High-Current Qualification Testing of an Arc-Flash Detection System

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***Abstract*—Arc-flash detection (AFD) systems provide a cost-effective way to reduce arc-flash energy by providing fast tripping after the onset of an arc-flash event. In order to demonstrate that an AFD system will work correctly under actual arc-flash conditions, a qualification test methodology is needed. Low-level signal (bench) testing provides an economical and safe starting point for testing the proper operation of an AFD system. However, low-level signal testing does not prove that the system will operate in actual arc-fault conditions. Complete qualification testing requires that actual arc-fault conditions be created using fault current, system voltages, and conductor gaps that are comparable to the intended operating environment of the AFD system.**

Qualification testing of a new AFD system was performed at a high-current test laboratory. This test program demonstrated the reliability and tripping speed of the AFD system at various combinations of fault current, system voltage, conductor gap, and AFD sensor placement. The test results show the performance of the system when the AFD sensors are engulfed by the arc blast, as well as the performance of the system when a self-test is performed during an arc-flash event. This paper provides test methods and results from the high-current qualification testing of the AFD system, thus demonstrating that the system provides AFD and tripping within the specified operating conditions.

I. Introduction

This paper demonstrates the reduction in arc-flash hazards achieved by utilizing an arc-flash detection (AFD) function in a protective relay. The hazard level of an arc flash is calculated using a mathematical model in IEEE 1584-2002 [1]. As described by Mark Zeller and Gary Scheer in [2], the hazardous energy produced by an arc-flash event is proportional to the voltage, current, and duration of the event (V • I • t). A protective relay can directly affect the duration of the event, resulting in a proportional reduction in arc-flash energy. Reference [2] shows that this reduction in arc-flash energy is significant.

II. Effects of Protective Relay Operate Times on Incident Energy

An example system is used to illustrate the effect of protective relay operate times on incident energy. This system is shown in Fig. 1.

The 60 Hz system is solidly grounded and comprised of three-phase, metal-clad switchgear rated at 4,160 V (line to line) with conductor spacing of 70 mm. The typical working distance is 910 mm. The bolted-fault current is given as 36,000 A.

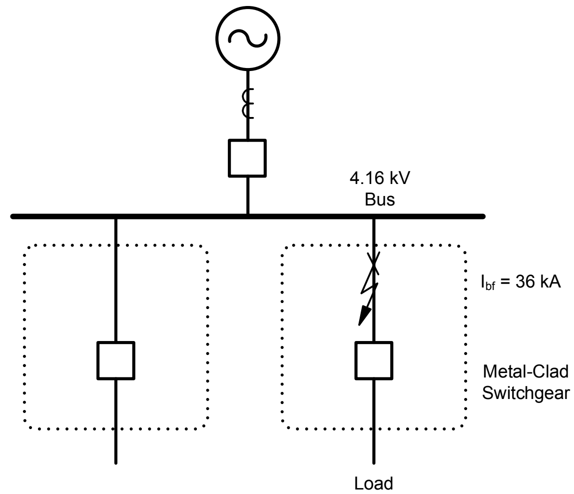

Fig. 1. Example system.

A. Determine the Arc-Fault Currents

According to [1], the impedance of the arc reduces the arc-fault current below that of the bolted-fault current. For medium-voltage systems, the arc-fault current is calculated as a function of the bolted-fault current.

$$\log I_a = 0.00402 + 0.983 \log I_{bf}$$
$$\log I_a = 0.00402 + 0.983 \log(36) = 1.534 \quad (1)$$
$$I_a = 10^{1.534} = 34.2 \text{ kA}$$

where:

I_{bf} is the bolted-fault current (kA).

I_a is the arcing current (kA).

B. Determine the Arc Duration

The arc duration is determined as the time it takes to detect and interrupt the arc current. For circuit breakers operated by protective relays, this duration is the sum of the following two operating times:

- The time it takes the protective relay to detect the arc-flash condition and then operate the trip output circuit. For the purposes of this paper, protective relay trip time is defined from the onset of the arc-fault current to the moment the trip output circuit conducts current.
- The time the circuit breaker trip circuit is energized by the relay to the time it interrupts the arc-fault current. For present technology circuit breakers, the arc-fault current is normally interrupted on a zero crossing of the ac waveform. This time is typically in the range of 2 to 5 cycles.

For a protective relay operating on an inverse-time overcurrent element, the operating time is determined by a combination of the arc-fault current magnitude and the inverse-time overcurrent curve characteristic.

The time it takes the circuit breaker to detect the trip signal and interrupt the arc current is normally specified by the manufacturer. It is often provided in units of ac cycles and must be converted to seconds for use in the incident energy equation.

As noted earlier, circuit breakers normally interrupt the fault current on a zero crossing. This has an important ramification on the relationship between arc-fault detection by the protective relay and the current interruption time of the circuit breaker. If the protective relay operate time is incrementally reduced, there is no change in the overall arc-fault duration until the protective relay operate time is reduced enough to allow the circuit breaker to interrupt the current one zero crossing earlier than would have otherwise occurred. For a 60 Hz system, the zero crossings are 1/120 s apart. In a polyphase system, successive zero crossings of the three phases will occur every 1/360 s or 2.8 ms. So a 1 ms improvement in the protective relay operate time will not shorten the arc-fault duration unless that happens to be all that is needed to allow the circuit breaker to interrupt the current one zero crossing earlier. In contrast, for a three-phase fault, a 2.8 ms improvement would virtually guarantee that the arc-fault duration would be reduced by one zero crossing. Given the severity and the amount of energy released during an arc-flash fault event, it is easy to see why it is very desirable to minimize the protective relay detection time. Reduction of the breaker operating time is much more difficult and can be quite costly, leading to alternate solutions such as arc diverters (fast shorting switches).

