Arc Flash Update for 480-V Network Protectors

2015 TECHNICAL REPORT

Arc Flash Update for 480-V Network Protectors

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Abstract

This report summarizes findings of tests on arc flash in 480-V network vaults and the use of optical sensor relays. The goal of the research is to evaluate realistic arc flash events inside and outside of network protectors and to evaluate optical sensors and relays as protection to clear either adjacent network protectors or medium-voltage switches.

This research helps increase industry knowledge of arc flash in 480-V networks, a situation with known arc flash hazards. Incident energies can be quite high, mainly because 1) available fault currents can be above 100 kA, and 2) clearing times may be long.

Prior work has shown that the severity of arc flash depends on equipment characteristics. In some equipment, arcs tend to self-extinguish at 480 V. Because severity is equipment-specific, a variety of faults were initiated inside and outside of network protectors. Utilities can use the test findings to help analyze arc flash in network scenarios and to specify suitable protective clothing for workers.

Because of long clearing times, solutions that can quickly clear the spot network will greatly reduce incident energy. Fiber-optic detection has been used successfully in other switchgear applications. Based on signals from the fiber-optic sensors, the relaying can trip adjacent network protectors or high-side, medium-voltage switches. Tests evaluated the performance of fiber-optic sensors, and results provide utilities with application guidance.

Keywords
Arc flash
Fiber optics
Overcurrent protection
Secondary networks
Spot networks

Executive Summary

This report summarizes findings of tests on arc flash in 480-V network vaults and the use of optical sensor relays. The goal of the research is to evaluate realistic arc flash events inside and outside of network protectors and to evaluate optical sensors and relays as protection to clear either adjacent network protectors or medium-voltage switches.

Self-Clearing of Arcing

For work in 480-V network protectors, the main new finding is that arcing did not sustain longer than 1.5 cycles if the back bus bars were de-energized. (See examples of self-cleared fault initiations in Figure ES-1.) Incident energy exposures are likely to be below 8 cal/cm^2. Based on this finding, workers could wear single-layer flame-resistant (FR) clothing.

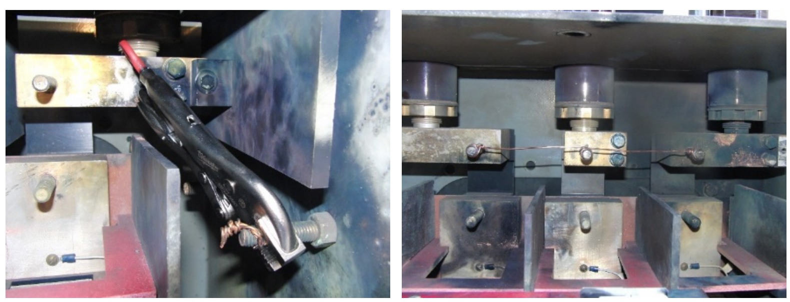

Figure ES-1
Fault initiations that self-cleared with the back bus bars de-energized

If the back bus bars are energized, either by the transformer in the back or with a closed circuit breaker, sustained faults are likely (see Figure ES-2). An analysis must be done to evaluate incident energy exposures.

In 480-V vaults outside of network protectors, all realistic open-air scenarios self-cleared within four cycles. As with network protectors with the back bus bars de-energized, exposures are likely to be below 8 cal/cm^2 (single-layer FR).

Figure ES-2
Arc flash with the back bus bars energized

Fiber-Optic Sensing and Relaying

The fiber-optic sensors (see Figure ES-3) performed well for detecting arcs in network protectors and external applications. Sensors and cabling were robust to nearby arcs, and performed well even when covered with soot.

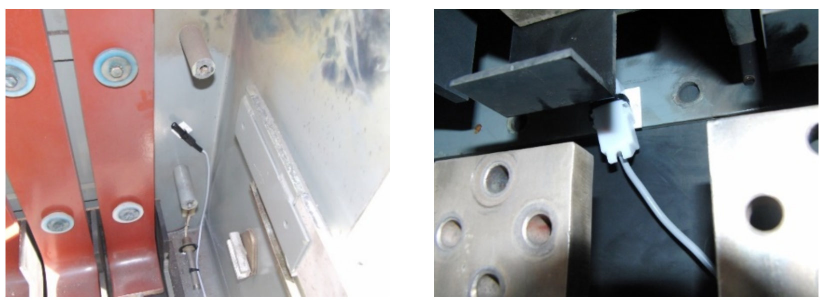

Figure ES-3
Examples of fiber-optic sensor use

Inside network protectors, one omnidirectional sensor on the back wall should be adequate for events with substantial arc energies. For increased sensitivity, three sensors could be used on the back wall. Some nuisance tripping may be seen in very high fault current faults.

Network protectors are an option for relaying schemes to protect workers from arc flash. The CM-22s tested successfully interrupted faults ranging from 5 kA to 23 kA multiple times with little damage to the arcing contacts. These tripped in an average time of 2.5 cycles.

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Section 1: Introduction

This report summarizes findings of tests on arc flash in 480-V network vaults and optical sensor relays. The goal of the research is to evaluate realistic arc flash events inside and outside of network protectors and to evaluate optical sensors and relays as protection to clear either adjacent network protectors or medium-voltage switches.

This research helps increase industry knowledge of arc flash in 480-V networks, a situation with known arc flash hazards. Table 410-1 in the National Electrical Safety Code [IEEE C2-2012] provides general guidance on protection of utility workers at voltages below 1000 V. This table does not provide a specific clothing protection level for 480-V network protectors, so utilities must analyze incident energy hazards in each vault. Incident energies can be quite high, mainly because (1) available fault currents can be above 50 or even 100 kA, and (2) clearing times may be long or even indeterminate in some vaults.

Previous testing of a 480-V network protector found that although some faults did not sustain, sustainable arcs were very possible in network protectors [EPRI 1020210, 2009; Eblen and Short, 2012]. Because arcs did not self-clear, incident energies were high with a large fireball in front of the enclosure (Figure 1-1). Incident energies were measured and predicted to be 50 cal/cm^2 to 100 cal/cm^2 or more. These results led to the NESC requirement for performing a study for worker protection in 480-V network protectors.

Because of long clearing times, solutions that can quickly clear the spot network will greatly reduce incident energies and allow workers to wear everyday fire retardant clothing rather than arc suits. Fiber optic detection has been successfully used in other switchgear applications. Based on signals from the fiber-optic sensors, the relaying can trip adjacent network protectors or high-side, medium-voltage switches.

Figure 1-1
Example 480-V network protector event [EPRI 1020210, 2009]

Incident energies that a worker may see increase with duration, and prior EPRI research has found that sustainable arcing is a key parameter at 480 V. The research addressed a number of questions related to arc flash in 480-V network vaults.

- If the back bus bars in a network protector are de-energized, is it possible for a worker to initiate an arc that sustains?
- What conditions are needed for sustained arcing?
- With the back bus bar energized, what scenarios can cause sustained arcing?
- Outside the network protector (above the network protector, in cable trays, or on exposed buswork), can line-to-ground or line-to-line faults sustain?

Schneider Electric's VAMP arc protection relay system was tested for use in detecting arc flash in network protectors and other vault situations. For protection with these fiber optic sensors, the EPRI team explored several questions:

- What is the best placement for fiber optic sensors?
- How many sensors are needed inside a network protector?
- Are directional or omnidirectional sensors more appropriate?

- How fast does the system detect arcs?
- Are these fiber optic sensors susceptible to damage for nearby arcing? Will damage prevent detection?
- Are these fiber optic sensors susceptible to false tripping from ambient light?
- Are these fiber optic sensors susceptible to false tripping from normal operations of the network protector (for both load and fault current clearing)?
- Can network protectors reliably clear faults? How much damage is there to contacts? How fast do they trip?

This report builds upon the following research related to 480-V networks:

- Distribution Arc Flash: Industry Practices. EPRI, Palo Alto, CA: 2009. 1018694.
- Distribution Arc Flash: Analysis Methods and Arc Characteristics. EPRI, Palo Alto, CA: 2009. 1018693.
- Distribution Arc Flash: 480-V Padmounted Transformers and Network Protectors, Technical Update. EPRI, Palo Alto, CA: 2009. 1020210.

Initial testing on network protectors [EPRI 1020210, 2009] found sustained arcing. Those test conditions most closely replicated faults in the back bus bars of network protectors. Since the 2009 testing, industry practices changed to focus on de-energizing the power source incoming to the network protector from the back connected transformer, eliminating the high incident energies from that source. Once the transformer is de-energized, the remaining hazard inside the network protector comes from the common secondary bus that enters the network protector from the top center mounted bushings. On CM22-style network protectors, there are fuses mounted inside the network protector between the breaker and the top of the cabinets. Removal and reinstallation of these internal fuses is the most common task performed on this style of network.

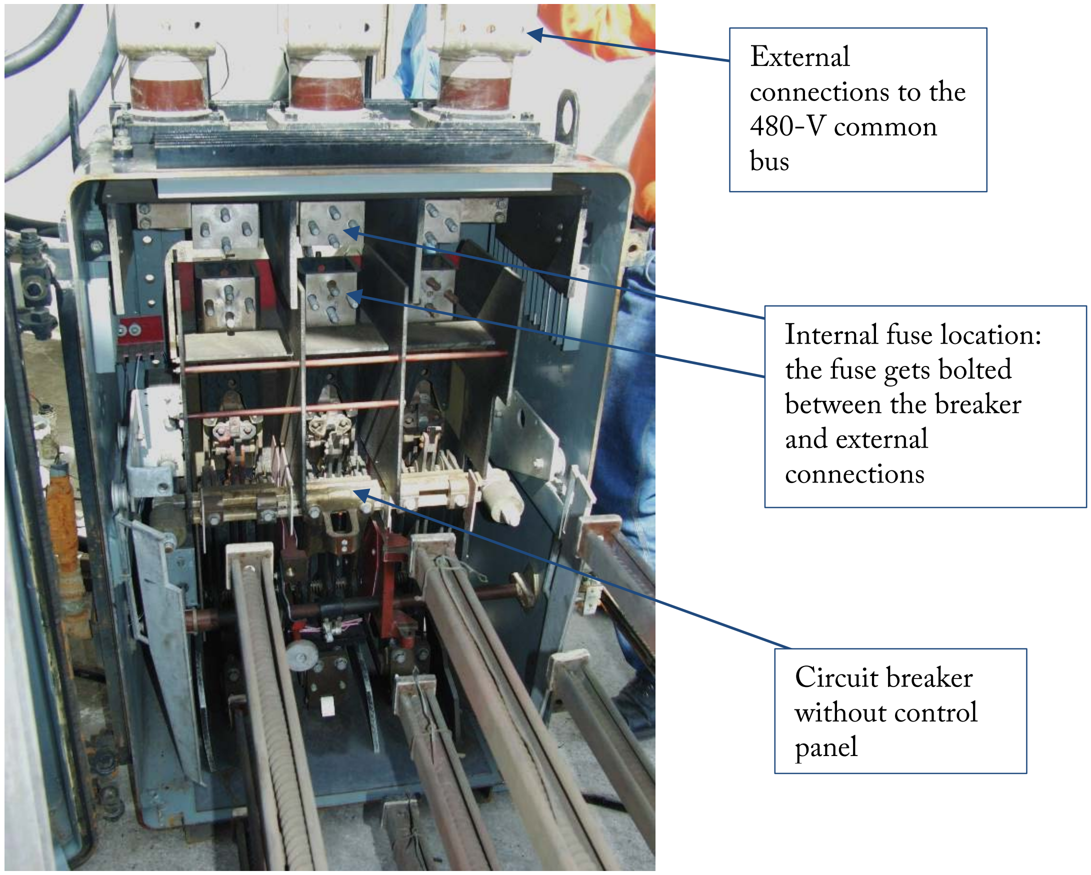


Figure 1-2
Interior of a CM-22 480-V network protector with the circuit breaker controls removed

Test Setup

Tests were performed at PG&E's High Current Laboratory in San Ramon, CA. Two 2500 kVA transformers, TX1 and TX2, were set up each feeding a functional Westinghouse CM-22 network protectors, NP1 and NP2, through back throat plate providing 50kA available bolted fault to top of a third sacrificial network protector, NP3. NP3 contained a circuit breaker that was installed fully into the network protector and left in the open position for most of the testing. The back bus bar of NP3 that would normally be connected to its own transformer, was left unconnected with a cover installed over the throat plate opening to mimic the enclosed nature seen in real service conditions. This allowed arc initiation in NP3 with a configuration that is as close as possible to what would be seen in actual operation if its transformer was de-energized. Figure 1-3 shows the single line diagram, Figure 1-4 shows the plan view of the physical layout, and Figure 1-5 is a photo of the test cell with the network protector setup.

