6.7 kA, were tested, and durations were varied from 0.25 to 1 sec, with most tests at a 0.5-sec duration. Incident energies were measured at distances ranging from 36 to 60 inches (1.2 to 2 m). This distance is from the electrode to the calorimeters, not the distance to the front of the enclosure.

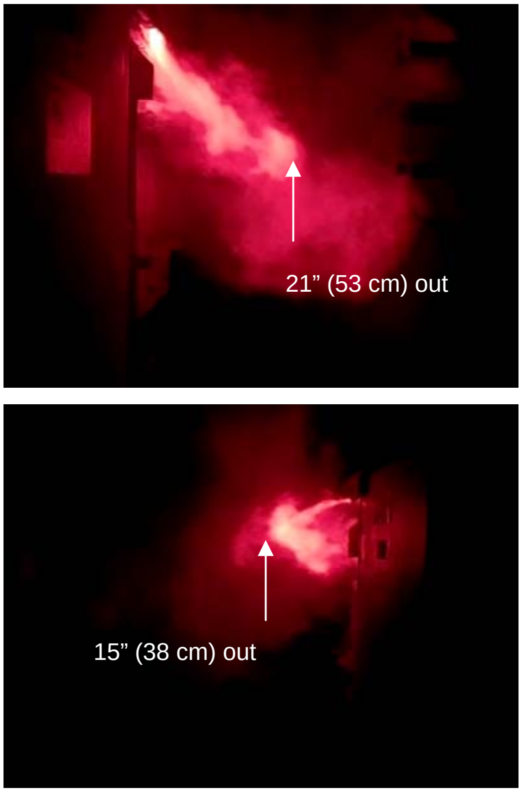


Fig. 18. Video frames through an infrared filter.

Fig. 19 compares peak incident energy measurements with predictions using IEEE 1584. In many cases, the IEEE 1584 predictions were low by a factor of three to four. Most of these tests were single phase, and the IEEE 1584 is based on three-phase faults, making the results even more surprising. ARCPRO underpredicts by even more. Consider a 6.9-kA, 0.5-sec test with an incident energy at 48 inches (1.5 m) measured to be 8.1 cal/cm^2. ARCPRO predicts only 0.64 cal/cm^2 for this case, assuming a 4-inch (10-cm) arc length. In the tests, the mean rms arc voltage of all of the tests was approximately 800 V. Assuming an arc length of 40 V/inches (16 V/cm), 800 V across an arc corresponds to an arc length of 20 inches (51 cm). With input of a 20-inch (51-cm) arc length, ARCPRO predicts 2.5 cal/cm^2 for this case.

Following the approach of IEEE 1584, we fit a linear regression model to the data. As a function of current, distance, and duration, we fit the following model:

$$E = 3547 \frac{I^{1.50}}{d^{2.10}} t^{1.35}$$

where,

E = incident energy, cal/cm^2

I = fault current, kA

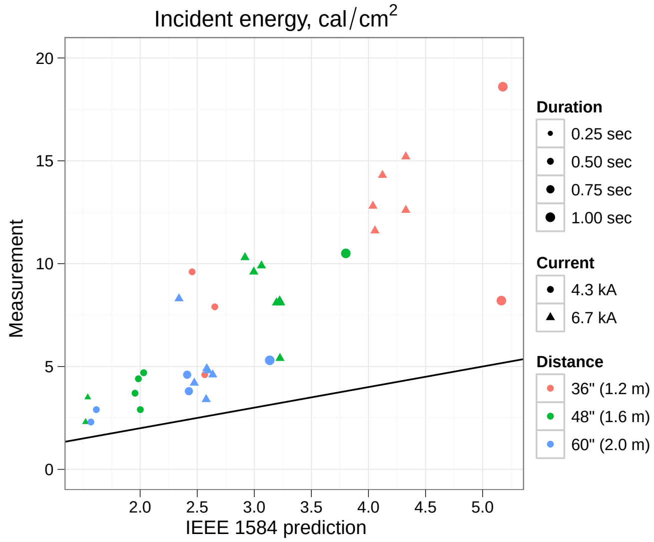


Fig. 19. Measurements versus IEEE 1584 predictions.

