

# Verify Performance and Safety of Arc-Flash Detection Systems

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**Abstract**—The technology to detect arc-flash hazards in switchgear has been available for several years. Until recently, the testing and commissioning of these systems have been done using crude tools such as camera flash and manual trip verification. Today, arc-flash detection systems can be tested and the trip timing verified using modern relay test sets. Arc-hazard boundaries are calculated and personal protective equipment is assigned based on the trip times specified by arc-flash detection system manufacturers. Specified timing and hazard calculations can now be validated with common relay test sets and a coordinated light source. This paper discusses the test setup and procedures necessary to perform arc-flash detection system testing.

## I. ARC-FLASH HISTORY

Protecting workers from electrical hazards is not a novel idea. Since the first power generating station was built in 1877, the benefits and hazards of electricity have been recognized. The top engineers in the power industry have continuously worked to make electric power more economical and reliable, as well as safer.

There have been many papers highlighting the hazards and possible prevention of electrical arc flash; a new focus was initiated in 1985, when Ralph Lee published the paper “The Other Electrical Hazard: Electric Arc Blast Burns.”

The National Fire Protection Association (NFPA) published *NFPA 70E®: Standard for Electrical Safety in the Workplace®* to document electrical safety requirements [1]. It defines specific rules for determining the category of electrical hazards and the personal protective equipment (PPE) required for personnel in the defined and marked hazard zones. The United States Occupational Safety and Health Administration enforces the NFPA arc-flash requirements under its general rule that a safe workplace must be maintained. These regulations are forcing employers to review and modify their electrical systems and work procedures to reduce arc-flash hazards.

IEEE 1584-2002 provides information on how to calculate incident energy [2]. The available bolted fault current is calculated as follows:

$$I_{bf} = \frac{V_t}{\sqrt{3} \cdot |Z_{sc}|} \quad (1)$$

where:

$I_{bf}$  is the maximum bolted fault current.

$V_t$  is the system voltage in kV.

$Z_{sc}$  is the magnitude of the short-circuit impedance.

The arcing current can be calculated from the available bolted fault current using (2) when the voltage is less than 1 kV or (3) when the voltage is greater than or equal to 1 kV.

$$I_a = 10^{K+0.662 \log I_{bf} + 0.0966V + 0.000526G + 0.5588V(\log I_{bf}) - 0.00304G(\log I_{bf})} \quad (2)$$

$$I_a = 10^{0.00402 + 0.983 \log I_{bf}} \quad (3)$$

where:

$I_a$  is the arcing current in kA.

$K$  is  $-0.097$  for box configurations.

$I_{bf}$  is the bolted fault current for three-phase faults in kA.

$V$  is the system voltage in kV.

$G$  is the gap between conductors in millimeters.

The incident energy was empirically determined by IEEE normalized for a time of 0.2 seconds and a distance from the possible arc of 610 millimeters. Once the normalized incident energy is determined, the incident energy at any working distance can be calculated as follows:

$$E_n = 10^{K_1 + K_2 + 1.081 \log I_a + 0.0011G} \quad (4)$$

where:

$E_n$  is the incident energy in joules/cm<sup>2</sup> normalized for time and distance.

$I_a$  is the arcing current.

$K_1$  is  $-0.555$  for box configurations.

$K_2$  is 0 for ungrounded or high-resistance-grounded systems and  $-0.113$  for grounded systems.

$G$  is the gap between conductors in millimeters.

The incident energy can then be calculated using the following formula:

$$E = 4.184(C_f)(E_n) \left( \frac{t}{0.2} \right) \left( \frac{610^x}{D^x} \right) \quad (5)$$

where:

$E$  is the incident energy in joules/cm<sup>2</sup>.

$C_f$  is a calculation factor (1.0 for voltages above 1 kV, and 1.5 for voltages below 1 kV).

$E_n$  is the normalized incident energy.

$t$  is the arc duration in seconds.

$D$  is the distance from the arc in millimeters.

$x$  is the distance exponent.

As shown by (1), (4), and (5), the energy produced by an arc-flash event is dependent on the system constants, voltage, current, and duration of the event. IEEE 1584-2002 concluded that arc time has a direct effect on incident energy. Therefore, reducing fault-clearing times proportionately reduces arc-flash hazards.

There are several key elements in clearing an electrical arc. The first step is detecting the flash, second is accurately determining if the flash is part of an electrical fault, third is signaling the circuit interrupting breaker, and the last is interrupting the current flow to the fault. Each step in the process contributes time to the overall time needed to clear the fault; therefore, a significant amount of research has been invested in each part.