1) Example Using Time-Overcurrent Protection

Using the relay time-overcurrent curves, we assume that the relay operate time is 41 cycles. The circuit breaker operate time is given by the manufacturer as 5 cycles. The total time to clear the arc fault is:

$$\begin{gathered} 41\text{ cycles} + 5\text{ cycles} = 46\text{ cycles} \\ 46\text{ cycles} \bullet \frac{1\text{ s}}{60\text{ cycles}} = 0.77\text{ s} \end{gathered} \tag{2}$$

2) Example Using AFD

In this example, it is assumed that the protective relay is capable of distinguishing an arc-flash fault within the switchgear from an external fault outside the switchgear. In the case of the arc fault, the relay will operate in 4 ms or less. The total time to clear the arc fault is:

$$4\text{ ms} \bullet \frac{60\text{ cycles}}{1\text{ s}} + 5\text{ cycles} = 5.24\text{ cycles} \tag{3}$$

As stated earlier, a typical circuit breaker can only interrupt the current at the zero crossing. In order to determine the exact duration of the arc-flash fault, we would need to know the starting point-on-wave for the arc-flash event. For this example, we assume that the fault begins on the zero crossing. We round 5.24 cycles up to the next zero crossing, which is 5.5 cycles. Converting to seconds, we have 0.092 s.

This example illustrates that small changes in AFD time will not necessarily change the arc-fault duration.

C. Determine the Incident Energy

Using the IEEE 1584-2002 model for calculating arc-flash hazards [1], the incident energy is calculated in two steps. First, the normalized incident energy is calculated for an arc time of 0.2 s and a distance of 610 mm. Second, the normalized incident energy is converted to the actual incident energy by adjusting for system voltage, arcing time, and distance from the arc point to the person.

Calculate the normalized incident energy:

$$\begin{aligned} &\log E_n = K_1 + K_2 + 1.081\ \log I_a + 0.0011\ G \\ &\log E_n = -0.555 - 0.113 + 1.081\ \log(34.2) + 0.0011 \bullet 70 = 1.067 \\ &E_n = 10^{1.067} = 11.67(\text{J/cm}^2) \end{aligned} \tag{4}$$

where:

E_n is the incident energy (J/cm^2) normalized.

K_1 is –0.555 for box configurations.

K_2 is –0.113 for grounded systems.

G is the gap between conductors (mm).

Calculate the actual incident energy in cal/cm^2 for time-overcurrent protection:

$$\begin{aligned} &E = C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{610^x}{D^x}\right) \\ &E = 1 \bullet 11.67\left(\frac{0.77}{0.2}\right)\left(\frac{610^{0.973}}{910^{0.973}}\right) = 30.44(\text{cal/cm}^2) \end{aligned} \tag{5}$$

where:

E is the incident energy (cal/cm^2).

C_f is 1.0 for voltages above 1 kV.

t is the arcing time (s).

D is the distance from the arc to the person (mm).

x is the distance exponent from [1].

Calculate the actual incident energy in cal/cm^2 for arc-flash detection:

$$E = 1 \bullet 11.67\left(\frac{0.092}{0.2}\right)\left(\frac{610^{0.973}}{910^{0.973}}\right) = 3.64(\text{cal/cm}^2) \tag{6}$$

The reduction in incident energy from 30.44 to 3.64 cal/cm^2 is significant. The 30.44 level corresponds to a National Fire Prevention Association (NFPA) 70E Category 4 arc-flash hazard [3]. The minimum personal protective equipment (PPE) rating for persons working on this switchgear is 40 cal/cm^2. Category 4 PPE can be very bulky and difficult to work in.

In contrast, 3.64 cal/cm^2 corresponds to an NFPA Category 1 arc-flash hazard. Category 1 PPE is very lightweight and much easier to work in.

III. AFD Operating Principle

A. Light Produced by an Arc Flash

An arc-flash event produces a very bright light flash that can be used to distinguish an arc flash from an external fault. A typical light intensity measurement from our test program showed that arc-flash light intensity ranged from 108,000 lux, measured 3 meters away from the arc-flash source, to more than 249,900 lux. Our light meter full-scale reading only went up to 249,900 lux. Several of the arc-flash events produced "off-the-scale" light measurements. By way of comparison, direct sunlight on a sunny day is about 100,000 lux. Bright office lighting produces only 500 lux. Thus the light intensity of the arc-flash is orders of magnitude greater than the ambient light available inside the switchgear. The arc flash produces a very large-magnitude light signal that can be used as part of the determination that an arc-flash event is occurring. Light spectrum (color) varies depending on the materials involved in the arc but cannot, in general, be distinguished from direct sunlight.

B. Overcurrent Produced by an Arc Flash

The light from an arc flash is bright enough to provide a reliable signal for an arc-flash trip. Unfortunately, light-based arc-flash tripping is not secure. Other light sources can be introduced into the switchgear that are bright enough to mimic an arc-flash event. These sources include a camera flash, light-emitting diode (LED) flashlight, laser pointer, and direct sunlight falling on a sensor. Example light source intensity values are listed in Table I. When cast directly upon the sensor face, each of these provides sufficient light to assert an arc-flash light sensor.