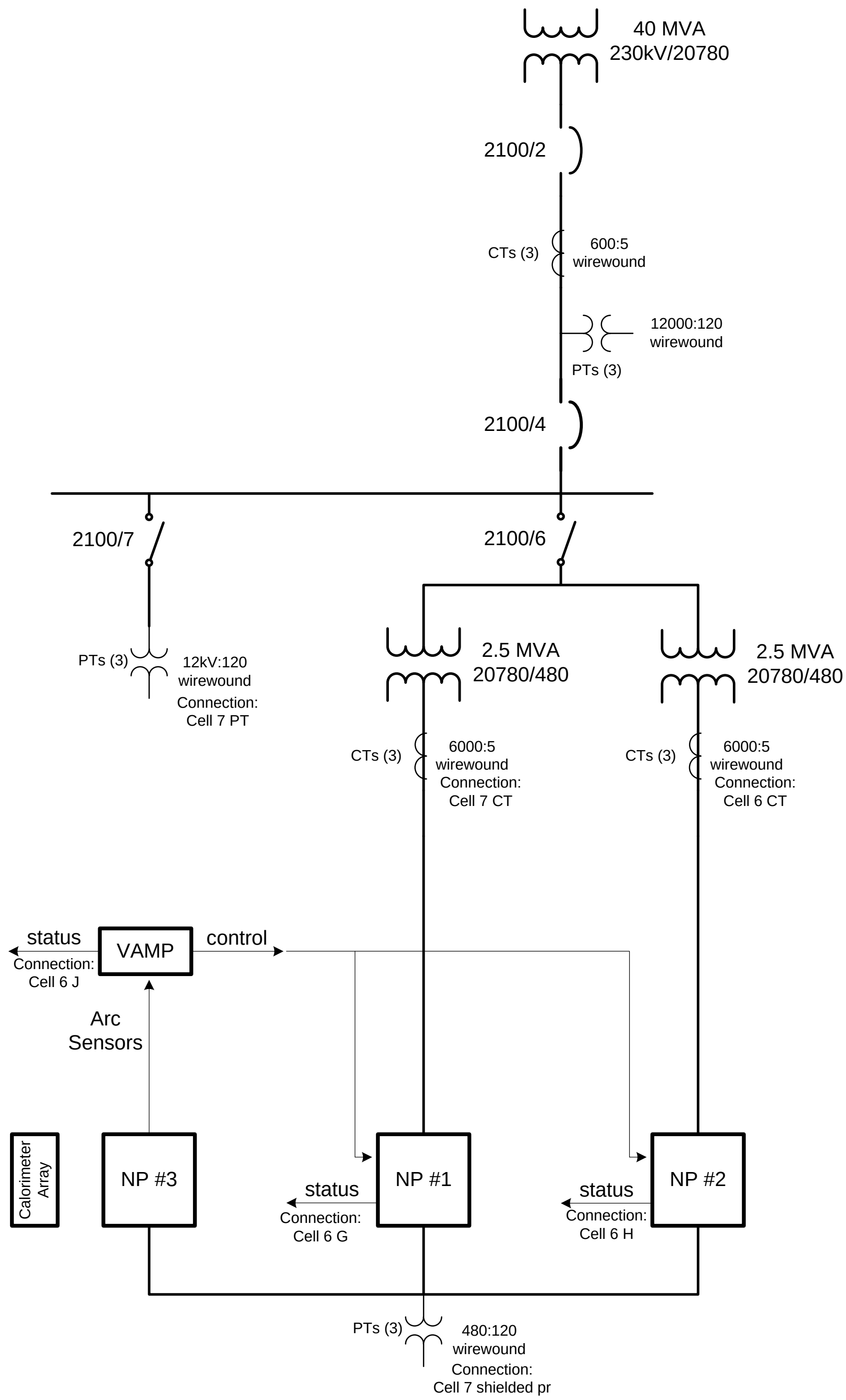


Figure 1-3
Single line diagram of the test setup

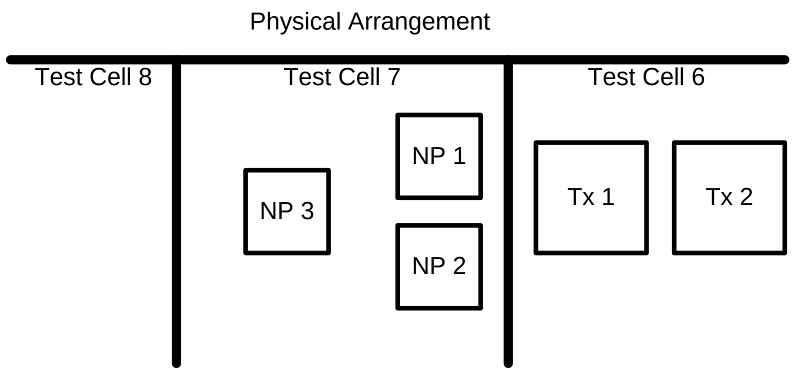


Figure 1-4
Plan view of the test setup

Figure 1-5
Side view of network protector setup

For the tests on NP3, incident energy was measured by nine copper calorimeters on stands spaced 8" apart and positioned 18" away from the top electrodes coming into the network protector. See Figure 1-6. Calorimeters were built and calibrated according to ASTM specifications [ASTM E 457 – 08, 2008; ASTM F1959, 2006].

Figure 1-6
Calorimeter array placement

All network protectors had their fuse links removed. NP1 and NP2 had the fuse links replaced with solid copper bus bar to eliminate tripping by fuse initiation. The test setup allowed variation of the available fault current to NP3. With both transformers feeding, 50kA of bolted fault current was available. With only one transformer feeding, 27.5kA of bolted fault current was available.

The main purpose of the testing was to determine the efficacy of using optical sensing arc detection sensors and relays to limit incident energy to employees working inside network protectors. Three different optical sensor were tested. For purposes of this test report, the sensors types will be categorized as follows:

- Omnidirectional Sensor-180 degree field of view (Schneider Electric VA1DA-x)
- Torpedo Sensor-90 degree field of view (Schneider Electric VA1EH-x)
- Fiber Sensor-Continuous fiber conductor-complete field of view (Schneider Electric Arc-SLmx)

The optical sensor relays were wired to trip either the breakers of NP1 and NP2 or the high-side breaker feeding the transformers. Because network protectors were not specifically designed to interrupt 480V fault current, the test plan included determining the durability of network protectors used for this purpose. NP3 was instrumented with different types of sensors placed in various locations to determine both sensor pick-up time and final total clearing time when the network protectors were used to clear the fault and when the high-side protective device was used to clear the fault. However, it became clear that the arcs were self-extinguishing much faster than the operating time of the high-side protective device. The test plan was expanded to fully explore arc sustainability in all possible arc initiation locations while gathering information of sensor pick-up and device clearing times. This included putting sensors inside NP2 (a functional network protector), to determine if normal fault current interruption would send a false trip signal.

Section 2: Sustainable Arcing Inside Network Protectors

A number of faults were initiated in network protectors to evaluate the severity of events at the same time as fiber optic sensors were tested. Whether the arcing fault sustains largely determines the severity. In this series of tests, all faults triggered with the back bus bars de-energized self-cleared in less than 1.5 cycles. Sustained arcing at 480 V requires tight spacings. If the length along the arc path is long enough, the voltage cannot retrigger the arc, and the fault current ends. This new information may allow more reasonable work practices on network protectors in cases where the back bus bar is de-energized (with the primary side de-energized and the circuit breaker on the network protector open).

If the back bus bars are energized, sustained arcing can occur along with incident energies above 100 cal/cm^2 possible.

Test Results with the Back Bus Bar De-Energized

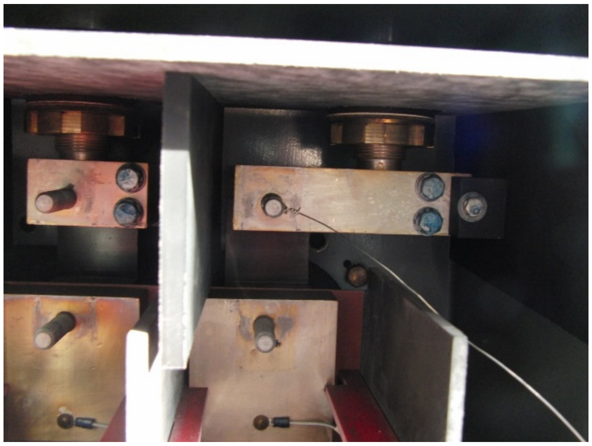
The industry has shifted operating practices for work on network protectors. Most utilities now de-energize the transformer of the network protector being worked on, normally by tripping the feeder. With the back bus bars de-energized, there are fewer places where workers may initiate arcs. The only exposed bus work is in the area near the fuses at the top of a network protector.

The internal construction of the inside top of the network protectors includes a substantial non-conductive barrier around and between the incoming buses from the top of the network protector along with non-conductive barriers between phases attached to the top of the breaker. See Figure 2-1. With these intact, direct phase-to-phase contact becomes unlikely; therefore, we started testing phase-to-case contacts on one of the outside phases. Actual in-service conditions would likely result in contact from a phase to the outside edge of the side case of the protector with some sort of tool or wrench. When these arcs failed to sustain, bolts protruding into the case were installed in the side wall of the protector, one near the front and one directly in-line with the incoming bus (shortest possible arc gap).

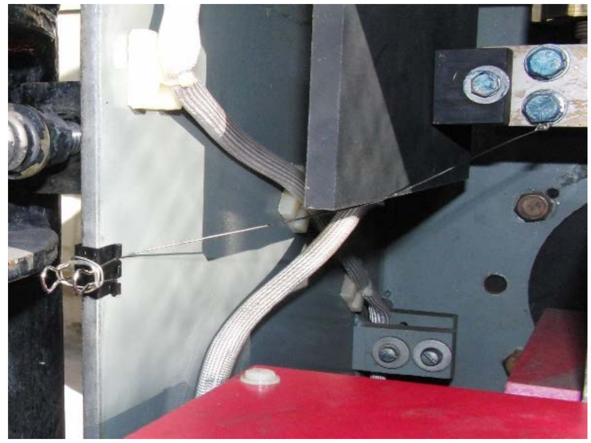
When these arcs failed to sustain, the incoming non-conductive barrier was completely removed, and three-phase arcs were initiated. While this is not a likely condition to be found, it does represent a worst case. If the arc fails to sustain with the barrier removed, then there is no plausible field condition that would do otherwise. To fully explore arc sustainability, testing began with small diameter wire, 20 AWG, and progressed to multiple stands of larger 14 AWG. Testing then used vise grips as a worst case simulation of an actual tool used inside the network protectors.

Figure 2-1
Interior NP3 with the non-conductive barrier installed

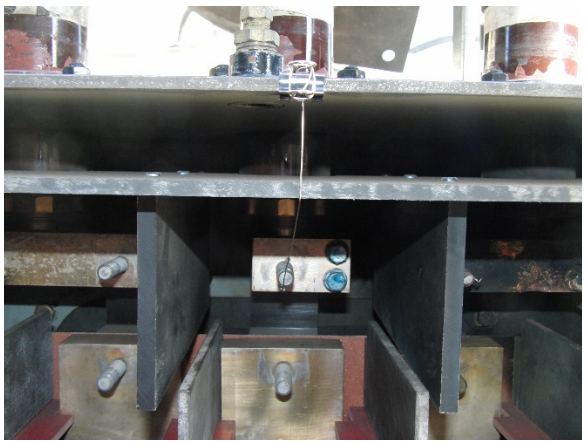
Figure 2-2 and Figure 2- show typical arc initiation points and arc durations for various phase-to-ground initiation points.



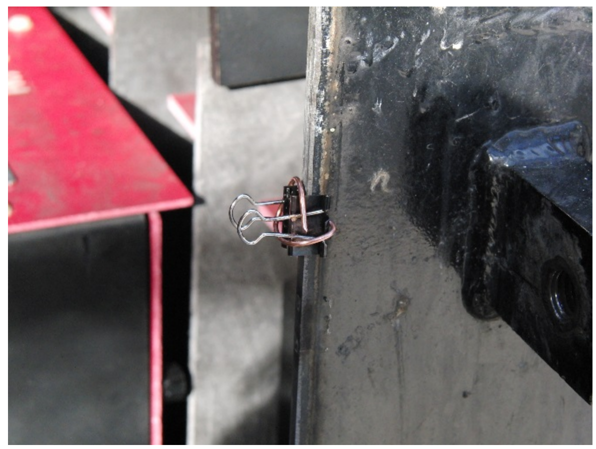
Test 13: AΦ to Case - 20 AWG - **0.14 cycles**



Test 33: CΦ to Case - 20 AWG - **0.17 cycles**

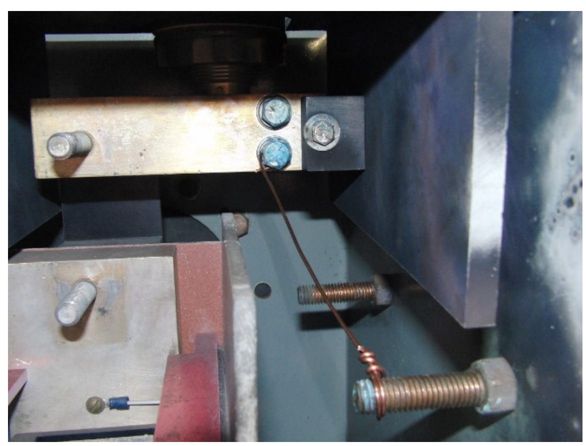


Test 34: BΦ to Case - 20 AWG - **0.17 cycles**



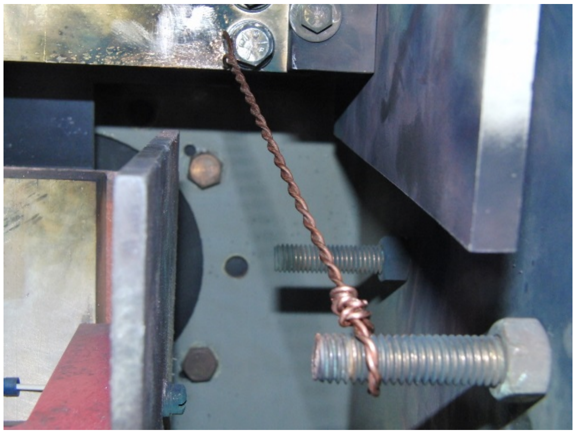
Test 14: AΦ to Case - 14 AWG - **0.25 cycles**

Test 15: AΦ to Case - 2-#14 - **0.35 cycles**

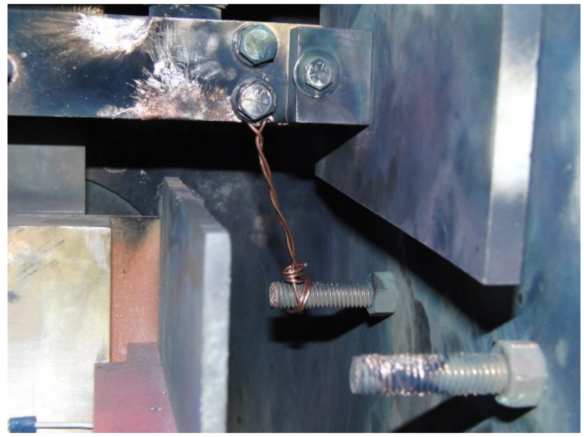


Test 16: AΦ to Front Bolt - #14 - **0.41 cycles**

Figure 2-2
Example interior arc initiation points and arc durations



Test ID 17: AΦ to Front Bolt- 2-14 AWG - **0.51 cycles**



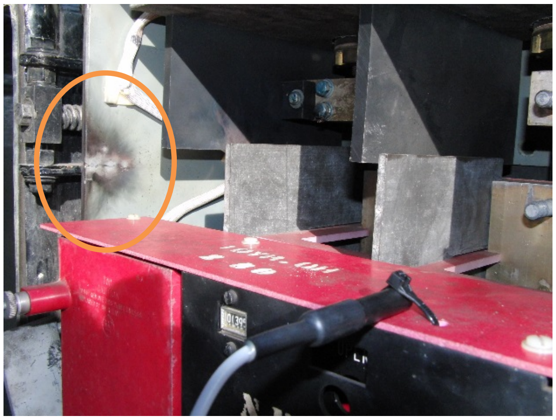
Test ID 23: AΦ to Back Bolt- 2-14 AWG - **0.55 cycles**

Test ID 18: AΦ to Front Bolt- Vise Grip - **1.5 cycles**

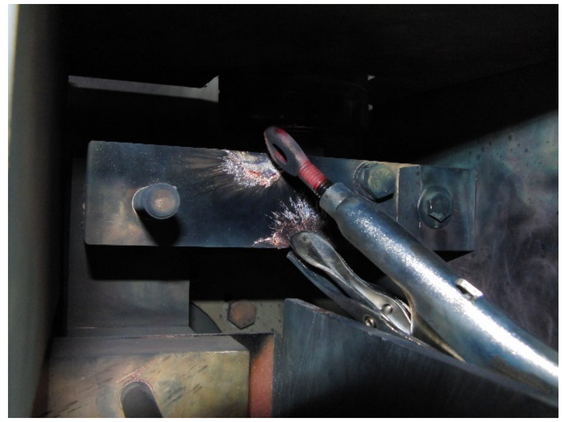
Test ID 19: AΦ to Front Bolt- Vise Grip - **1.0 cycles**

Figure 2-2 (continued)
Example interior arc initiation points and arc durations

These short-duration arcs resulted in very little damage to the inside of the network protector. Figure 2-4 shows typical damage after some events.