Many of the safe work practices, personal protective equipment, approach boundaries, and warning labels are dependent on the protection system that is in place to perform at the speed and sensitivity specified by the equipment manufacturer. A performance (by any of the components) that is slower than specified can dramatically increase the available incident energy. Personnel protection and procedures are based on properly working and performing equipment. Until recently, no proper test system was in place to evaluate the arc-flash detection equipment performance. Users are now able to verify not just the performance of the arc-detection equipment but also the system as a whole by including the breaker in the commissioning circuit. Although this paper only evaluates arc-flash detection systems, it is a straightforward extrapolation to include feeder and main breakers as well as communications links in the system while commissioning the arc-detection system.

## II. TYPES OF ARC-FLASH DETECTION SYSTEMS

Arc-hazard detection systems have been evaluated that are triggered from sound, pressure, current, and light, as well as predictive systems based on ion detection or thermal imaging. This paper focuses on arc-flash detection methods and leaves the predictive methodologies to present their own merits. Although an arc blast contains considerable sound and pressure waves, in the race to fastest detection, these waves are much slower than light. The fastest detection systems on the market today all use light as the primary arc-detection medium. They include the following:

- Light detection
- Current detection
- Combined light and current detection

Light detection systems have been commercially available for many years and have proven to be reliable and effective. Arc-flash safety considerations over the last few years have elevated an interest in detecting and interrupting arc-flash incidents faster and with high security. Table I provides a general range of response times published by arc-flash detection system manufacturers.

TABLE I  
DETECTION TECHNOLOGY IN ARC-DETECTION SYSTEMS

| Detection Technology           | Published Response Time |
|--------------------------------|-------------------------|
| Light only                     | 1 to 7 ms               |
| Current only, instantaneous    | 24 ms                   |
| Light with current supervision | 1 to 7 ms               |
| Light and overcurrent          | 1 to 7 ms               |

### A. Light-Only Detection Systems

Light detection systems are based on the principle that during an arc-flash event, enough light will be detected by the receptor to indicate a flash. This is generally accepted as a sound principle because the amount of light given off during an arc flash is significant and contains nearly the entire light spectrum. Light is fast and relatively easy to detect [3].

Generally, there are two types of light detectors. The first is a remote-mounted receiver that converts the light given off by the flash to some other form of signal that is transmitted to the tripping device. This type of sensor often uses a copper conductor for the transmission signal carrier, as shown in Fig. 1. Copper wire is common, reliable, and flexible but also has the capability to carry current in the event of contact with the bus bars or even with the ionized plasma from an arc flash.

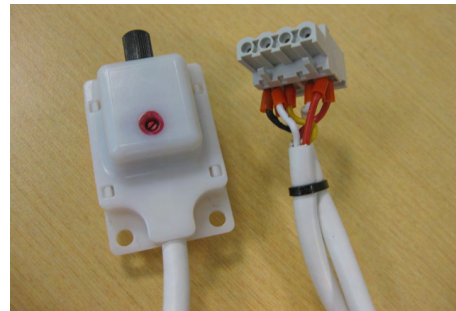


Fig. 1. Arc-flash sensor with copper wires

The second type of detector acts as a lens to collect the light produced from the flash and channel it back to a receptor in the tripping device. This channeling of the light is accomplished through fiber-optic cables (see Fig. 2). Fiber-optic cables have the advantage of not conducting electricity, thereby avoiding the installation of a conductor in the electrical gear. Fiber optic also has the advantages of electrical isolation between the receptor and the tripping device, easy installation, online complete functional testing, and choice of sensors. The disadvantages of fiber-optic cables include that they are easy to damage during installation, with either a too tight bending radius or scarring of the fiber wall, and the possible need for special splicing tools.



Fig. 2. Fiber-optic cable and arc-flash point sensor

The main disadvantage of a light-only detection system is the risk of tripping from a light source not related to an arc flash. These sources include high-intensity light-emitting diode (LED) flashlights, camera flashes, spotlights, and even bright sunlight. Any source of light exceeding the detection level in the relay will initiate a trip. Because of the very high-speed trip times of light-only systems, security is a serious concern.

### B. Overcurrent-Only Detection Systems

Overcurrent-only detection schemes, although not intended specifically for this purpose, were the first arc-flash detection systems invented. Generally, they were built to protect the equipment, not the people in the area. Because they were initially installed for equipment protection, settings were normally chosen based on preventing equipment damage, not personnel safety. As personnel safety has become a higher priority, the trip settings have been modified to provide separate levels of protection for equipment and personnel.

A common practice today is to implement a maintenance switch (Fig. 3) that changes the protection settings in a relay from time-coordinated protection (equipment-level protection) to instantaneous (personnel-level protection) settings while people are working in or around the energized equipment. Although instantaneous settings can reduce the arc-flash hazard under some conditions, they can also create hazards if misapplied.