Table I
Light Source Intensity

Source	Lux at 457 mm (18 in)
Camera flash	234,000
Direct sunlight (at any distance)	100,000
High-intensity AA LED flashlight	28,000
Common AA LED flashlight	4,560

While these sources are generally not present in the switchgear environment, it is impractical to exclude all possible sources of high-intensity light over the lifetime of the switchgear. In order to prevent one of these external light sources from causing a misoperation, light-based arc-flash protection systems are often supervised with an instantaneous overcurrent element. Once established, an arc fault provides a low-impedance, nonlinear load that will draw from 60 to 100 percent of the available bolted-fault current. This relatively large current signal can be used to securely supervise the arc-flash light element.

In the event of an overcurrent condition without a light-flash event, the relay will not perform an arc-flash trip. Instead, conventional overcurrent protection elements will be used (e.g., inverse-time overcurrent). This allows the relay to provide both fast arc-flash protection and conventional time-coordinated overcurrent protection.

C. Sensors Assert Before Being Damaged

The arc-flash light sensors are exposed to harsh environmental conditions and may often be located in the immediate vicinity of the fault. Because the arc-flash event may occur anywhere within the protected compartment, it is almost guaranteed that the light sensor will be exposed to arc plasma, ejected particles, high temperature, pressure, mechanical shock, and intense infrared radiation. Depending on the voltage level and the distance of the sensor to the fault, it is even possible that the sensor will be engulfed by the arc, exposing it to high-intensity electric and magnetic fields.

Additionally, the arc-flash sensor information needs to be communicated to a remotely located protection device and ultimately to the breaker capable of clearing the fault.

Given the critical nature of the light sensor function and the severity of the operating environment, it is easy to see that metallic (wire-based) communications and the use of active electronics should be avoided in favor of a simple, passive-sensor technology, such as optical fiber-based light sensing.

Sensors used in the testing were constructed using industry standard optical fibers. These are available in two variants: the fiber-optic loop (bare-fiber) and the fiber-optic point sensor, which is shown in Fig. 2. Loop sensors are optimized for protection of large, distributed resources such as low- and medium-voltage buses, which may span multiple switchgear compartments. The loop length (typically from 1 to 50 m) can be custom-tailored to match the application. Point sensors are optimized for protecting individual compartments, offering precise localization of the arc-flash event. Sensors can be located remotely (away from the relay), with maximum fiber length reaching 35 m.

Fig. 2. Fiber-optic point sensor used in the test.

The actual measurement of the light intensity is performed by photo sensors located within the relay enclosure. Fiber-optic cable, loop, and point sensor materials are rated to withstand the same –40° to +85°C ambient temperature as the protective relay. However, during the arc-flash event, the temperatures in or near the arc-flash plasma cloud are estimated to approach 16,000°C, well outside the normal operating range.

Based on the initial investigation, it was expected that these extreme temperatures would damage or destroy the optical sensors. However, the simplicity and robustness of the sensor design led us to believe that the sensors would conduct a light signal to the relay (perform their function) before being damaged by the extreme temperatures. This is based on the reasoning that light travels very fast compared to the time it takes to achieve high temperatures. This approach is aided by extremely fast relay operation, with the relay trip decision being made within 2 ms of the initial flash event. Once the trip decision is made, further operation of the sensors becomes irrelevant. One goal of the testing was to validate these assumptions.

D. Light Sensor Self-Test

The mechanical and optical integrity of the arc-flash sensors is automatically and periodically tested by performing a loopback test. An LED couples test light into one of the two arc-flash sensor fibers. For a loop sensor, this light travels through the fiber-optic cable back to the optical sensor in the relay. For a point sensor, the light travels through the fiber-optic cable to the point sensor translucent dome. The light is scattered by the optical properties of the dome. A portion of the scattered light is coupled into the adjacent fiber-optic cable and returns to the optical sensor in the relay. For either sensor type, the light sensed during the self-test is compared against high and low limits, thus verifying the health of the light sensor electronics and measuring the fiber-optic path attenuation. A self-test result that falls outside of test limits results in a warning alarm, indicating that the sensor may be defective, disconnected, or damaged.

The self-test function is exceptionally valuable, given the critical nature of the arc-flash protection function. It enables easy, user-friendly installation, while at the same time ensuring that all system components are intact and ready to operate at a moment's notice. Fiber cuts, kinks, and scratches are easily detected and reported to the operator. The system also includes an ambient light intensity metering function, which is used to aid in setting the light intensity threshold, and a light oscillography function, used to aid analysis of any trip event.

In everyday operation, it is quite possible that an arc-flash event could occur during a periodic arc-flash sensor self-test. This possibility requires that a protection device be able to distinguish between light produced by an arc flash and light produced by the self-test. One goal of the testing was to prove that the self-test would not interfere with AFD.

IV. Test Approach

It is typical for electric power system equipment to have industry standard performance tests for proper operation of the device. For example, high-accuracy electricity meters are tested to ANSI C12.20 and IEC 62053-22. Protective relays are tested to the IEEE C37.90 and IEC 60255 series of standards. Unfortunately, there are currently no industry standards for testing the performance of an AFD relay. As a result, we had to develop our own test approach.

A. Bench Testing and Limitations

Initial testing was performed on the engineering bench using low-level light signals. We developed a low-level light source to test the light-sensing capability of the relay. We also designed a light intensity calibration fixture, able to measure three-dimensional sensitivity patterns.