Post Test ID 33: CΦ to Case - 20 AWG



Post Test ID 18: Vise Grip

Figure 2-3
Examples of post-test damage

Figure 2-5 shows the arc initiation points and arc durations for three-phase initiations both with and without the insulating barrier installed. You can see from the Test ID#44 photo, that the damage from Test ID#43 was minor.

Test ID 43: AΦ-BΦ-CΦ 20AWG with Barrier - **0.34 cycles**

Test ID 44: AΦ-BΦ-CΦ 20AWG without Barrier - **0.28 cycles**

Figure 2-4
Three-phase initiation with and without barriers

Figure 2-6 shows a histogram of all the fault durations for the initiation inside the network protector. Complete results are shown in Appendix A. In all of these cases, the incident energies at 18 inches barely registered on the instrumentation.

Realistic events all self cleared in less than 1.5 cycles with negligible incident energy.

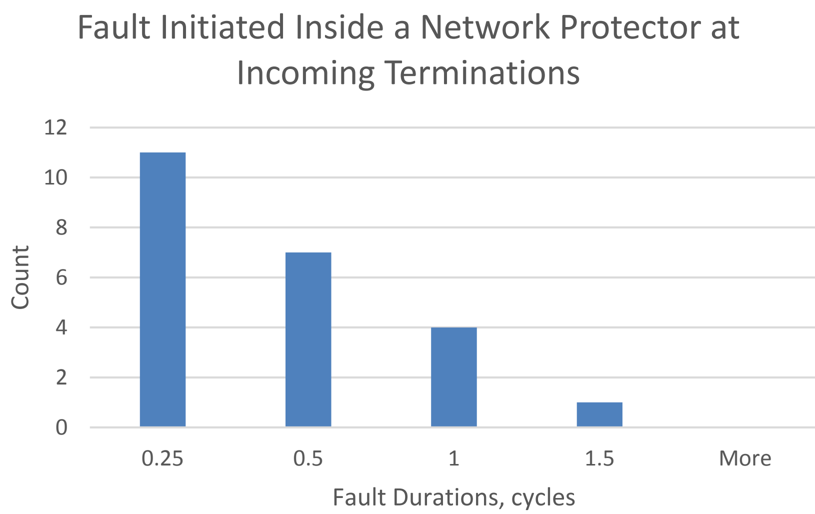


Figure 2-5
Fault duration histogram

Extreme Energizations

Test ID 57 and 61 to 64 were efforts to get an arc to sustain under extreme conditions. Table 2-1 summarizes these events, including initiation conditions, and Figure 2-7 shows photographs of the fault initiations. Network crews are highly unlikely to produce conditions similar to these. Even with these extreme conditions, three of the five tests self-extinguished. The two tests that did not self-extinguish may have burned themselves clear if the faults were not cleared so quickly by the adjacent network protectors.

Table 2-1
Extreme fault initiations

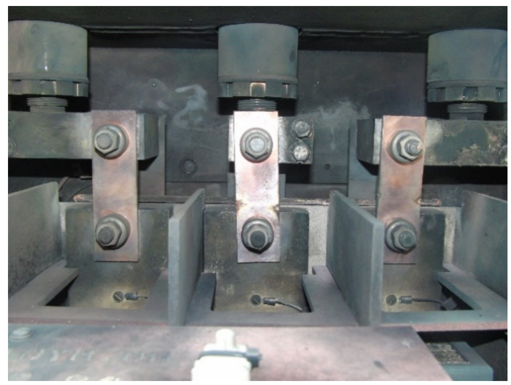
Test ID	Self Extinguish	Current Duration		Vamp Trip Signal [msec]	Device/ Clearing time [msec]	Maximum Incident Energy [cal/cm^2]	Condition
		cycles	msec				
057	Yes	0.46	7.6	16.5	NP/38.7	0.2	Internal-barrier removed; bus bar laying just below fuse terminals (close proximity conductive surface) #14 wire A-B-C between fuse terminals
061	Yes	0.71	11.9	16.2	NP/36.6	NA	Internal-barrier removed; bus bar laying across the front of fuse terminals. No calorimeters
062	No	2.54	42.4	17.4	NP/42.2	NA	Internal-barrier removed; bus bar laying across back of fuse terminals A-B-C. No calorimeters
063	No	2.57	42.9	16.1	NP/42.5	0.5	Internal-barrier removed; Cu bar installed in all fuse link positions bus bar laying across back of the breaker terminals A-B-C
064	Yes	4.21	70.1	17.1	Lab/201.2	1.0	Internal-barrier removed; Cu bar installed in all fuse link positions bus bar laying across back of the breaker terminals A-B-C

All of these cases had a flat metal bar laid between phases. Obviously, with the insulating barriers in place, this condition is impossible. As the fault starts, the magnetic forces will tend to push away from the source. In some cases, these forces will push the bar out of contact. In other cases, these forces reinforce the contact. If the bar is firmly in contact, the fault is bolted, so there is little arc energy.

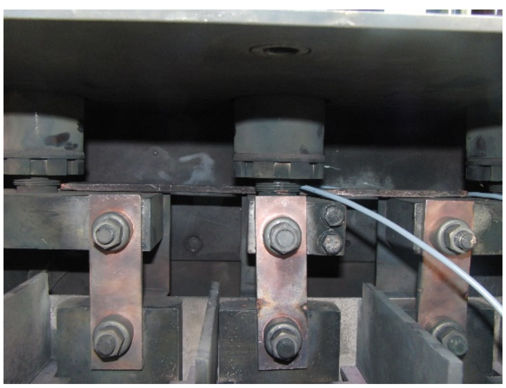
Test ID 57: 3Φ with a conductive plane

Test ID 61: 3Φ bar front fuse terminal

Test ID 62: 3Φ bar back fuse terminal



Test ID 63: 3Φ bar top breaker



Test ID 64: 3Φ bar back fuse terminal

Figure 2-6
Extreme fault initiations

Energized Back Bus Bars

If the transformer behind the network protector is not de-energized, more exposed bus work is available for arc initiations. Figure 2-8 shows a fault initiated with a copper bar running from the upper middle phase to an outer phase of the back bus bar on an outer phase. The bar also makes contact with the back wall of the network protector. The back bus bars were energized because the circuit breaker was closed. (There was no connection to a source from the back.)

This event had sustained arcing. This event progressed to three phase even though the fault was initiated from phase to phase to ground. The fault ended because the lab relaying tripped the circuit breaker (as intended to minimize damage to the protector in case arcing did not self extinguish). This confirms the previous testing that predicted very high energies with no self-extinguishing if an arc were to start on the back energized bus bar [EPRI 1020210, 2009].

With the back bus bars energized, plausible fault scenarios can lead to high incident energies.

Although the insulating barriers were removed in this event, the angles suggest that this type of event is plausible even with the barriers in place. With the barriers in place, there was space for a tool to bridge from a front phase to a back phase. Of course with the back bus bars energized, many additional initiations are possible, including phase-to-back wall and phase to phase. These initiations involve tighter spacings between electrodes in a confined area, conditions much more conducive to sustained arcing.

The calorimeters measured a maximum incident energy of 7.3 cal/cm^2 for the 12-cycle event. The 7.3 cal/cm^2 is approximately half of what IEEE 1584-2002 predicts. Because the energy was pushed out the sides and bottom the calorimeters may not have been in a position to measure the maximum energy, and/or the circuit breaker blocked heat. In any case, using IEEE 1584-2002 to predict incident energy when the back bus bar and transformer is energized will still be conservatively accurate.

An event causing sustained arcing. Replicates a scenario where a worker drops a tool that falls to the back bus bars.

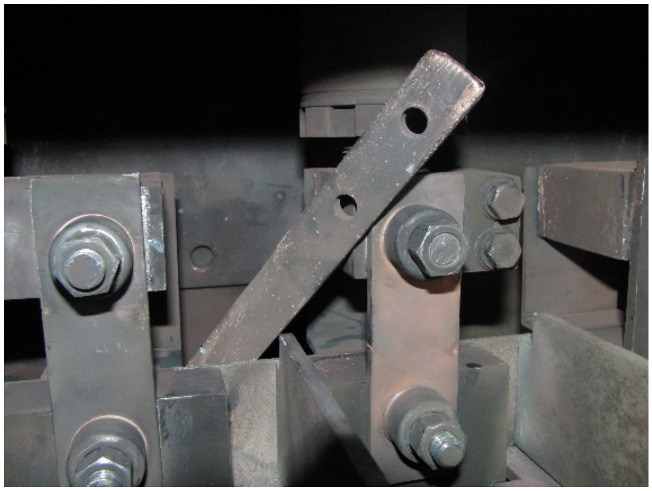


Figure 2-7
Test ID 65: Phase-to-phase-to-wall fault initiation

Figure 2-9 and Figure 2-10 show the evolution of the incident energy throughout the event. As can be seen the presence of the breaker causes the energy to come out wherever possible. At the end of the 4th cycle, you can see energy coming out the bottom of the enclosure, indicating full involvement of the back bus bar. By the 7th and 8th cycle, arcs have propagated to all parts of the breaker, including just below the arc chutes. See Figure 2-11 and Figure 2-12 for post-test damage below the arc chutes.

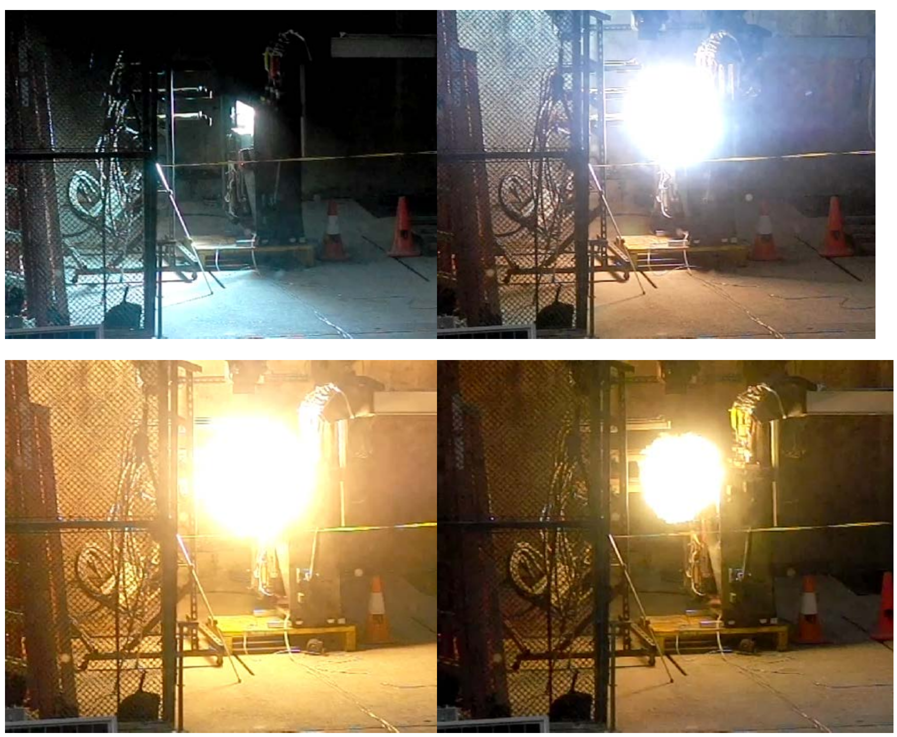


Figure 2-8
Test ID 65: First cycle

Arcing shifts to the bottom part of the protector.

End of 4th cycle

End of 5th cycle

Start of 6th cycle

Middle of 7th cycle

Middle of 8th cycle

Middle of 12th cycle

Figure 2-9
Test ID 65: Arcing propagation during twelve cycles

Figure 2-10
Post Test ID 65: Damage at the circuit breaker

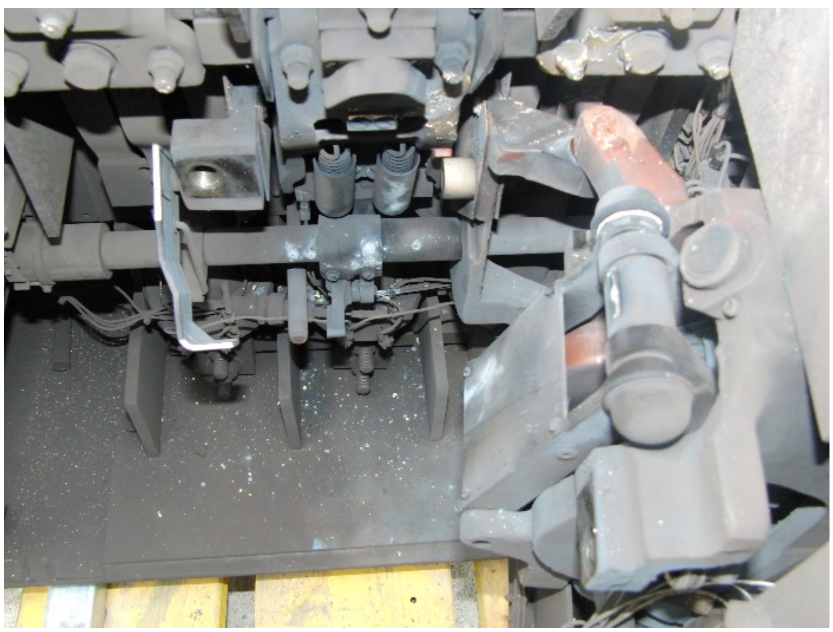


Figure 2-11
Post Test ID 65: Damage below arc chutes, behind the control module

Discussions on Arc Sustainability

To better understand the arc sustainability results, we review prior work on arc sustainability. At 480 V, arcs will self-extinguish in many scenarios. Tests on a variety of equipment at 480 V has shown that sustained arcing is much more likely with:

Arc sustainability depends on many factors.