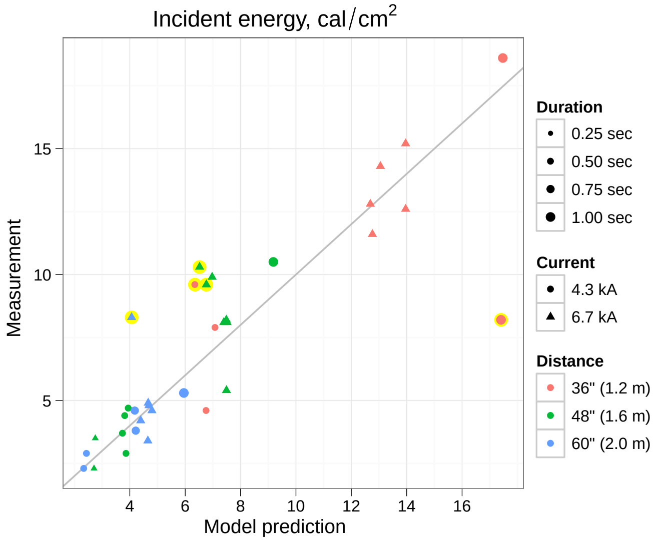


Fig. 20. Measurements versus predictions for the incident-energy model for the padmounted PMH switch.

d = working distance, inches (1 inch = 2.54 cm)

t = duration, sec

The R^2 value for this model is 0.91, meaning that all but 9% of the variance is explained by the model. All model coefficients are statistically significant. Fig. 20 shows predictions versus measurements for this model. The data points highlighted in yellow were excluded from the model fit. The four excluded points above the prediction curve are events that evolved to multiple phases. This model is for single-phase faults, because we determined that multiphase faults were uncommon. If multiphase faults do occur, they may add another 60% to incident energies. The one excluded point below the prediction curve had signs of internal flashover in the switch and much less energy than expected.

Another surprise in the measurements is that the incident energy is not linear with time. Most arc flash calculations (including IEEE 1584 and ARCPRO) assume that the heat rate is constant, so doubling the duration will double the incident energy. Based on the regression model for the PMH switch, if you double the duration, incident energy increases by a factor of 2.55.

The nonlinear effect of duration may be at least partially explained by the propagation of the fireball as time progresses. Fig. 21 shows an example of video from a 300 frame-per-second video for a 6.8-kA, 0.5-sec (30-cycle) event with the calorimeters positioned at 60 inches (1.5 m). In this event, the fireball does not reach the calorimeters until about 10 cycles into the event. Assuming that a significant portion of the energy absorbed by a calorimeter is from convection from the hot gases, the incident energy will increase the longer the calorimeter is engulfed in the fireball. The rate of expansion of the fireball diminishes with time.

With the incident energy model, we can find a clothing curve for a given working distance and clothing rating. We can solve the following equation:

$$t^{1.35} = \frac{E\,d^{2.10}}{k \cdot 3547 I^{1.50}}$$

where k is a safety multiplier to increase incident energy predictions. The regression model provides an average fit. By adding a safety multiplier of k=1.15, we cover most of the test points in Fig. 20, especially at larger incident energies.