A specialized "arc-flash tester" (AFT) device was developed to provide a high-intensity white LED light flash, which can be time-coordinated with an overcurrent event, as shown in Fig. 3. The AFT is used in conjunction with an external current source to provide a simultaneous light flash and overcurrent to the protective relay.

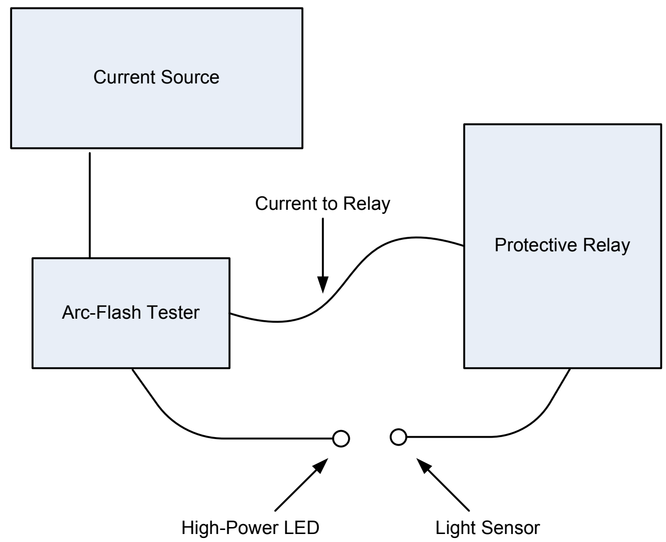

Fig. 3. AFT provides synchronized light and current.

Bench testing using the AFT provided a practical, safe, and economical method to test the AFD functions during the development of the product. But the AFT could not fully emulate the actual arc-flash event. For example, the white LED was driven by a regulated-current dc source. In contrast, arc-flash light is generated by the ac current of the arc fault. The light intensity waveforms for these two sources are quite different (by several orders of magnitude).

In addition, the development of the AFT required us to make some assumptions about the timing (relative to the current waveform) and intensity of the arc-flash light. These assumptions needed to be verified in an actual arc-flash environment.

B. Need for High-Current Testing

In addition to the light source and timing issues described above, there are several other characteristics of an arc-flash operating environment that require testing the relay in the presence of a real arc-flash event.

1) Light Intensity and Sensor Placement

The actual light intensity of an arc flash is described in literature in general terms. This information is not specific enough to determine the requirements for arc-flash sensor placement as a function of arcing current magnitude, conductor gap, and system voltage. A goal of the high-current testing was to determine the requirements for optical sensor placement, including distance from the arc flash and fiber-optic cable length limitations. For the loop sensor, we additionally needed to determine the minimum length of bare fiber exposed to the arc flash.

In actual switchgear, there are line-of-sight obstructions between possible sensor locations and arc-flash source locations. A goal of the testing was to determine the sensitivity to sensor placement in the actual switchgear environment.

2) *Harsh Environment Issues*

As described earlier, an arc-flash sensor must be able to operate in the presence of an extremely hot plasma cloud generated by the arc flash. In addition, an arc flash produces a shock wave, vaporized metal deposits, and smoke. A testing goal was to determine if the fiber-optic light sensor would operate correctly in this environment and that any significant damage to the sensor occurred after the arc-flash light was detected by the relay.

V. Test Method Design

A. *"Arcs in a Box"*

Our basic test setup was created by adapting the "Laboratory Test Programs" section in IEEE 1584-2002 to our particular application. The typical use of AFD systems is within metal-clad and metal-enclosed switchgear. Consequently, we used the IEEE 1584-2002 Test Setup C, "arcs in a box with parallel electrodes," in a five-sided, 762 mm x 762 mm x 1,143 mm (30 in x 30 in x 45 in) metal test box, as shown in Fig. 4.

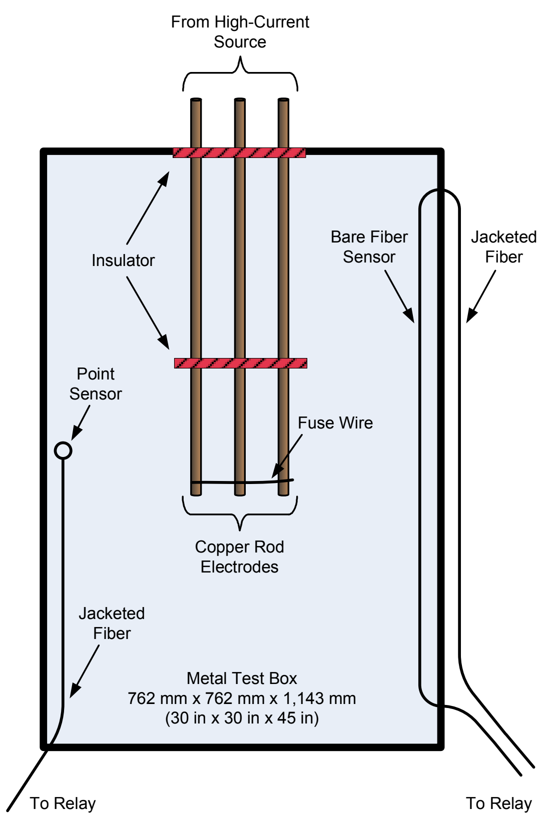

Fig. 4. Arc-flash test box.

The test box is equipped with up to three 6.35 mm (0.75 in) copper rod electrodes that enter the box from the top 762 mm x 762 mm (30 in x 30 in) panel. The spacing and number of electrodes can be adjusted to match various low- and medium-voltage configurations.