- *Tight electrode spacings*—If the path along an arc is longer than approximately five inches, arcs are unlikely to sustain. If a tool bridges the gap, the magnetic forces push the tool away.
- *Thicker electrodes*—Arcs burn away smaller conductors and bus bars, leaving longer arc paths. The bus supports on thicker bus bars are also normally more rigid; if these are flimsy, magnetic forces may break them during faults.
- *Confined space*—If an arc has space to balloon out, it is more likely to extinguish. Tight cabinet spacings help contain the arc and fireball.
- *End barriers*—Confinement is particularly important near the ends of electrodes. Magnetic forces push arcs away from the source, often causing arcs to jet out of the ends of electrodes. If there is a barrier beyond the ends of the electrodes, this barrier will trap hot gasses and help sustain arcing. If the barrier is conducting, it will also provide a path to connect arcs. Barriers less than ten inches from the tips of the electrodes will help sustain arcing, even with wider electrode spacings. See Figure 2-17 for an example of this effect.
- *Parallel bus bars with facing plates*—With rectangular bus bars in parallel, arcing is more likely to sustain if the wide parts of the bus bars are facing each other. If the narrow parts are facing, the arcs will tend to run to the edges of the bus bars, and this increased space may not sustain arcing.
- *Three-phase arcing*—Three-phase arcing is more likely to sustain because of multiple arcs and higher voltages (480 versus 277 V). With multiple arcs, when one arc extinguishes temporarily at a current zero, there are still adjacent arcs generating heat.
- *Fault current magnitude*—This may seem counterintuitive, but in several pieces of equipment with borderline arc sustainability, higher fault currents caused arcing to self-clear faster. Higher currents burn electrodes more quickly (as the current squared), increasing spacings. The increased magnetic fields also propel arcs faster, and these forces are more likely to shift conductors and break apart bus supports.

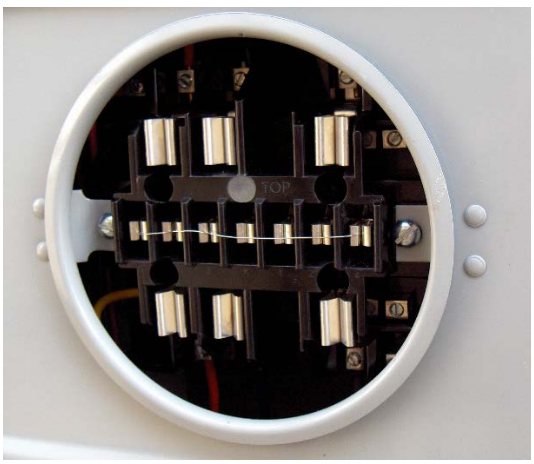
These factors make arc flash severity quite equipment dependent at 480 V. Figure 2-13 through Figure 2-15 show several examples of 480-V equipment from equipment where faults clear quickly to equipment where sustained arcing is likely.

Padmounted transformers

These electrode spacings are wide enough for arcs to clear in a few cycles, even with a tool bridging the gap.

EPRI 1020210, 2009.

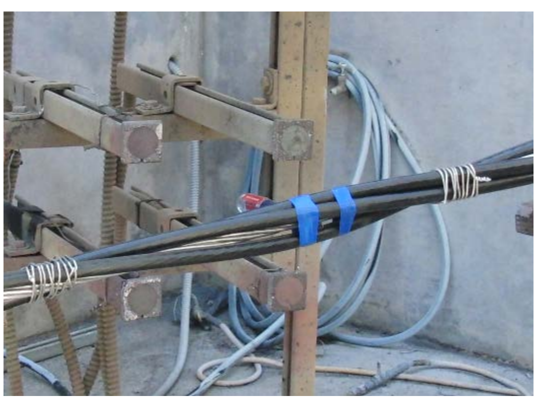
Transformer-rated meter sockets



Although these have tight spacings and a confined enclosure, arcs extinguish quickly because the small leads (#10 in this case) between the main power panel and the meter panel burn clear, clearing the fault current like a fuse.

EPRI 1018693, 2009.

Overhead quadraplex



Although these have tight spacings, there is no arc confinement. In addition, faults were started either as phase to neutral or phase to phase. In both cases, there is just a single arc.

EPRI 1022002, 2011.

Figure 2-12
Examples of 480-V equipment where faults burn clear quickly

Ringed self-contained meter sockets

These meter sockets meet many of the criteria for sustained arcing: tight confinement, close electrodes, and three-phase arcing. The main factor that limits duration is the amount of metal in the enclosure—arcing sustains until metal burns back enough for arcs to self clear. Faults clear faster at higher fault currents.

EPRI 1018693, 2009.

Ringless meter sockets

The ringless design has less confinement but more metal than the ringed design. In tests, peak incident energies were lower in the ringed design because the fireball out the front was less focused. Electrode size again limited arcing.

EPRI 1023267, 2011.

Small panelboards

For the panelboards with 50- and 100-A ratings, faults normally self-cleared because of mechanical damage to the bus bars. On these, the bracing is not sufficient to hold together the bus bars for longer-duration faults. These bus bars were not facing, another factor reducing the likelihood of sustained arcing. As with the meter sockets, faults cleared faster at higher currents.

EPRI 1018693, 2009.

Figure 2-13
Examples of 480-V equipment with borderline arc sustainability

Multi-bank meter sockets

These meter sockets have much more robust electrodes than the single-meter sockets above. With the robust electrodes, tight spacings, and enclosure confinement, faults can arc for long durations.

EPRI 1022002, 2011.

Large panelboards with facing electrodes

Panelboards like this have prime conditions for sustained arcing: large electrodes with robust supports, tight electrode spacings, facing electrodes, and a conducting barrier at the top that confines the fireball and provides a conducting path for current.

EPRI 1018693, 2009.

2009 network protector tests

In these tests, gutted protectors were fitted with a conducting back plane and bottom plane. Because the bus bars are flat rather than facing, arcs tend to separate. Arcing sustains because the back and front planes provide confinement and conductive arc paths.

EPRI 1018693, 2009.

Figure 2-14
Examples of 480-V equipment with sustained arcing

The figures above illustrate the impacts of electrode size, orientation, and spacings. Enclosure effects are also an important consideration for sustained arcing. These results again reinforce that at 480 V, arc sustainability is highly dependent on equipment. Many of these test results formed the basis of the table 410-1 in the 2012 NESC [IEEE C2-2012], the table requiring clothing protection levels under 1000 V.

Network Protector Faults

Keeping in mind the requirements for sustained arcing identified in the previous section, arc initiations near the top of the network protector meet several of the requirements for sustained arcing:

- Large, robust electrodes
- Tight spacings

The main factors that prevent sustained arcing are:

- No arc/fireball confinement
- Long distances to the side of the equipment (the most likely contact point)
- Flat electrodes (not facing)

If the back bus bars are energized, these factors change significantly, particularly:

- Phase-to-tank spacings are tight
- Arcs are much more confined

Result of tests on network protectors published in EPRI 1020210 [2009] provided the basis for the network requirements in the 2012 NESC. These tests found sustained arcing with incident energy rates comparable to those predicted by IEEE 1584-2002. The main difference between the 2009 tests and the tests in this report is arc confinement. A conductive bottom barrier was included in the 2009 tests (see Figure 2-16). This barrier was normally one to two inches from the bus bars, but distances of four, six, and ten inches were also tested. At ten inches, arcs did not sustain, but at six inches and below, arcs sustained.

Figure 2-15
Distance to the bottom barrier in the 2009 tests

Figure 2-17 shows an example of the end-barrier effect. With the wide bus bars in the network protector, the arcs tend to push away to the edges of the bus bars and flair away from each other. The conducting barrier at the bottom provides a path for current flow.

Figure 2-16
Examples of arc paths with the end barrier in the 2009 tests in a network protector

The 2009 tests were done in a stripped network protector housing. These conditions more closely match the situation with a fault on the back bus bars. The back bus bars (Figure 2-18) have tight spacings to the back wall and arc confinement provided by the bottom of the enclosure (the arcs will motor to the bottom of the enclosure).

In the 2015 testing in this report, the faults initiated at the top bus bars did not have the bottom barrier. Without this to provide containment and conducting paths for the current, arcs did not sustain with the back bus bars de-energized. The test with the back bus bars energized was comparable to the 2009 tests.

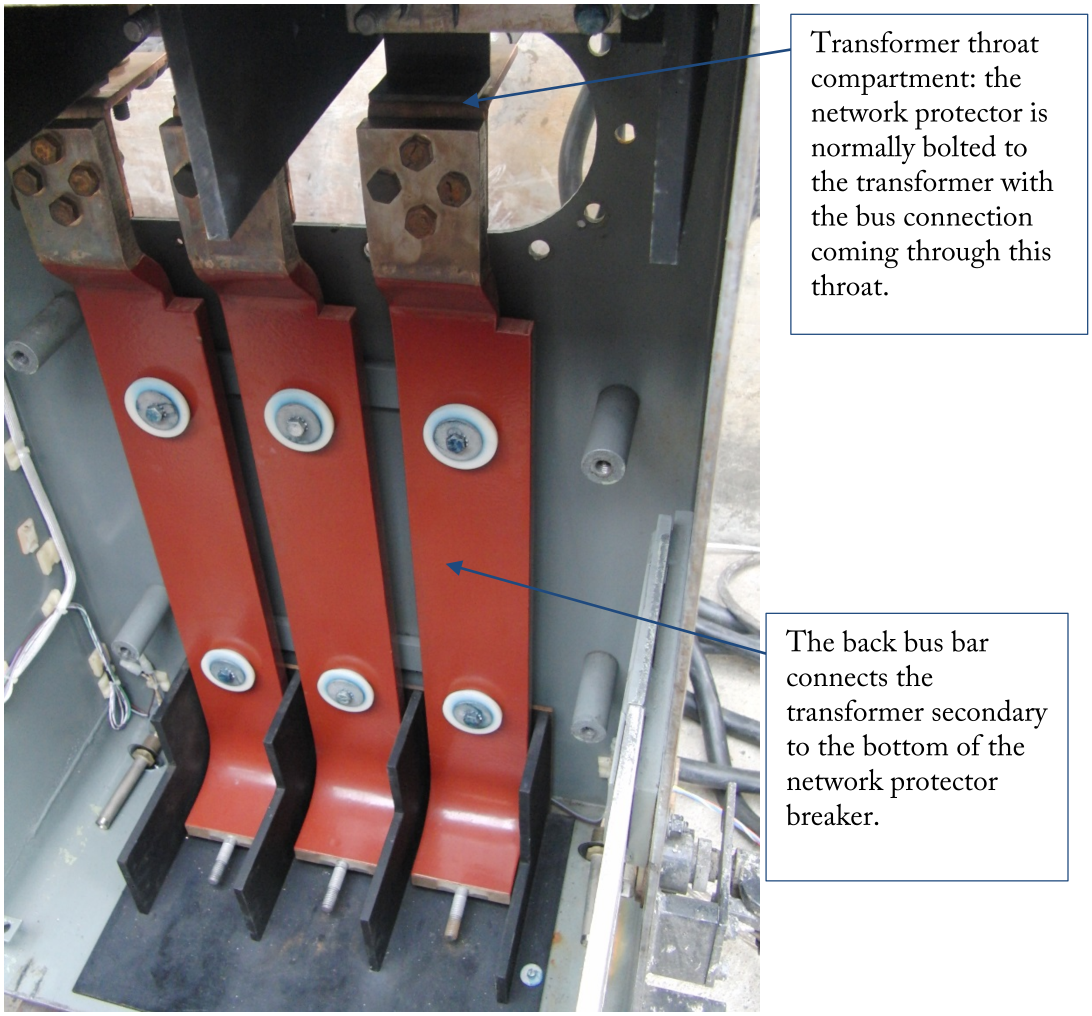


Figure 2-17
Interior of a CM-22 480-V network protector with the circuit breaker removed

Implications for Practices and Analysis

These results reinforce the benefit of de-energizing the transformer behind the network protector being worked. This can be done by tripping the feeder. Another good option is using a high-side interrupter if one is available in the vault. With the transformer-side de-energized and the circuit breaker open, the back bus bars are de-energized. With the back bus bars de-energized, arcs did not sustain longer than 1.5 cycles during tests.

Single-layer clothing is sufficient where the back bus bars are de-energized.

For analysis purposes, consider using a duration of three or four cycles. As an example, for a four-transformer spot network with infeeds from three 1500-kVA transformers (Figure 2-19), the bolted fault current is 77 kA, and IEEE 1584-2002 predicts the arcing current to be 30 kA. For a four-cycle duration at a working distance of 18 in, IEEE 1584-2002 predicts an incident energy of 4.8 cal/cm^2. With the transformer sizes increased to 2000 kVA, the predicted incident energy increases to 6.2 cal/cm^2. For most 480-V applications, workers can wear single-layer clothing. An alternative to calculations is to assume that this work has 8 cal/cm^2 exposure.

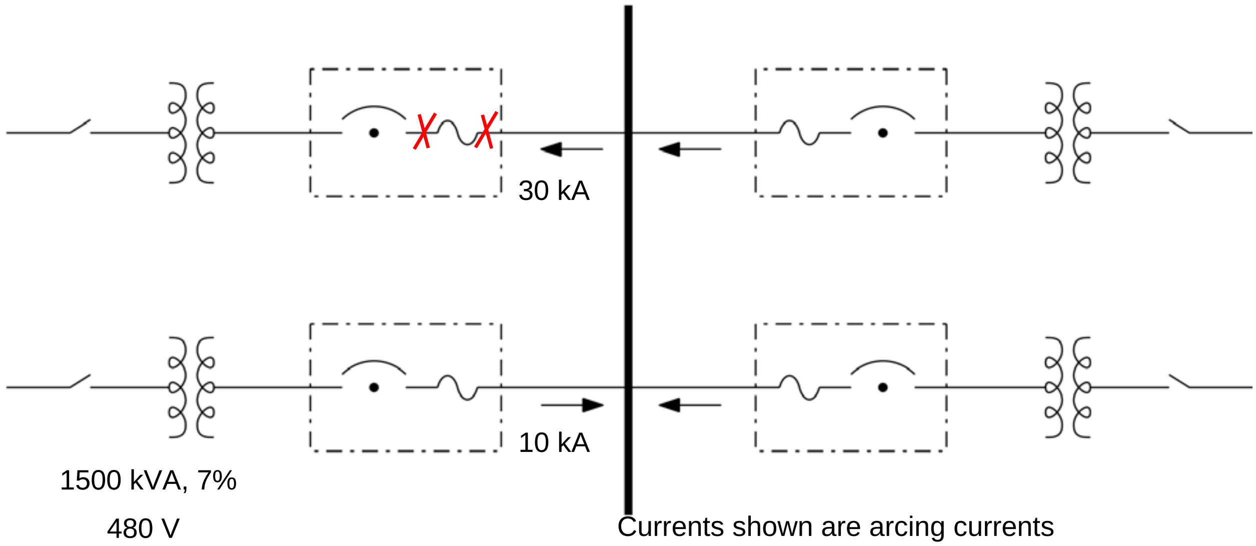


Figure 2-18
Spot network example showing infeeds to the network protector in the top left

As seen when attempting to initiate faults in different locations, the insulating barriers help prevent many possible contact scenarios. Given that, consider having workers check that the barriers are in place and in reasonable shape before starting work.