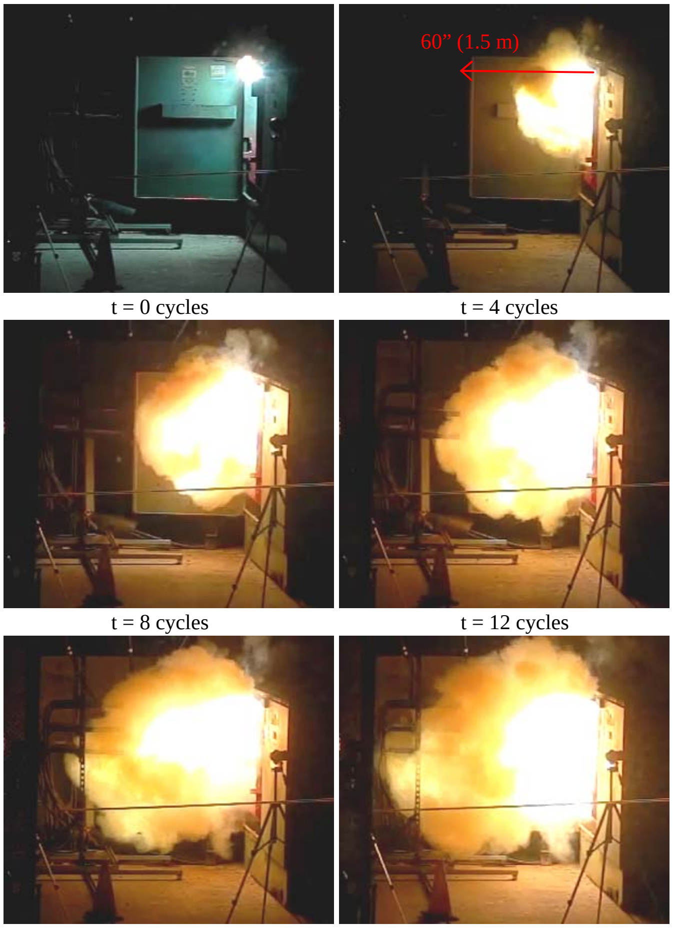
For clothing with an 8-cal/cm^2 rating, and a working distance of 48 inches (1.5 m), the time-current equation is:

$$t^{1.35} = \frac{E\,d^{2.10}}{k \cdot 3547 I^{1.50}} = \frac{8 \cdot 48^{2.10}}{1.15 \cdot 3547 I^{1.50}}$$

$$t = \frac{4.07}{I^{1.11}}$$

Fig. 22 shows time-current curves for 8-cal/cm^2 clothing at several working distances. Utilities can use such clothing curves to coordinate clothing systems with minimum approach distances and upstream protective relaying. Also shown in Fig. 22 are clothing curves typically assumed for overhead systems using NESC-2007 assumptions. Depending on the minimum approach distance, exposure at a PMH switch can be more limiting than overhead-line exposure when using the NESC assumptions.

These tests were on a 25-kV switch energized at 21 kV. Performance is likely to be similar for other distribution primary voltages. The main effects driving the incident energy are fault current and the horizontal geometry of the internal buses in the switch. These effects will be the same regardless of system voltage. Similar results are also expected in other live-front equipment with horizontal busbars arranged to point out of the enclosure.