B. *Test Scenarios*

The high-current test laboratory provided various voltage and arc-fault current levels to simulate test scenarios, as summarized in Table II.

TABLE II
SUMMARY OF TEST SCENARIOS*

Voltage Class	**600 V**	**2,400 V**	**15 kV**
Configuration	Three-phase	Phase-to-phase	Phase-to-phase
Gap (mm/in)	25.4/1	70/2.75	203/8
Initial voltage	600	2,400	3,000
Fault current (kA)	2, 5, 15, 22	1, 4, 17, 35	0.8, 1.4, 5

*All tests performed at 60 Hz.

Because of test station limitations, three-phase faults were performed only at the low-voltage level. For medium-voltage tests, only phase-to-phase tests were performed. This is reasonable in that arc faults are likely to start out as a phase-to-phase or phase-to-ground fault and then progress to a three-phase fault later on. In testing an AFD system, we are most interested in determining how quickly the smaller initial phase-to-phase arc fault can be detected.

C. *Arc-Fault Voltage*

Another limitation of the test station is the ability to provide 15 kV at large fault currents. This had no impact on our test because in an actual arc fault, once the arc is initiated, the voltage at the electrodes is only a fraction of the open-circuit voltage.

As an example, for a 152 mm (6 in) conductor gap, the arcing voltage is a nonsinusoidal waveform with a root-mean-square (rms) magnitude of only 250 V, as shown in Fig. 5 (recorded during one of the tests).

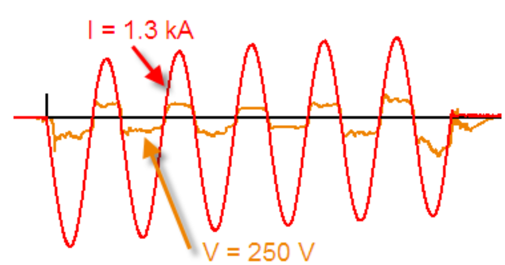

Fig. 5. Arc-fault voltage and current.

Fig. 5 demonstrates the nonlinear load characteristic of an arc fault. Once established, the arc will conduct as much fault current as is available at the small arcing voltage. The initially applied voltage has very little relationship to the resultant arc-fault voltage and incident energy. This can be seen mathematically in the IEEE 1584-2002 incident energy formulas (4) and (5). Voltage has no effect on E_n. For E, voltage only affects the C_f calculation factor. As a result, our 15 kV voltage class tests were performed with a 203 mm (8 in) electrode spacing, corresponding to the large spacing found in 15 kV switchgear. The initial applied voltage was only 3,000 V because the high-current laboratory could not provide high fault currents at 15 kV.

D. Relays Under Test

Three feeder protection relays were used as the equipment under test. The relays were placed next to the test box, protecting them from the direct blast of the arc flash. Each relay was equipped with four arc-flash sensors. This provided 12 sensor performance results for each arc-flash test. The sensor type, point or loop, and the fiber-optic cable lengths were varied for the tests.

E. Optical Sensor Placement

Point and bare-fiber sensor were mounted inside the test box. These sensors were 0.5 m away from the electrodes. We also needed to test the performance of the sensors at various distances from the electrodes, specifically 1, 2, and 3 m. These distances required the use of external test stands to mount the point sensors and bare-fiber sensors.

F. Laboratory Instrumentation

Three 2000:5 current transformers (CTs) were installed on the supply bus and connected in series to the three relays. Separate CTs were connected to the laboratory waveform recorder (LWR). These CTs measured the arc-fault current in each electrode.

The high-speed relay trip output contact of each relay was provided with a 48 Vdc wetting voltage and connected to an input on the LWR. The LWR recorded the fault currents and all three relay trip outputs. This allowed the LWR to precisely determine the arc-flash operate time of each relay as measured from the application of fault current to the conduction of current by the relay trip output contact.

The test laboratory was also equipped with a high-speed camera capable of recording 2,000 frames-per-second (fps) video. This camera included instantaneous analog input data acquisition channels that record the analog value for each frame of the video. These analog inputs were used to record the fault current and one of the relay trip output contacts shown in the top part of Fig. 6. The high-speed video camera provided an independent method to record the arc-flash light and compare that to the fault current and relay trip output performance.

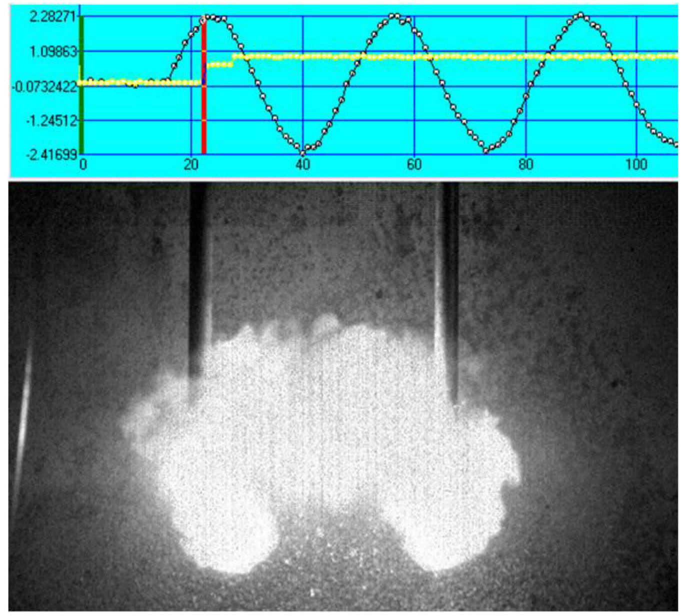

Fig. 6. High-speed video frame showing plasma cloud size at the moment of arc-flash trip, 3.4 ms from the onset of fault current.