If the transformer behind the network protector is not de-energized, assume sustained arcing. IEEE 1584-2002 estimates of incident energies are reasonable for analyzing these situations.

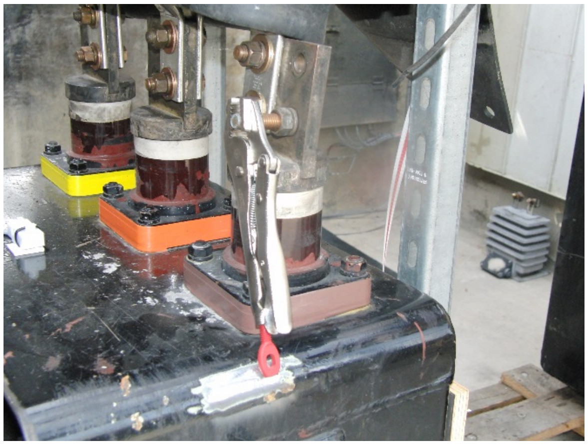
Section 3: Sustainability in Other Vault Scenarios

Previous tests have shown that it is difficult to sustain arcing in open-air conditions in a 480-V network vault. These tests confirm those findings. Realistic faults all self-cleared within four cycles for faults initiated at the following equipment:

- Outer terminations of the network protector
- Cables in cable trays
- Ceiling-mounted bus work (simulated)

External Terminations

The construction of older network protectors typically has multiple large insulated cables terminated on the NEMA pad that sticks out of the top of the network protector going to the 480-V common bus. These are often taped after installation but can be left un-taped. In any event, if the network protector is being replaced, these bolted terminations must be exposed to allow removal of the bolts. The most likely scenarios for faults to occur is wrench contact with the case or an adjacent phase during bolt removal or a loose cable coming into contact with an adjacent phase during cable removal. The EPRI team varied fault initiation to come as close as possible to these field conditions. Figure 3-1 and Figure 3-2 show the arc initiation points and arc durations for various conditions and the post-test damage. Complete results are shown in Appendix A.



Test ID 46: AΦ to case, vise grip; **0.14 cycles**

Post Test ID 46

Test ID 48: AΦ-BΦ vise grip; **2.65 cycles**

Post Test ID 48

Test ID 55: CΦ-BΦ cable; **1.57 cycles**

Post Test ID 55

Figure 3-1
Exterior arc initiation points, arc durations, and post-test damage

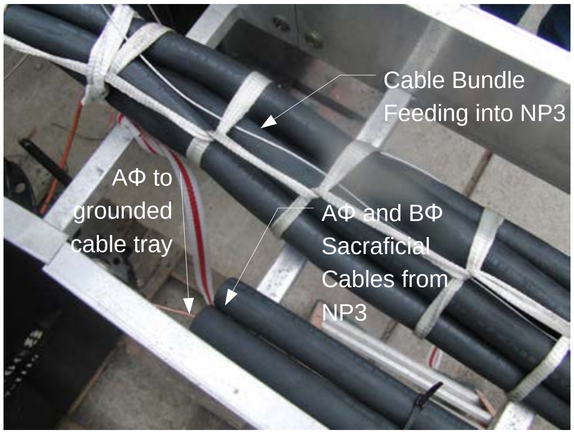

Test ID 56: CΦ-BΦ cable; **1.09 cycles**


Post Test ID 56

Figure 3-1 (continued)
Exterior arc initiation points, arc durations, and post-test damage

480-V Cable Trays

The construction of some network protector systems have insulated cable in cable tray as the 480-V common bus. To access a voltage source or to make additional connections, these cables are sometimes tapped into while still energized. To simulate these types of faults, a spare 500-kcmil cable was connected to the top of NP3 for two phases and laid into the cable tray with the feeder cables already in it. The ends of these cables were left with no termination on it, leaving bare copper exposed inside the cable tray. Fault initiation occurred at these open ends or at mid insulation points where windows of insulation were removed after the ends were taped up. The cable was restrained to keep movement to a minimum during the fault. Figure 3-3 and Figure 3-4 show arc initiation points, arc durations, and post-test damage for various tests.



Test ID 50: AΦ Ground end; **0.56 cycles**

Post Test ID 50

Test ID 51: AΦB Φ end; **1.09 cycles**

Post Test ID 51

Test ID 52: AΦ Ground middle; **3.52 cycles**

Post Test ID 52

Figure 3-2
Cable tray arc initiation points, arc durations, and post-test damage

Test ID 53: AΦ-BΦ Middle; **1.54 cycles**

Post Test ID 53-Note: Only AΦ cable remained in the tray; BΦ flew out of tray

Test ID 54: AΦ-Ground middle; **2.59 cycle**s

Post Test ID 54

Figure 3-2 (continued)
Cable tray arc initiation points, arc durations, and post-test damage

Ceiling-Mounted Open Bus Work

The construction of some network protectors systems have ceiling-mounted, open-air bus bar for the 480-V common bus. Ceilings are normally made of concrete, which is relatively non-conductive. To simulate work in this situation bare stranded copper wire was attached to a non-conductive surface (wood) and mounted underneath the cable tray between the functional network protectors (NP1 and NP2) and the sacrificial network protector (NP3). There was approximately seven inches of space between the bare wires. Most installations have spacings wider than seven inches.

Faults on the bus bar would travel to the end points away from the sources due to magnetic forces. In field conditions, it is conceivable that the bus bar could extend completely to a wall or a piece of equipment. To allow simulation of this condition, one end of the bare wires were attached to the NP3 termination, and the other ends of the bare wires were continued to a solid surface that was either covered with a rubber blanket or left as exposed metal. See Figure 3-5.

Cables attached to NP3

Cables end at a solid surface

Figure 3-3
Bus bar test setup

Figure 3-6 shows the arc initiation points, arc durations, and the post-test damage for the bus bar simulations. Complete results are shown in Appendix A.

Fault Initiation | **Post-Test Damage**

Test ID 66
AΦ-BΦ at an insulated barrier
Arc duration: 0.9 cycles

Test ID 67
AΦ-BΦ-CΦ at an insulated barrier
Arc duration: 0.49 cycles

Test ID 68
AΦ-BΦ at a metal barrier
Arc duration: 1.92 cycles

Test ID 69
AΦ-BΦ-CΦ at a metal barrier
Arc duration: 1.42 cycles

Figure 3-4
Bus bar simulation-fault initiation, arc durations, and post-test damage

External Fuse Compartments

External fuse compartments are another option to improve worker safety by moving the fuses outside of the network protector. Figure 3-7 shows examples of fault initiations from a series of tests done by EPRI at the PG&E San Ramon test laboratory in 2012. These compartments were insulated, making phase contact difficult. With a design like this, workers can open or replace fuses one phase at a time.

In nine tests in this series, faults were initiated at 480 V with #12 conductors with a mix of single-, double-, and three-phase faults. All fault currents self-cleared in less than one cycle. Damage was minimal.

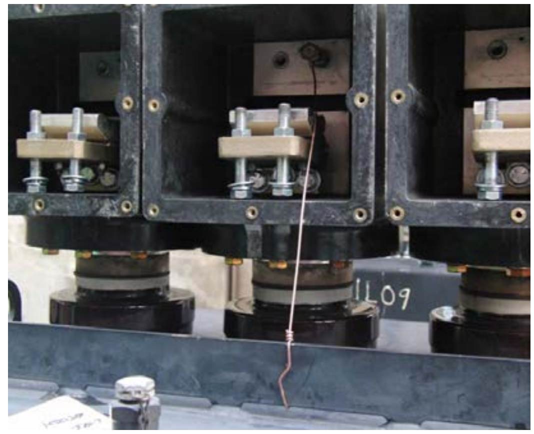
External fuse compartments have several features that tend to prevent arcs and encourage self-clearing:

External fuse compartments have many features that prevent arc hazards.

- Fault paths are difficult to create.
- Possible arc paths are long.
- Phase-to-phase connections are long and difficult to initiate.
- There is no flashover path that involves a confined arc.

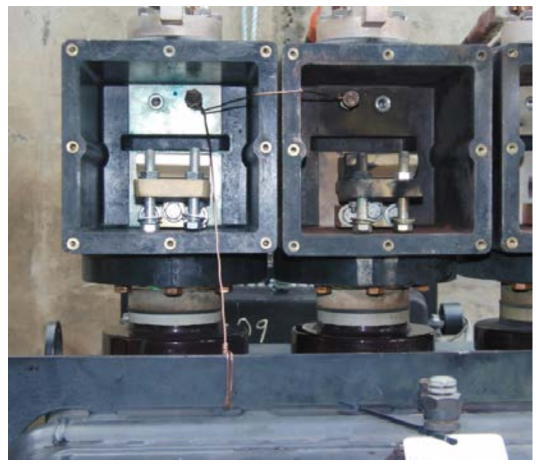
These features make external fuse compartments attractive for worker protection. External fuse compartments also have the advantage that they can be worked on without de-energizing the primary. Even with the back bus bars hot, external fuses should be safe.

Test 2012-2: AΦ to case; **0.53 cycles**

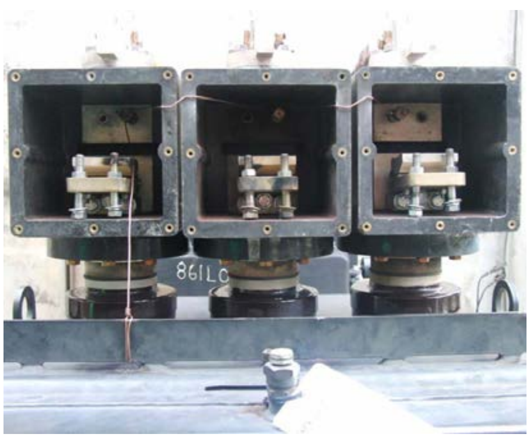


Test 2012-3: BΦ to case; **0.71 cycles**

Test 2012-5: BΦ to AΦ to case; **0.67 cycles**



Test 2012-6: CΦ to BΦ to case; **0.35 cycles**



Test 2012-7: Three-phase to case; **0.45 cycles**

Figure 3-5
Fault initiations and fault durations in external fuse compartments

Extreme Energizations

Two extreme faults were initiated above NP3 as shown in Figure 3-8. A pair of vise grips was attached with wire ties to bridge the gap from phase to the case. These arcs did not self-clear. They were cleared by laboratory circuit breakers (test ID 47) or by network protectors (test ID 49). Clearing times were under four cycles. With longer clearing times, the arcs may have burned clear. While these arcs are bolted faults, there are no arcs to generate energy. Because the durations were so short, the incident energies measured were too small to estimate heat rates from. It is likely that the heat rates are low because the faults are nearly bolted. Damage was minimal because the duration of the events were under four cycles. This fault event is not considered realistic.

Test ID 47: Vise grip tie-wrapped

Test ID 49: Vise grip tie-wrapped

Figure 3-6
Extreme faults initiated above the test network protector

Implications for Practices and Analysis

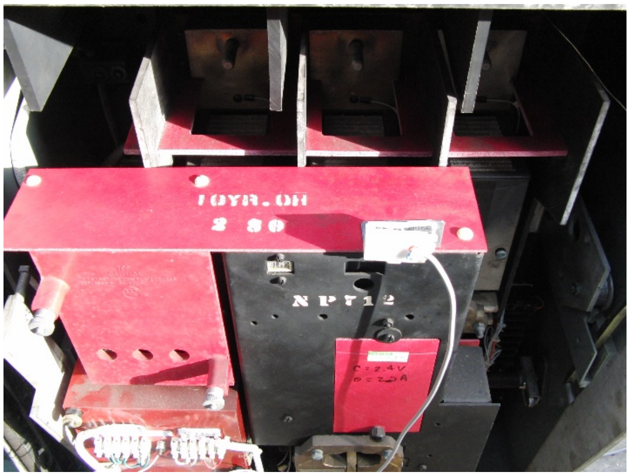
Tests of realistic arcs initiated on equipment outside of network protectors at 480 V all self-cleared in less than four cycles. Consider using four cycles as the duration when analyzing incident energies in these cases. This should lead to incident energies below 8 cal/cm^2. An alternative is to assume that these are all 8 cal/cm^2 exposures.

Section 4: Fiber-Optic Detection

Fiber optic sensors have been successfully used in switchgear for detection and relaying. In this section, we evaluate the performance and suitability of fiber optic detection for 480-V network applications. Arcs were initiated in several different ways to evaluate the sensitivity of the sensors, how fast they operate, and what placements work best.

Sensor Sensitivity and Placement

Both the omnidirectional sensor (180° field of view) and the torpedo sensor (90° field of view) were placed inside NP3 on top of the breaker control module to determine the sensor and relay pickup time during fault initiation. The 20AWG fuse wire generated the least intense arc flash, but the sensors in this position detected the flashes successfully. In order to detect AΦ initiation (the most severe position), the torpedo sensor had to be moved as far as possible away from the back of the NP3 network protector. See Figure 4-1 and Figure 4-2.