t = 0 cycles

t = 4 cycles

t = 8 cycles

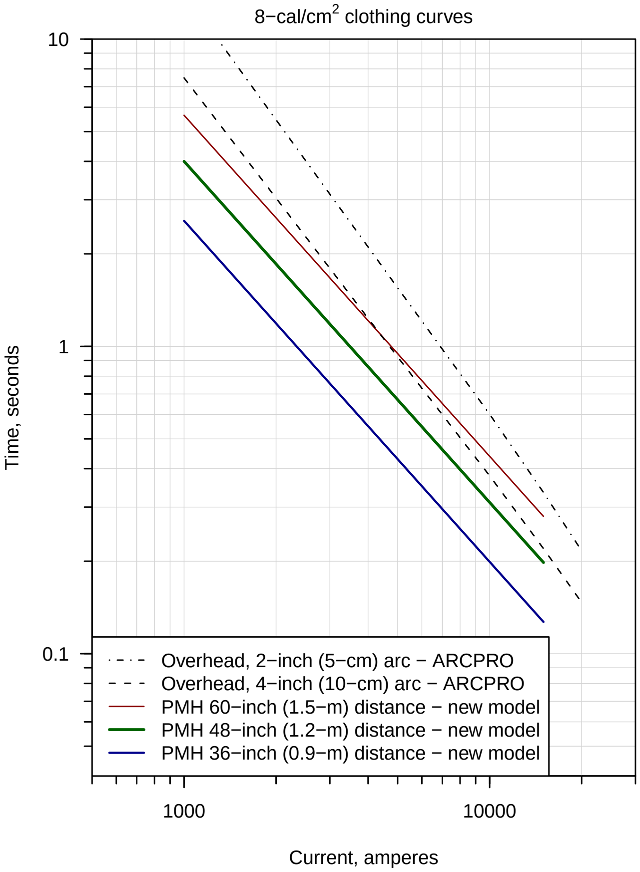
t = 12 cycles

t = 16 cycles

t = 20 cycles

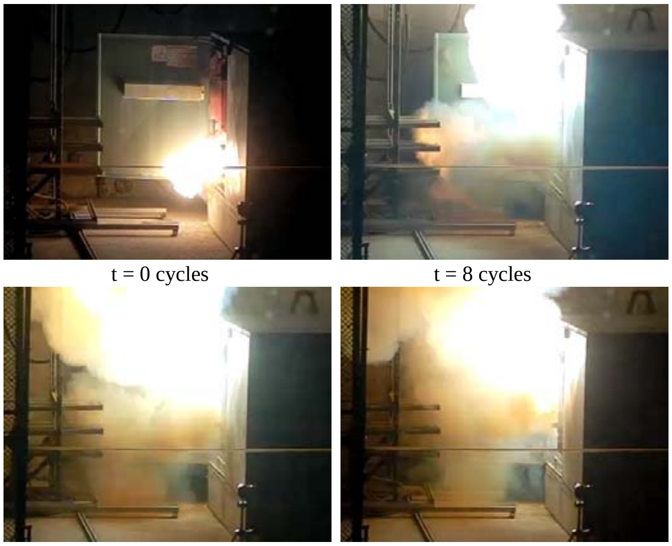
Fig. 21. Progression through time of test 9.

Three faults were also initiated in the PMH switch on the bottom of the fuse tube with the fuse open and with the bottom energized. This may happen if the switch is used in a backfeed or alternate-source scenario. We measured significantly less energy than with faults initiated at the top. High-speed videos showed that the fireball and arcs tended to move up, rather than horizontally out of the enclosure. In a 6.7-kA, 0.5-sec event shown in Fig. 23, we measured 2.1 cal/cm^2 at 48 inches (1.2 m), compared to approximately 7 cal/cm^2 for faults initiated at the top receptacle. The fireball largely missed the calorimeters in this case. With the same parameters but with the calorimeters moved in to 36 inches (0.9 m), peak incident energies of 7.0 and 8.9 cal/cm^2 were measured in two separate tests. These are less than the 13 cal/cm^2 from top initiations at 36 inches (0.9 m). The calorimeters were moved up to catch more of the fireball. The differences in fault initiation point highlight the importance of the bus orientation.



Overhead curves are based on a 15-inch (38-cm) working distance.

Fig. 22. Comparison of arc flash time-current clothing curves for overhead and padmounted switch exposure.



t = 0 cycles

t = 8 cycles

t = 16 cycles

t = 24 cycles

Fig. 23. Progression through time during a bottom initiation.

IV. CONCLUSIONS

The test results discussed here show that it is important to evaluate the specific equipment or arc flash scenario to better refine arc flash analysis approaches. Future work could include tests on live-front padmounted transformers and different styles of medium-voltage switchgear. For overhead work, more industry analysis and feedback on appropriate analysis assumptions are needed. If anyone would like copies of the test data reported here, please request it from one of the authors.

ACKNOWLEDGEMENTS

Northeast Utilities deserves special recognition for providing the capability to perform arc flash tests at the EPRI Lenox test facility. Dave Thomas of NU was particularly helpful. We would also like to thank EPRI’s Dave Childs, Dave Crudele, and Mike Clary who helped support the Lenox test work. In support of the PG&E tests, we would like to thank the dedicated work of Ralph Seban, Dan Kaufman, and Ryan Sparacino.

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