G. Initiating the Arc Fault

Before each test, a length of 28 AWG (American Wire Gauge) wire was connected across the electrodes to initiate the arc fault once the bus was energized. This is shown in Fig. 7.

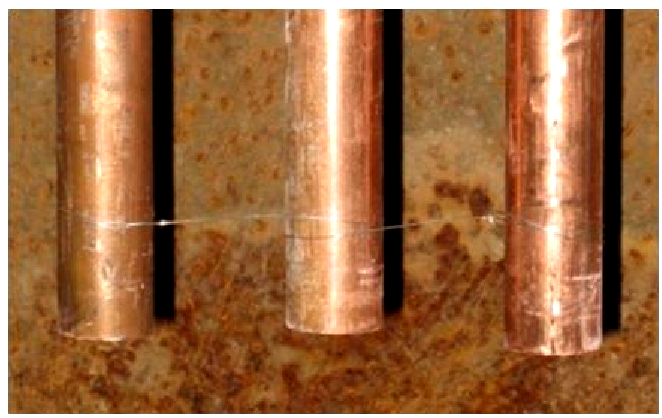

Fig. 7. 28 AWG fuse wire on electrodes.

The actual duration of each arc-flash test was controlled by the laboratory operator control panel and the associated vacuum circuit breakers. For most tests, the arc-flash duration was limited to 3 ac cycles, simulating the fault-clearing time of a 3-cycle breaker. The arc-flash duration was kept short to limit the cumulative damage to the test box and electrodes. The trip output of the relays under test always occurred in the first 0.25 cycle of the arc fault. Thus there was no testing requirement to allow the fault to continue longer.

VI. Test Results

A. First Test Results

The first high-current test performed was a three-phase, 600 V test, with a fault current of 2,000 A.

1) LWR Data

The fault current and Relay 1 trip output waveform are shown in Fig. 8. The trip time from the onset of current for Relay 1 was 3.1 ms. Relays 2 and 3 were 3.7 and 3.6 ms, respectively. Relay output contact operation is shown as the blue trace at the bottom of the figure.

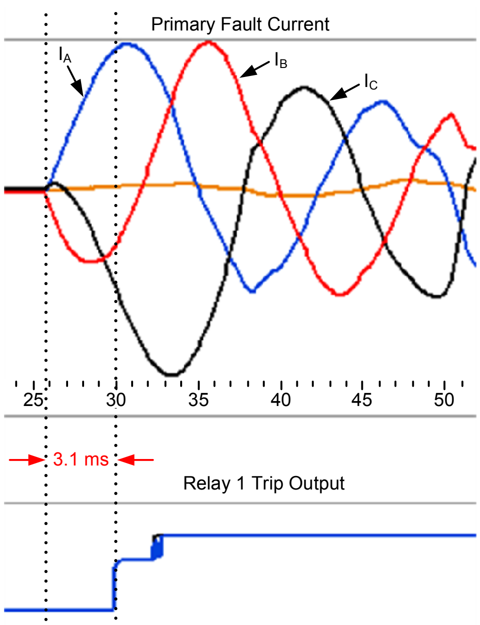

Fig. 8. LWR capture from first test shows a 3.1 ms trip time.

2) High-Speed Camera Results

Frame-by-frame examination of the high-speed camera data shows that the visible light from the arc flash time-lags the application of current by an average of 1.5 ms (three frames at 2,000 fps). This was determined by stepping through the video frames until the first frame is encountered showing the arc-flash light.

The lag between the application of current and the show of light is expected because the creation of the plasma cloud requires a finite amount of time. This lag places a physical limit on the time it takes for optical AFD to trip. Simply put, the relay cannot detect an arc-flash event until the light flash begins. Table III shows the trip time from application of current, as measured by the LWR, and from first light. The trip time from the first appearance of light was calculated by subtracting 1.5 ms from the onset of current results.

TABLE III
SUMMARY OF FIRST TEST TRIP TIMES

	Trip Time (ms)	
Relay	**From Application of Current**	**From Appearance of Light**
1	3.1	1.6
2	3.7	2.2
3	3.6	2.1

B. Subsequent Tests

A total of 20 “arcs in a box” tests were performed. These tests covered all of the test scenarios in Table II. For the 20 tests, the average trip time (as measured from the application of fault current to the conduction of current by the relay trip output contact) was 3.7 ms. The average trip time from the onset of visible light is estimated at 2.2 ms. This is calculated by subtracting the 1.5 ms delay between application of fault current and onset of visible light from the measured 3.7 ms.

C. Sensor Durability

We expected that the optical sensors would be damaged by an arc-flash event. The expectation for system use is that the arc-flash sensors will be replaced after being exposed to an arc-flash event. The heat, smoke, and vaporized metal deposits can cause permanent damage to sensors that could prevent or impact the sensors from detecting a subsequent arc-flash event.

The tests showed that the sensors are actually much more resistant to arc-flash damage than was anticipated. As part of the 17 kA and 35 kA, 2,400 V tests, we placed a point sensor and a bare-fiber loop sensor right between the electrodes, as shown in Fig. 9.