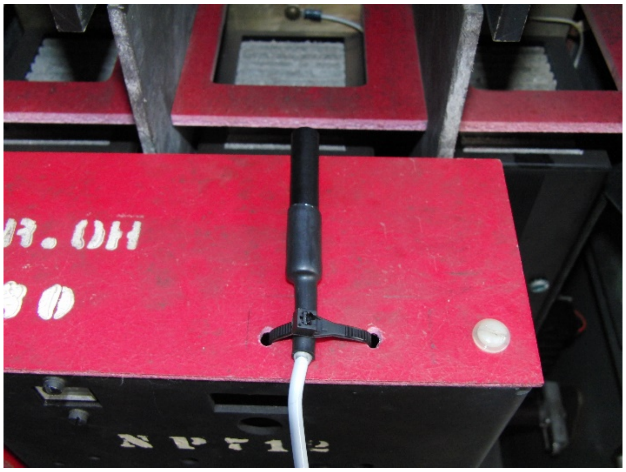
Omnidirectional sensor pointed in:

- Top front edge of breaker module
- Successfully detected arcs started at any location at the top of NP3 with 20AWG wire

Omnidirectional sensor pointed up:

- Top front edge of breaker module
- Successfully detected arcs started at any location at the top of NP3 with 20AWG wire

Figure 4-1
Omnidirectional sensor at the top of the breaker module



Torpedo sensor pointed in

- Top of breaker module
- Did not detect arc started at AΦ with 20 AWG wire

Torpedo sensor pointed in

- Top of breaker module pulled back
- Did detect arc started at AΦ with 20 AWG wire

Figure 4-2
Torpedo sensor at the top of the breaker module

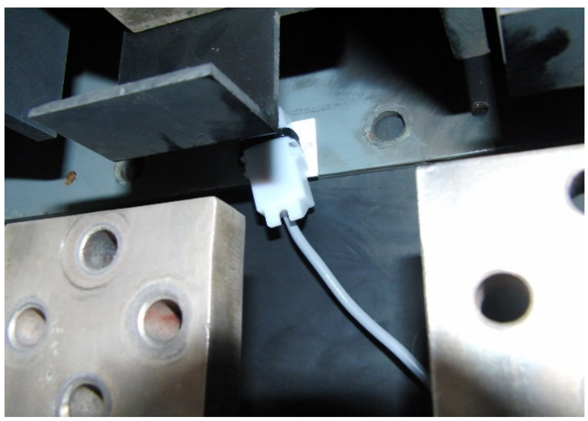
There was some concern that the sensor location at the top of the breaker module would be susceptible to false tripping from external light entering the network protector cabinet through the viewing window on the front door. Therefore, the sensors were moved to the back wall of the network protector to see if a location there would be able to detect arcs. The torpedo sensor was located at the bottom right of the protector, pointing up at a 45° angle. This position points the sensor at faults that might start from the upper fuse link terminals. See Figure 4-3.

Torpedo sensor on the bottom of the back wall pointing up at a 45° angle

- The sensor did not pick up for AΦ, BΦ, or CΦ to case initiations.
- It did pick up when AΦ was initiated with a wire to the back bolt.

Figure 4-3
Torpedo sensor on the back wall

Figure 4-4 shows placement of and omnidirectional sensor on the back wall behind the middle phase. Arcs were then initiated to determine if the sensor would detect the arcs.



Omnidirectional sensor on the back wall behind BΦ pointing forward

- The sensor did not pick up for AΦ case, #20 wire even with door closed.
- The sensor did pick up AΦ was initiated with wire to front bolt with #14 wire.

Figure 4-4
Omnidirectional sensor on the back wall

Fiber optic relays sent trip signals in less than 1.5 cycles.

In all cases where the sensor detected the arc, relay pickup times were fairly constant between 15 msec and 22 msec. See Figure 4-5 for a histogram of the relay pickup times. The relay trip signal was then sent directly to either the NP1 and NP2 or the high-side trip device, the laboratory vacuum circuit breaker. The network protectors tripped on average faster than the high-side breaker, the network protector trip times averaged 2.5 cycles versus the laboratory circuit breaker trip times that averaged 3.5 cycles.

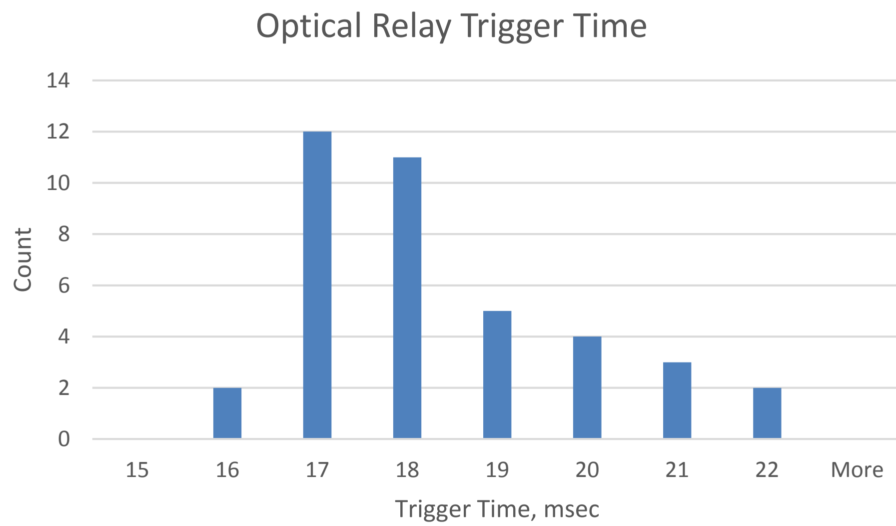


Figure 4-5
Optical relay trigger times

When the fault initiation was made inside the cable tray, the sensor type was changed to a continuous fiber cable. The cable was run inside the power cable bundle and was deliberately located on the side away from the arc initiation points. See Figure 4-6.

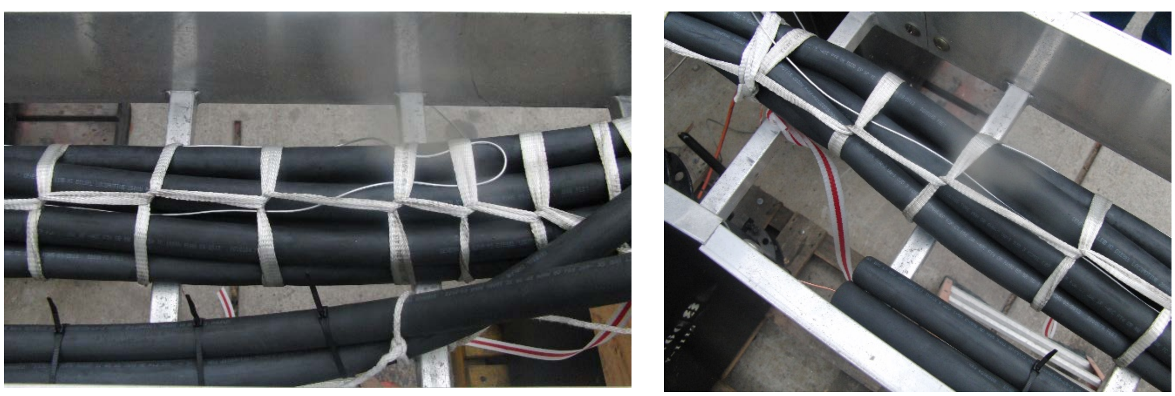


Figure 4-6
Continuous-fiber cable sensor

In all cases, the sensor detected the arc, and a trip signal was sent to the high-side breaker. The average relay time was 17.9 msec; the average breaker tripping time was 56.3 msec.

When the fault initiation was made on the simulated bus bar, the sensor type used was the torpedo sensor located at the source end to the 'bus bar' pointed towards the end as shown in Figure 4-7.

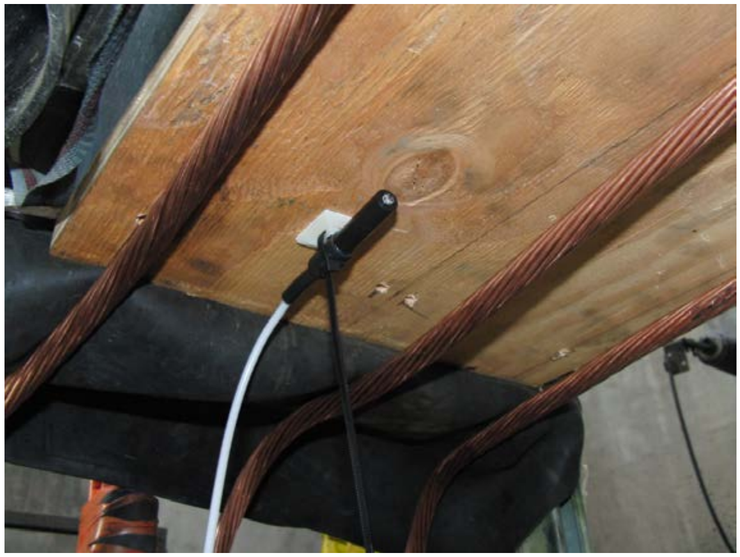


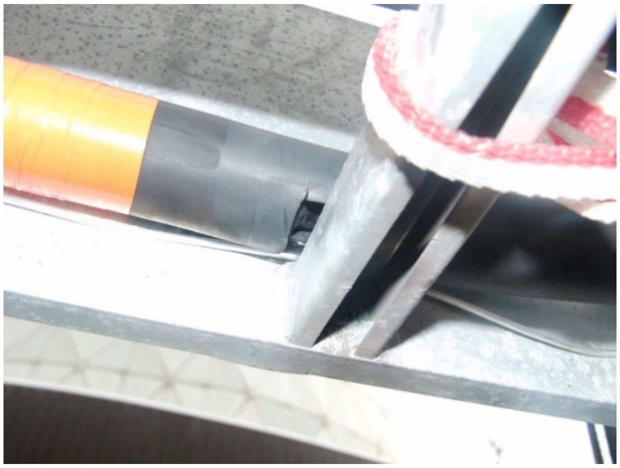
Figure 4-7
Torpedo sensor for the simulated bus bars

In all cases, the sensor detected the arc, and the trip signal was sent to NP1 and NP2. The average relay time was 16.7 msec; the average network protector tripping time was 39.9 msec.

Sensor Durability

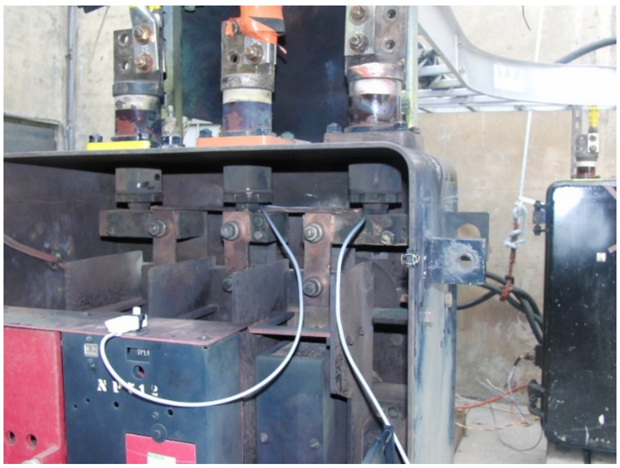
All of the fiber optic sensors were extremely durable, even when placed directly in the arc flash event. Figure 4-8 shows some extreme locations of the continuous fiber cable and the omnidirectional sensor wire bundle. Also, NP3 was fully instrumented with four omnidirectional sensors during the extreme attempts to sustain an arc inside a network protector. The four sensors were connected to the relay input terminals as follows:

1. Top middle of the breaker module
2. Back wall, behind AΦ fuse terminal
3. Back wall, behind BΦ fuse terminal
4. Back wall, behind CΦ fuse terminal



Test ID 54: Continuous Fiber Cable:

- Located in cable tray between phase conductor and the ground plane
- Sensor detected arc
- Relay sent trip signal: 15.2 ms
- Sensor remained functional post test: arc duration 43.7 ms



Test ID 64: Omnidirectional Sensor Cable:

- Located around the shorting bar inside the network protector
- Sensor detected arc
- Relay sent trip signal: 17.1 ms
- Sensor remained function post test: arc duration 70.1 ms

Figure 4-8
Sensor durability

These sensors remained functional through all tests. They successfully detected and sent trip signals for all of the internal extreme initiated arcs, Test ID's 60 through 65. This includes the sustained fault of 12 cycles of 50 kA available fault with over 7 cal/cm^2 of measured heat. They were very dirty but still were able to sense fault current and send the trip signal. See Figure 4-9 for sensor placement and Figure 4-10 for sensor condition after testing.

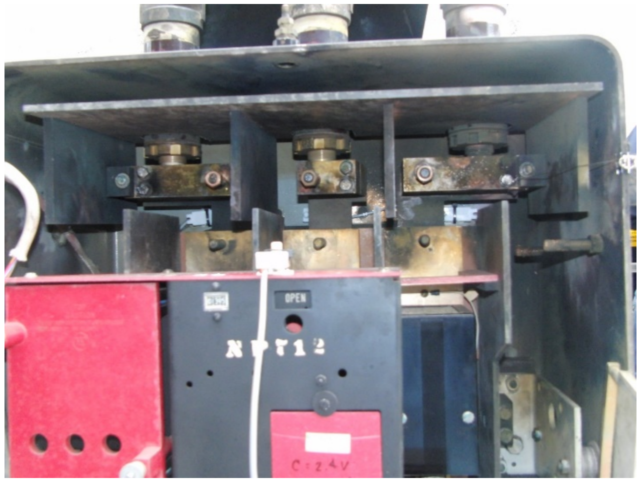


Figure 4-9
Sensor positions inside NP3

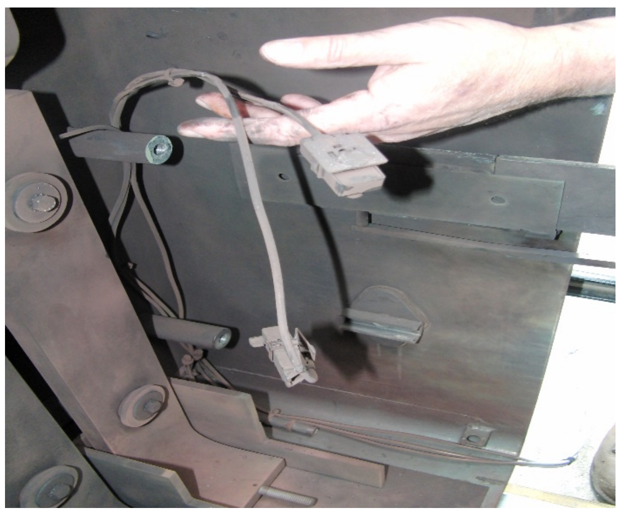


Figure 4-10
Post Test 65: Condition of the omnidirectional sensors on the back wall

Performance for Normal Network Protector Operations

Starting with Test ID 60, NP2 was fully instrumented with optical sensors to determine if any of them would send a trip signal from the arcs extinguished inside the arc chutes of the breaker. Five sensors inside NP2 were connected to the relay input terminals as follows:

1. Torpedo Sensor: Top middle of the breaker module
2. Omnidirectional Sensor: Top middle of the breaker module
3. Omnidirectional Sensor: Back wall, behind AΦ fuse terminal
4. Omnidirectional Sensor: Back wall, behind BΦ fuse terminal
5. Omnidirectional Sensor: Back wall, behind CΦ fuse terminal

Test IDs 60 through 65 had sensor inputs 1 through 4 inside NP3, Test ID 66 through 69 had sensor input 1 looking at the simulated bus bar, and Test ID 70 through 74 had sensor inputs 1 and 10 looking at the top of NP3 (arc locations). Table 4-1 lists the sensors that sent trip signals for each of these tests.

Table 4-1
Sensor pickup for Test ID 60 through 74

Test	Test ID	Self extinguish	Current duration		VAMP trip signal [msec]	Device clearing time [msec]	Sensors that picked up	Sensor locations in addition to 5,6,7,8,9 inside NP2
			cycles	msec				
Extreme Conditions Inside NP3	060	Y	0.16	2.6	17.3	40.3	1,2	1,2,3,4 Inside NP3
	061	Y	0.71	11.9	16.2	36.6	1,2,3,4	
	062	N	2.54	42.4	17.4	42.2	1,2,3,4,5	
	063	N	2.57	42.9	16.1	42.5	1,2,3,4,5,6	
	064	Y	4.21	70.1	17.1	201.2	1,2,3,4	
	065	N	12.23	203.9	16.0	204.3	1,2,3,4	
Bus Bar Simulation	066	Y	0.4	6.7	16.3	39.4	1	#1 torpedo looking down bus bar between two phases
	067	Y	0.49	8.2	17.4	38.8	1	
	068	Y	1.92	32.0	16.5	42.5	1,5,8	
	069	Y	1.42	23.5	16.6	39.0	1	
Bolted Fault Interruption	072	N	6.53	108.8	16.8	108.8	1,10	#1 omnidirectional and #10 torpedo added to top NP3
	073	N	0.38	6.3	17.1	6.3	NA	
	074	N	6.83	113.8	20.3	114.0	1,5,6,8,9,10	

For test ID 62 and 63, the sensors mounted inside NP2 on the top of the breaker module (inputs 5 and 6) picked up from flash through the arc chutes. This would have represented a nuisance trip from sensors in that location. For test ID 68, we believe the flash reflected off the back wall and went into NP2 through the open throat plate on the back (sensor inputs 5 and 8). After this test, the open throat plate was covered with rubber blankets to prevent this reflection. Test ID 74 had sensors 5, 6, 8, and 9 inside NP2 picked up. However, subsequent to this test, NP2 was opened and inspected. Considerable arcing occurred at the fuse clip location in both BΦ and CΦ. These sensors would have definitely picked up on that arcing, so it is indeterminate if arcing in the arc chutes would have caused a nuisance trip for sensors in this location. See Figure 4-11.

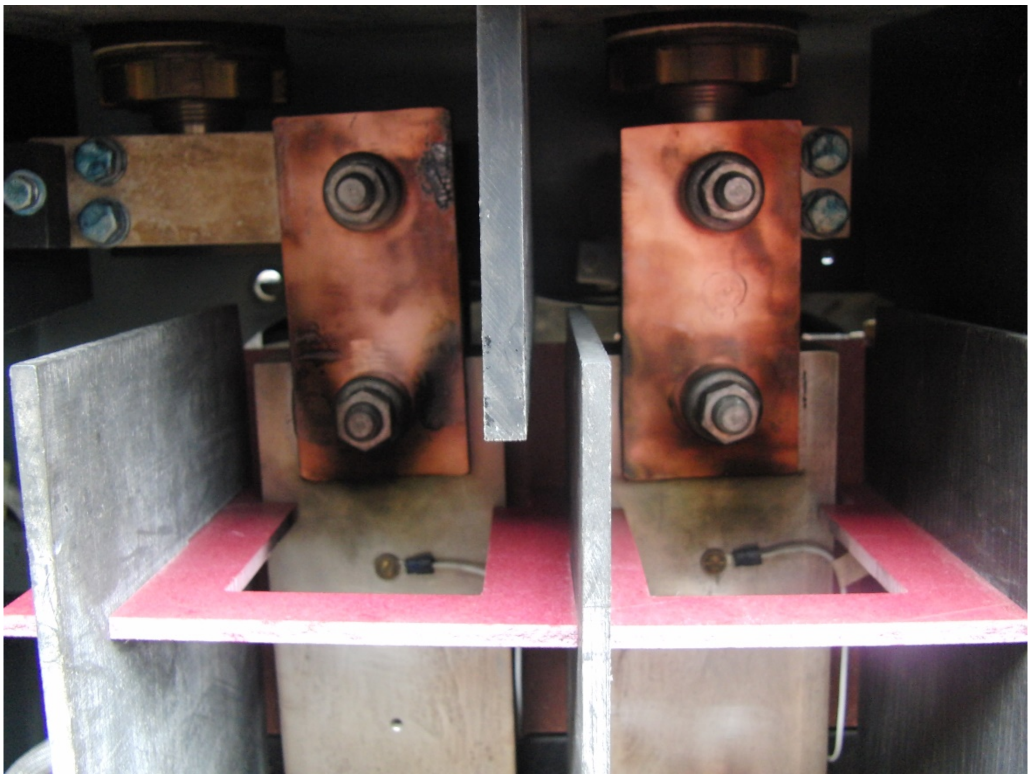


Figure 4-11
Arcing inside NP2 at fuse terminal location C Φleft-B Φright

Summary

Overall, the fiber optic sensors worked well:

- When faults were detected, trip signals were sent within 1.5 cycles.
- For the higher-energy arcing events, the sensors are sensitive enough that almost any placement will work.
- Sensors and cabling is very durable and will functionally service most faults.

The main issues with placement and sensitivity are false trips. The units respond to steady-state light threshold (not a change in intensity), and direct sunlight will trip the VAMP relay. Inside a network protector, the back wall is the best location to capture arcing but also to avoid sunlight from the front. For the most sensitive application that can catch all low-energy arcs near the top of the protector, three omnidirectional sensors are needed at back wall just behind the fuse location. However, one omnidirectional sensor on the back wall should be adequate for events with substantial arc energy (the events of most concern). Some nuisance tripping may be seen due to arcing when the network protector clears high fault currents.

For bus bars, the torpedo sensor (point sensor) worked well. Fiber sensors worked well for cable trays, but they may be susceptible to false tripping from sunlight.

Section 5: Network Protectors for Interrupting Fault Current

A high-side vacuum interrupter may be the best way to clear faults in a network protector, but many utilities do not have these in 480-V network vaults. Use of the network protectors in the spot network to clear faults has been discussed in the industry. Network protectors were not designed for this, but they have circuit breakers that should be rated for this duty. Tests were done to evaluate the performance of the CM22 units to clear faults. The main concern is whether they will clear faults, and the second consideration is how fast they can clear faults. Network protectors could be used in a relaying scheme with fiber optic relays or other relaying schemes such as reverse power detection.

Test ID 62, 63, and 65 lasted long enough for the network protectors to interrupt 12 kA to 15 kA of arcing fault current. For test ID 70 through 74, a sustained bolted fault current was created outside NP3 at the top terminations. Table 5-1 shows the fault currents that were interrupted by the network protectors.

Several attempts to get NP2 to interrupt fault current were made. In order to test higher-magnitude faults, a bolted faults was created by connecting CΦ to BΦ with a solid 500-kcmil copper cable. In order for the optical relaying to pick up, a fuse wire was run from AΦ to the case, and this caused an arc big enough for the optical sensor to pick up and send a trip signal to NP2. Only one transformer fed the fault to determine if NP2 could successfully interrupt approximately 25 kA of bolted fault current in both BΦ and CΦ. The rating of this network protector is only 30kA. During this test (test ID 74), NP2 successfully interrupted 22 kA on both of the faulted phases.

Table 5-1
Network protector fault interruption

Test ID	NP1 Fault Current (kA)	NP2 Fault Current (kA)	Phases involved
47	5.8	5.4	A
49	5.1	4.6	A
62	15	12	A B C
63	16	15	A B C
74	NA	22	B C

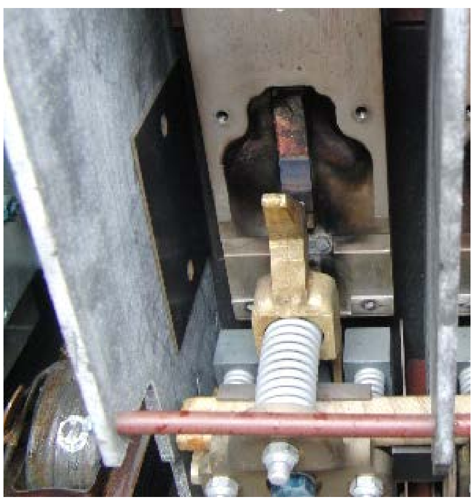
Network protectors successfully cleared faults and should survive a few such events.

Before Test ID 60 and after Test ID 74, the arc chutes of NP2 were removed and examined. Minor arcing damage could be seen after Test ID 74 as shown in Figure 5-1. While the network protector is not likely to survive many arcs of this magnitude, it can clearly survive a few of them

The network protectors cleared quickly. The average network protector tripping time was 2.4 cycles (39.9 msec).

Pre-Test ID 60: Arcing Contact

Pre-Test ID 60: Arcing Chute



Post Test ID 74: Arcing Contact

Post Test ID 74: Arcing Chute

Figure 5-1
Conditions of arcing contacts and arc chutes

Section 6: Conclusions

For work in 480-V network protectors, the main finding is that fault currents do not sustain longer than 1.5 cycles if the back bus bars are de-energized. Incident energy exposures are likely to be below 8 cal/cm^2. Based on this finding, workers could wear single-layer flame-resistant (FR) clothing.

If the back bus bars in a network protector are energized, sustained faults are likely. Back bus bars may be energized through the network-protector transformer or from the load side if the circuit breaker in the network protector is closed. In these situations, an analysis must be done to evaluate incident energy exposures.

In 480-V vaults outside of network protectors, all realistic open-air scenarios self-cleared within four cycles. As with network protectors with the back bus bars de-energized, exposures are likely to be below 8 cal/cm^2 (single-layer FR).

Fiber optic sensors performed well for detecting arcs in network protectors and external applications. Sensors and cabling were robust to nearby arcs, and performed well even when covered with soot.

Inside network protectors, one omnidirectional sensor on the back wall should be adequate for events with substantial arc energies. For increased sensitivity, three sensors could be used on the back wall. Some nuisance tripping may be seen when clearing faults with very high current.

Network protectors are an option for relaying schemes to protect workers from arc flash. The CM-22's tested successfully interrupted faults ranging from 5 kA to 23 kA multiple times with little damage to the arcing contacts. These network protectors tripped in an average time of 2.5 cycles.

Section 7: References

ASTM F1959, *Standard Test Method for Determining the Arc Rating of Materials for Clothing*, ASTM International, 2006.

ASTM E457-08, *Standard Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter*, ASTM International, 2008.

Eblen, M. L. and Short, T. A., "Arc Flash Testing of Typical 480-V Utility Equipment," IEEE IAS Electrical Safety Workshop, Memphis, TN, 2010. Paper ESW2010-05.

Eblen, M. L. and Short, T. A., "Arc-Flash Testing of Typical 480-V Utility Equipment," *IEEE Transactions on Industry Applications*, vol. 48, no. 2, pp. 581-592, March-April 2012.

EPRI 1018693, *Distribution Arc Flash: Analysis Methods and Arc Characteristics*, Electric Power Research Institute, Palo Alto, CA, 2009.

EPRI 1018694, *Distribution Arc Flash: Industry Practices*, Electric Power Research Institute, Palo Alto, CA: 2009.

EPRI 1020210, Distribution Arc Flash: 480-V Padmounted Transformers and Network Protectors Electric Power Research Institute, Palo Alto, CA: 2009.

EPRI 1022697, *Distribution Arc Flash: Phase II Test Results and Analysis*, Electric Power Research Institute, Palo Alto, CA, 2011.

EPRI 1023267, *Arc Flash Testing of Clothing and 480-V Meter Sockets*, Electric Power Research Institute, Palo Alto, CA, 2011.

EPRI 1022002, *480-V Distribution Arc Flash Updates*, Electric Power Research Institute, Palo Alto, CA, 2011.

IEEE 1584-2002, *IEEE Guide for Performing Arc Flash Hazard Calculations*.

IEEE C2-2012, *National Electrical Safety Code*.

OSHA 1910.269, Electric Power Generation, Transmission, and Distribution, Occupational Safety and Health Administration, US Department of Labor, Regulations (Standards—29 CFR), 2014.

OSHA 1926 Subpart V, Power Transmission and Distribution, Occupational Safety and Health Administration, US Department of Labor, Regulations (Standards—29 CFR).

Appendix A: Test Results

Fault Location-Condition	Test ID	Date	Time	Self Extinguish before Device Opening Y/N	Current DurationTest Length (cy)	(ms)	# Trans Feeding Fault	Calo Max (cal/ cm^2)	VAMP trigger time (ms)	Total device opening time (ms)	Test Comments
Inside NP3	013	2/2	9:42	Y	0.14	2.3	2	0.0	17.0	42.0	Omni sensor centered on B ph fuse link position. NP1 and NP2 closed. #20 Fuse wire from A to case. Calo #8 centered on A ph fuse link position. 18" from arc.NP 1 & 2 opened 25 ms after the VAMP signal. A ph current peak of 2800 amps for 2.3 ms. No heat increase on calorimeters.
	014	2/2	10:06	Y	0.25	4.2	2	0.1	16.8	39.4	Omni sensor centered on B ph fuse link position. NP1 and NP2 closed. #14 Fuse wire from A to case. Calo #8 centered on A ph fuse link position. 18" from arc.NP 1 opened 19.2 ms after the VAMP signal NP 2 opened 21.2 ms after VAMP. NP1 A ph current peak of 7818 amps. NP2 ph current peak of 7254 amps. No heat increase on calorimeters.
	015	2/2	10:36	Y	0.35	5.9	2	0.1	18.2	42.0	Omni sensor centered on B ph fuse link position. NP1 and NP2 closed. 2 #14 Fuse wire from A to bolt to case. Calo #8 centered on A ph fuse link position. 18" from arc.NP 1 opened 21 ms after the VAMP signal NP 2 opened 23 ms after VAMP. NP 1 A ph current peak 12172. NP 2 A Ph current peak 11074.
	016	2/2	11:40	Y	0.41	6.8	2	0.0	19.5	96.5	Omni sensor centered on B ph fuse link position. NP1 and NP2 closed. 1 #14 Fuse wire from A to new drilled hole 2" from front of case. Calo #8 centered on A ph fuse link position. 18" from arc. NP trip disabled. 2100/2 trip enabled.open 2100/2 early command didn't work.
	017	2/2	11:54	Y	0.51	8.4	2	0.0	21.4	66.5	Omni sensor centered on B ph fuse link position. NP1 and NP2 closed. 2 #14 Fuse wire from A to new drilled hole 2" from front of case. Calo #8 centered on A ph fuse link position. 18" from arc. NP trip disabled. 2100/2 trip enabled.
	018	2/2	13:32	Y	1.5	24.9	2	0.1	17.5	133.5	Omni sensor centered on B ph fuse link position. NP1 and NP2 closed. ViseGrip installed on phase bolt and wedged to the face of the electrode plate. Calo #8 centered on A ph fuse link position. 18" from arc. NP trip disabled. 2100/2 trip enabled.
	019	2/2	13:52	Y	1	16.6	2	0.0	18.9	133.5	Omni sensor centered on B ph fuse link position. NP1 and NP2 closed. ViseGrip installed on phase bolt and wedged to under the bus plus a #14 wire tying ViseGrip to bus. Calo #8 centered on A ph fuse link position. 18" from arc. NP trip disabled. 2100/2 trip enabled.