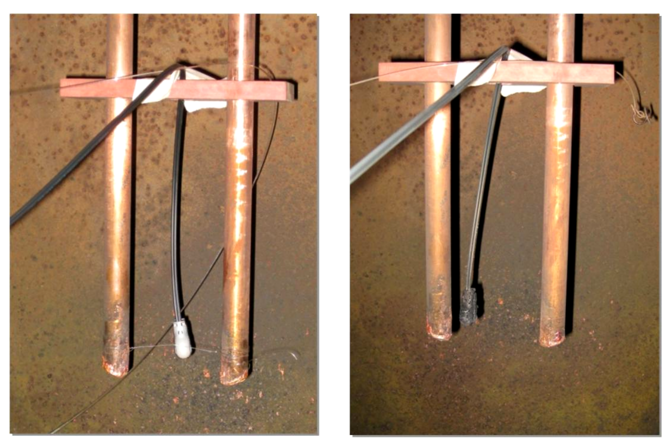

Fig. 9. Point and loop sensors between the electrodes, before (left) and after (right) an arc-flash test.

Once the fault current was applied, both of these sensors provided a full-scale light signal, allowing the relay to perform an arc-flash trip. This is illustrated in the relay waveform capture report shown in Fig. 10.

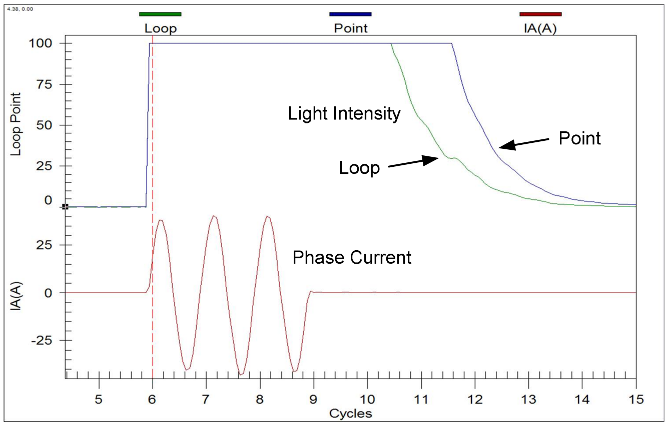

Fig. 10. Arc-flash sensors report the complete event.

Subsequent inspection of the point sensor showed damage to the outer surface of the sensor material. This can be seen as blackening of the white sensor material in the Fig. 9 photograph. An unexpected result was that this sensor continued to perform within specification. We reused the sensor in the next test, placing it 1 m away from the arc. The damaged sensor still provided a full-scale signal to the relay. While interesting from the engineering standpoint, such reuse should never be attempted in real life. All sensors involved in an arc-flash event should be replaced, regardless of the apparent lack of damage.

Subsequent inspection of the loop sensor showed that it melted completely through. This was expected. Examination of the high-speed video showed that the fiber melted through about 1.5 ac cycles into the event. This is 1.25 cycles after the relay performed the arc-flash trip.

These tests demonstrate that the sensors provide a light signal to the relay before being damaged by the arc-flash event, even if placed directly in the arc path.

VII. Sensor Placement

Point and loop sensors that were placed inside the test box at 0.5 m away from the electrodes consistently provided a 100 percent level light signal to the relay. This indicates that the light received by these sensors is so bright that the photo detector circuit goes into a saturated condition. This is a desirable result for AFD.

Point and loop sensors were also placed at distances of 1, 2, and 3 m from the electrodes. These tests showed the expected result: sensors placed closer to the arc flash detect more light.

The length of the fiber-optic cables was varied during the test from a minimum of 10 m to a maximum of 30 m. These tests showed the expected result: the fiber-optic cables attenuate light in proportion to their length.

For loop sensors, the length of exposed bare fiber was adjusted from 0.25 m through 2 m. This adjustment was made to determine the effect of exposed fiber length on the amount of light signal received. These tests showed the expected result: the light signal received by a loop sensor is proportional to the length of bare fiber exposed to the arc flash.

Based upon a thorough analysis of these data, the following installation recommendations were made. Point sensors should be installed within 2 m of the anticipated arc-flash light source with maximum fiber-optic cable length of 35 m. Loop sensors should be installed within 2 m of the anticipated arc-flash light source, with a minimum of 0.5 m of bare fiber exposed, allowing a maximum loop length of 70 m, including the bare and jacketed fiber sections.

VIII. Switchgear Tests

In the "arcs in a box" testing, there are no obstructions between the arc flash and the sensors. A clear line of sight is always present. In contrast, switchgear contains numerous components, such as insulating separator boards, which can block the direct line of sight between the initial arc location and the sensors.

A switchgear test was conducted to determine the performance of the sensors in their intended operating environment. The switchgear used for the test was a Westinghouse Model 150-DHP-750C circuit breaker, rated at 15 kV with 1,200 A continuous current.

A total of 12 sensors were attached at various locations within the breaker cell. Five of the sensors were located on the rear wall of the breaker cell. Another four sensors were placed on the side walls. The line of sight to these sensors was blocked by the insulated side walls of the breaker truck. The remaining three sensors were placed on the ceiling of the breaker cell. The line of sight to three of these sensors was blocked by the arc chutes.

In preparation for the tests, fuse wires were installed across the porcelain stand-off insulators on the circuit breaker. The breaker truck was then installed (racked) in the unenergized breaker cell. With the test personnel sequestered in a remote control room, the breaker cell was energized with an open-circuit voltage of 8 kV (line to ground), resulting in an arc fault. A total of three tests were performed with arc-fault currents of 1,260, 10,390, and 10,350 A.