Fault Location-Condition	Test ID	Date	Time	Self Extinguish before Device Opening Y/N	Current DurationTest Length (cy)	(ms)	# Trans Feeding Fault	Calo Max (cal/ cm^2)	VAMP trigger time (ms)	Total device opening time (ms)	Test Comments
Inside NP3	022	2/2	14:29	Y	0.46	7.7	2	0.0	21	133.5	Omni sensor centered on B ph fuse link position. NP1 and NP2 closed. 2 #14 wire from back bolt to fuse bus. Calo #8 centered on A ph fuse link position. NP trip disabled. 2100/2 trip enabled.open 2100/2 early command didn't work.
	023	2/2	14:45	Y	0.55	9.1	2	0.0	22	132.4	Omni sensor centered on B ph fuse link position. NP1 open and NP2 closed. 2 #14 wire from back bolt to fuse bus. Calo #8 centered on A ph fuse link position. NP trip disabled. 2100/2 trip enabled.open 2100/2 early command didn't work.
	030	2/3	9:13	Y	0.19	3.2	2	0.0	NT	133.6	NP1 and NP2 closed. #20 fusewire from front bolt to A Ph fuse bus. Torpedo sensor aimed at B phase. Calorimeter #8 centered on NP3.VAMP did not trigger.
	031	2/3	9:25	Y	0.25	4.1	2	0.0	17.9	51.5	NP1 and NP2 closed. #20 fusewire from front bolt to A Ph fuse bus. Torpedo sensor aimed at B phase. Sensor moved back 3". Calorimeter #8 centered on NP3.
	032	2/3	9:46	Y	1	16.7	2	0.0	16.7	38.9	NP1 and NP2 closed. #20 fusewire from C Ph to binder clip on left side of NP. Torpedo sensor aimed at B phase same as previous test Calorimeter #8 centered on C Ph. NP trip test.
	033	2/3	10:23	Y	0.11	1.8	2	0.0	NT	133.6	NP1 and NP2 closed. #20 fusewire from C Ph to binder clip on left side of NP. Torpedo sensor aimed bottom back right side pointed up. Calorimeter #8 centered on C Ph. NP trip test. No Rubber blanket.VAMP did not trigger.
	034	2/3	10:36	Y	0.17	2.9	2	0.0	NT	133.6	NP1 and NP2 closed. #20 fusewire from B Ph to binder clip on top of NP. Torpedo sensor aimed bottom back right side pointed up. Calorimeter #8 centered on B Ph. NP trip test. Rubber blanket added.VAMP did not trigger.
	035	2/3	10:47	Y	0.18	2.9	2	0.0	NT	133.6	NP1 and NP2 closed. #20 fusewire from A Ph to binder clip on right side of NP. Torpedo sensor aimed bottom back right side pointed up. Calorimeter #8 centered on A Ph. NP trip test. Rubber blanket added.VAMP did not trigger.
	036	2/3	11:15	Y	0.13	2.1	2	0.0	NT	133.6	NP1 and NP2 closed. #20 fusewire from C Ph to binder clip on left side of NP. Torpedo sensor aimed bottom back right side pointed up. Calorimeter #8 centered on C Ph. NP trip test. No Rubber blanket.VAMP did not trigger.
	037	2/3	11:28	Y	0.17	2.9	2	0.0	NT	133.6	NP1 and NP2 closed. #20 fusewire from A Ph to binder clip on left side of NP. Torpedo sensor aimed bottom back right side pointed up. Calorimeter #8 centered on A Ph. NP trip test. No Rubber blanket.VAMP did not trigger.

Fault Location-Condition	Test ID	Date	Time	Self Extinguish before Device Opening Y/N	Current DurationTest Length (cy)	(ms)	# Trans Feeding Fault	Calo Max (cal/ cm^2)	VAMP trigger time (ms)	Total device opening time (ms)	Test Comments
Inside NP3	038	2/3	11:38	Y	0.27	4.6	2	0.0	18.3	41.4	NP1 and NP2 closed. #20 fusewire from A Ph back bolt to the fuse bus. Torpedo sensor aimed bottom back right side pointed up. Calorimeter #8 centered on A Ph. NP trip test. No Rubber blanket.
	039	2/3	12:15	Y	0.20	3.3	2	0.0	NT	133.6	NP1 and NP2 closed. #20 fusewire from A Ph to binder clip on side of NP. Omni sensor mounted on back wall just below opening. Calorimeter #8 centered on A Ph. High side trip test.
	040	2/3	12:54	Y	0.33	5.5	2	0.0	19.8	55.1	NP1 and NP2 closed. #14 fusewire from A Ph to front bolt. Omni sensor mounted on back wall just below opening. Calorimeter #8 centered on A Ph. High side trip test.
	042	2/3	13:09	Y	0.19	3.2	2	na	NT	133.6	NP1 and NP2 closed. #20 fusewire from A Ph to front edge of door. Omni sensor mounted on back wall just below opening. No Calorimeter. Door closed. High side trip test.
	043	2/3	13:33	Y	0.34	5.7	2	0.1	16.8	51.8	NP1 and NP2 closed. #14 fusewire from A-B-C Ph on fuse link. Omni sensor centered on B ph fuse link position. Calorimeter #8 centered on B. Barriers intact. High side trip test. Sensor damaged with copper and replaced.
	044	2/3	13:57	Y	0.28	4.7	2	0.3	16.1	50.0	NP1 and NP2 closed. #14 fusewire from A-B-C Ph on fuse link. Omni sensor centered on B ph fuse link position. Calorimeter #8 centered on B. Barriers removed. High side trip test.
Ext Term NP3	046	2/3	14:37	Y	1.45	24.2	2	0.1	17.9	53.4	Vise grip on the top of the NP A Ph to the case . Paint buffed off case. Omni sensor on top of the NP pointing up. NP1 & NP2 closed. High side trip.
Extreme Con-ditions	047	2/3	14:46	N	3.85	64.2	2	0.1	19.0	64.2	Vise grip on the top of the NP A Ph connected to the buffed case tyraped to the terminal. Omni sensor on top of the NP pointing up. NP1 & NP2 closed. High side trip.Arc sustained and VAMP stopped it.
Ext Term NP3	048	2/3	15:00	Y	3.18	53.0	2	0.7	17.6	60.2	Vise grip on the top of the NP attached to B Ph resting on A Ph. Omni sensor on top of the NP pointing up. NP1 & NP2 closed. High side trip.restrikes, 3 1/2 cycles of current. VAMP stopped it.
Extreme Con-ditions	049	2/4	8:41	N	2.58	43.0	2	0.1	19.5	43.0	Vise grip on the top of the NP A Ph connected to the buffed case tyraped to the terminal. Omni sensor on top of the NP pointing up. #8 calo centered on A phase. NP1 & NP2 closed. NP trip.
	050	2/4	10:32	Y	0.56	9.3	2	na	17.6	51.3	A to ground with #14 in cable tray. B cable exposed end in cable tray. Fiber sensor looped in cable bundle in tray. High side trip. No calorimeters.
	051	2/4	10:54	Y	0.65	10.8	2	na	17.6	51.5	A to B with #14 in cable tray. Fiber sensor looped in cable bundle in tray. High side trip. No calorimeters.

Fault Location-Condition	Test ID	Date	Time	Self Extinguish before Device Opening Y/N	Current DurationTest Length (cy)	(ms)	# Trans Feeding Fault	Calo Max (cal/ cm^2)	VAMP trigger time (ms)	Total device opening time (ms)	Test Comments
Cable Tray	052	2/4	11:22	Y	3.52	58.6	2	na	20.3	62.5	Cable ends taped. 2" insulation striped from the bottom of cable A in cable tray and in contact with tray cross member. Tyraped to tray. Fiber sensor looped in cable bundle in tray. High side trip. No calorimeters.cable tray burned away at contact area.
	053	2/4	12:35	Y	1.54	25.7	2	na	18.1	65.7	Cable ends taped. Windows cut in A and B and they are tyraped together in the cable tray. Fiber sensor looped in cable bundle in tray. High side trip. No calorimeters.B phase blew clear and ended early.
	054	2/4	13:04	Y	2.59	43.2	2	na	15.7	50.7	Cable ends taped. 2" insulation striped from the bottom of cable A in cable tray and in contact with tray cross member. Tyraped to tray. Fiber sensor tied between cable and tray. High side trip. No calorimeters.
Ext loose cable NP3	055	2/4	13:55	Y	1.57	26.1	2	0.1	19.5	133.6	500 mcm tied securely to A ph bushing of NP3 and touching B ph bushing of NP3. Cable restrained to restrict movement. Omni sensor on top of NP 3 but not used. Time trip only. Calorimeter #8 centered on C ph.B ph current stopped after 1/2 cycle.
Ext loose cable NP3	056	2/4	14:16	Y	1.09	18.1	2	0.1	NA	133.6	500 mcm tied securely to A ph bushing of NP3 and wedged to B ph bushing of NP3 with a cable connector. Cable restrained to restrict movement. Omni sensor on top of NP 3 but not used. Time trip only. Calorimeter #8 centered on C ph.VAMP disconnected.
Extreme Conditions	057	2/4	14:54	Y	0.46	7.6	2	0.2	16.5	38.7	#14 Fusewire ABC across fuse link terminals. Busbar laying below fusewire resting on top of the phase partition. Omni sensor as before on top of breaker. NP trip.
	060	2/5	10:26	Y	0.16	2.6	2	0.0	17.3	40.3	NP1 & NP2 closed. #20 fusewire A Ph to binder clip to frame in NP3. 2 sensors in NP3. Calorimeters on NP3 #8 centered on A ph. Vamp to trip NPs. 5 sensors installed on NP2 to monitor the trip.
	061	2/5	10:45	Y	0.71	11.9	2	0.0	16.2	36.6	NP1 & NP2 closed. Cu busbar resting on top fuse link terminals ABC in NP3. 4 sensors in NP3. No Calorimeters. Vamp to trip NPs. 5 sensors installed on NP2 to monitor the trip.
	062	2/5	11:13	N	2.54	42.4	2	0.0	17.4	42.2	NP1 & NP2 closed. Cu busbar resting on top fuse link terminals moved to back ABC in NP3. 4 sensors in NP3 new omni on top of the breaker. No Calorimeters. Vamp to trip NPs. 5 sensors installed on NP2 to monitor the trip.
	063	2/5	12:05	N	2.57	42.9	2	0.5	16.1	42.5	NP1 & NP2 closed. Install Cu bars in place of fuse links. Put busbar on top of breaker back behind phase barriers in NP3. Replaced omni sensor in NP3. 4 sensors in NP3. Calorimeters used. Vamp not used. 5 sensors installed on NP2.

Fault Location-Condition	Test ID	Date	Time	Self Extinguish before Device Opening Y/N	Current DurationTest Length (cy)	(ms)	# Trans Feeding Fault	Calo Max (cal/ cm^2)	VAMP trigger time (ms)	Total device opening time (ms)	Test Comments
	064	2/5	13:21	Y	4.21	70.1	2	1.0	17.1	201.2	NP1 & NP2 closed. Cu busbar resting on top fuse link terminals moved to back ABC in NP3. 4 sensors in NP3. Calorimeters used. Vamp not used to trip. 5 sensors installed on NP2.
	065	2/5	14:06	N	12.23	203.9	2	7.3	16.0	204.3	NP1 & NP2 & NP3 closed. Xfmr link and Cu fuselinks installed. Cu busbar wedged between B fusebus and C back bus and ground on the back case of NP3. 4 sensors in NP3 2 sensors dangeing on the back wall. Calorimeters used. Vamp not used to trip. 5 sensors installed on NP2.
Simulated Ceiling Mounted Bus Bar	066	2/6	8:38	Y	0.4	6.7	2	na	16.3	39.4	3x 250 MCM with 6" spacing busbar fault C-B #14. No calorimiters. Torpedo sensor looking at busbar between A and B. NP trip.
	067	2/6	8:45	Y	0.49	8.2	2	na	17.4	38.8	3x 250 MCM with 6" spacing busbar fault A-C-B #14. No calorimiters. Torpedo sensor looking at busbar between A and B. NP trip.
	068	2/6	8:53	Y	1.92	32.0	2	na	16.5	42.5	3x 250 MCM with 6" spacing busbar fault C-B #14. No insulation on barrier. No calorimiters. Torpedo sensor looking at busbar between A and B. NP trip.
	069	2/6	9:21	Y	1.42	23.5	2	na	16.6	39.0	3x 250 MCM with 6" spacing busbar fault A-C-B #14. No insulation on barrier. Reinforced barrier with unistrut. Back openiong on NP2 blocked. No calorimiters. Torpedo sensor looking at busbar between A and B. NP trip.
NP2 Full Fault Current Trip	070	2/6	9:46	N	6.3	105.0	1	na	NT	105.0	ABC bolted fault on NP3. #20 wire A ph to gnd on top of NP3. Omni sensor on top of NP3 A ph. NP1 open. NP 2 trip.VAMP did not pick up. NP1 closed entire test Fuse wire blew off instantly without sensor pickup Bolted Fault remained till lab back up tripped.
	071	2/6	10:00	N	6.38	106.3	1	na	Late	106.3	ABC bolted fault on NP3. #14 wire A ph to gnd on top of NP3. Omni sensor on top of NP3 A ph. Added torpedo sensor. NP1 open. NP2 trip.
	072	2/6	10:08	N	6.53	108.8	1	na	Late	108.8	VAMP picked up but NP2 opened late torpedo Sensor add to top of NP3 in #10 input position.
	073	2/6	10:23	N	0.38	6.3	1	na	NA	NA	#14 wire A ph to gnd on top of NP3 only checking sensor operability. Omni sensor on top of NP3 A ph. Added torpedo sensor. NP1 open. NP2 trip.VAMP picked up and NP2 opened as expected.
	074	2/6	10:32	N	6.83	113.8	1	na	20.3	114.0	BC bolted fault on NP3. #14 wire A ph to gnd on top of NP3. Omni sensor on top of NP3 A ph. Added torpedo sensor. NP1 open. NP2 trip.VAMP picked up on 1, 10, 5, 6, 8, 9.

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