For the three tests, the average trip time (as measured from application of fault current to the conduction of current by the relay trip output contact) was 3.9 ms. The average trip time from the onset of visible light is estimated at 2.4 ms.

The test results show that sensors attached to the back wall of the breaker cell provide the largest signal levels. For each of the three tests, all five of the sensors attached to the back wall provided signals with sufficient magnitude to initiate an arc-flash trip. This result is expected. The back side of the breaker truck is where the arc fault was initiated. The sensors mounted on the back wall had the fewest line-of-sight obstructions.

In contrast, the sensors attached to the side walls and the ceiling provided lower signal levels on at least one of the three tests. In some instances, the signal levels from these sensors were insufficient to initiate an arc-flash trip.

The switchgear tests demonstrate that arc-flash sensors perform reliably in the intended operating environment.

IX. Sensor Self-Tests

During one of the arc-fault tests, one of the relays was performing a sensor loopback test at the same time as the arc-flash test. The relay waveform capture in Fig. 11 shows the sensor self-test as periodic light pulses on the given sensor. The relay detected the arc flash on this particular sensor without any interference or degradation in performance. This test demonstrates that the relay is able to distinguish between the light from a loopback test and that from an arc flash.

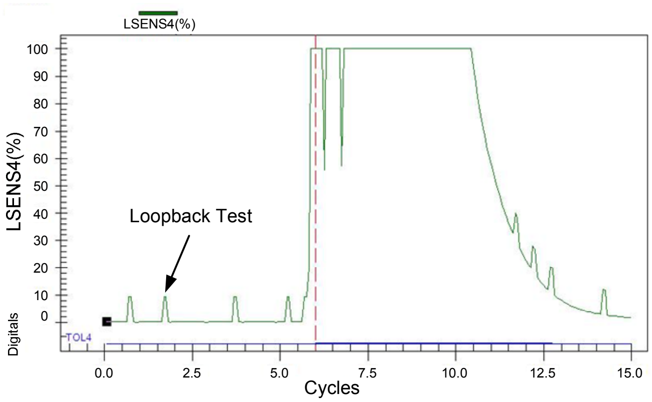

Fig. 11. Arc-flash sensor self-test does not interfere with AFD.

X. Conclusion

The AFD relay provides a significant reduction in incident energy. For the example system, arc-flash incident energy levels are reduced by 88 percent from 30.44 cal/cm^2 using inverse-time overcurrent protection to 3.64 cal/cm^2 using AFD. This reduction from NFPA 70E Category 4 to Category 1 represents a significant improvement in safety. Additional incident energy reduction is possible by combining the AFD relay with the arc diverter (fast shorting switch). This application takes full advantage of the relay fast operating time (typically 3.6 ms).

The light produced by an arc flash provides a very large-magnitude signal that is used by the protective relay to detect an arc-flash event. However, some other bright light sources, such as a camera flash, can mimic an arc-flash event. A high-speed instantaneous overcurrent element is used to supervise the light element. This provides high security to prevent misoperations.

The light sensors and overcurrent elements were demonstrated to work together in actual arc-flash conditions to provide an average trip time of 3.6 ms from the application of current and 2.2 ms from the appearance of the arc flash. The sensors work reliably in actual arc-flash conditions, even when fully engulfed by the arc-flash plasma cloud.

The arc-flash sensor loopback test increases the system reliability by performing a health test on the sensor without any personnel intervention. The sensor self-test does not interfere with the ability to sense an arc-flash event at the same time as the self-test.

The usefulness of event reports was demonstrated in the test regimen. These event reports record the signal levels measured by the optical sensors, the current inputs, and the arc-flash relay trip operation. This feature will be of use to relay technicians in documenting arc-flash trip events.

XI. Acknowledgment

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XII. References

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XIII. Biographies

Bob Hughes received his B.S. in electrical engineering from Montana State University in 1985. He is a senior marketing engineer in the protection systems department at Schweitzer Engineering Laboratories, Inc. Bob has over 20 years experience in electric power system automation, including SCADA/EMS, distribution automation, power plant controls, and automated meter reading. He is a registered professional engineer and a member of IEEE.

Veselin Skendzic is a principal research engineer at Schweitzer Engineering Laboratories, Inc. He earned his B.S. in electrical engineering from FESB, University of Split, Croatia; his M.Sc. from ETF, Zagreb, Croatia; and his Ph.D. from Texas A&M University, College Station, Texas. Veselin has more than 25 years of experience in electronic circuit design, has lectured at FESB, and spent more than 20 years working on problems related to power system protection. He is a senior member of IEEE, has written multiple technical papers, and is actively contributing to IEEE/IEC standard development. Veselin is a member of IEEE PES and the IEEE Power System Relaying Committee (PSRC) and is chairman of the PSRC Relay Communications Subcommittee (H).

Dhruba Das holds a B.S. and M.S. from IT Banaras Hindu University in India. He earned an M.S. in electrical and computer engineering from the University of Wisconsin, Madison. Dhruba has over 30 years of combined experience in switchgear and protective relaying industries, most of which was spent in the design and development of protective relays. He has coauthored several related technical papers and holds one patent. Dhruba joined Schweitzer Engineering Laboratories, Inc. in 1999 and is currently a senior firmware development engineer for research and development.

Joshua Carver received his B.S. in electrical engineering from Washington State University. He joined Schweitzer Engineering Laboratories, Inc. in 1998 and is currently a hardware engineer for research and development.