Fig. 3. Breaker control with maintenance switch

IEEE defines an instantaneous setting as having no intentional delay in the output [4]. Notice, however, that this does not specify how fast a trip element needs to respond in order to qualify as instantaneous. This allows for significant variation in the response times of instantaneous elements between manufacturers and even from model to model of protective relays. All instantaneous trip elements are not created equal. Instantaneous trip response times are dependent on the magnitude and duration of the overcurrent. Internal signal filtering and the speed of the processing logic within the relay result in variations in instantaneous responses. Historic testing has found that traditional instantaneous elements have a pickup time of two cycles.

When protection engineers build protective relays, they must balance the often competing characteristics of sensitivity and security. For a protective relay, security can be defined as the ability to trip when needed and not trip when not needed.

Although this is a simplistic definition of security, differentiating between an overcurrent signal and noise on the input channel must be carefully considered. Protective relay manufacturers have a detailed understanding of current transformer signal variation and the effects of saturation on the current signal; this may not be true of all manufacturers of arc-flash detecting devices. Therefore, when selecting a relay to be used for arc-flash hazard mitigation, carefully evaluate each manufacturer for experience, speed, sensitivity, and security.

One challenge of an instantaneous current detection system is selecting the proper trip settings. The settings must be high enough to ignore normal variation in current, yet low enough to quickly detect an event. Instantaneous settings that are too high endanger personnel and provide a false sense of safety. For example, by changing the settings on a feeder relay from the time-coordinated delay of 0.5 seconds to an instantaneous setting of 0.12 seconds, you could assume the arc-hazard energy dropped by about the same ratio [5]. This assumes that the current remains at the calculated available fault current. If the fault current is reduced (because of higher-than-expected impedance) to below the instantaneous setting, the relay would not trip on the instantaneous element. In that case, even with a lower fault current, the available arc-flash energy would be higher than the previously calculated level and personnel working in PPE rated for the lower hazard would be in jeopardy.

A second issue with this method is determining the trip time to use in the incident energy calculations. Because the trip time varies with the magnitude of the fault, the protection engineer is left without a fixed time duration to use for incident energy, approach boundary conditions, safety procedures, and personal protective equipment.

### C. Light With Current Supervision Systems

Any arc-detection scheme that only evaluates a single quantity has serious security concerns. One security improvement is to supervise the light detection with a current element. This system measures the current and only enables the light detection trip element if the current is above some predetermined level. This application does not monitor for a fault current; it only disables the light trip element when the current is below a preset point. Supervision systems typically recommend current enable levels just below the expected normal operating load. Setting the supervision level too high disables the light portion of the arc detection. Setting it too low removes the security benefit of current monitoring. Current supervision systems only provide a modest improvement in security during low-current conditions.

### D. Light and Overcurrent Detection Systems

Modern protection systems make full use of both overcurrent and light detection to create a scheme that is both fast and secure. Combining the fault current detection in an AND logic manner with the light detection element and tripping only when both are present create a very secure scheme.

One of the challenges of combining the two elements is to make sure the fault detection element for the current is as fast as the light detection element. This is accomplished by using special high-speed sampling and logic to match the response times of both elements with no delay. Although there is some reduced security with the faster current detection element, the combination of overcurrent and light detection more than compensates for any sacrifice in the current security.

### E. Consequences of Misoperation

The consequences of misoperation of the arc-flash detection scheme depend on the process and arc suppression system. When isolating the fault with a standard circuit breaker, the result of a false trip (tripping when no fault is present) can be evaluated based on the consequences of the load lost. Failure of the system to trip when a fault is present will result in normal circuit protection with the associated incident energy. If personnel working in an area with PPE expect high-speed arc detection and the system responds with slower overcurrent protection, serious injury may result. Therefore, it is imperative that the system is reliable and tested often. Self-checking systems can increase confidence and provide a warning in the event of a failure before personnel enter the risk zone. Modern arc-flash systems continuously test not just the relay, but the continuity and function of the sensors as well.

Some systems, rather than just isolating the faulted circuit, also provide an alternate path to ground for the fault circuit. These systems use a crowbar circuit or an arc containment system to redirect the current. In addition to the concerns previously stated, a false trip (tripping when no fault exists) creates a strain on all the equipment in the system. Fault current, although not from a fault, is created by the system itself as it attempts to divert the system current to ground while isolating the presumed circuit.

## III. TESTING PROCEDURES

Arc-flash detection systems were tested in the configurations designated in the respective manufacturer instruction manuals. The testing was executed with the same test system and used a single arc-flash test device to generate the flash. The block diagram of the testing setup is shown in Fig. 4.

The purpose of the tests was to demonstrate the performance of each type of arc-flash detection system. Testing included subjecting the systems to a light flash, an overcurrent surge, and a combination of both light and overcurrent.

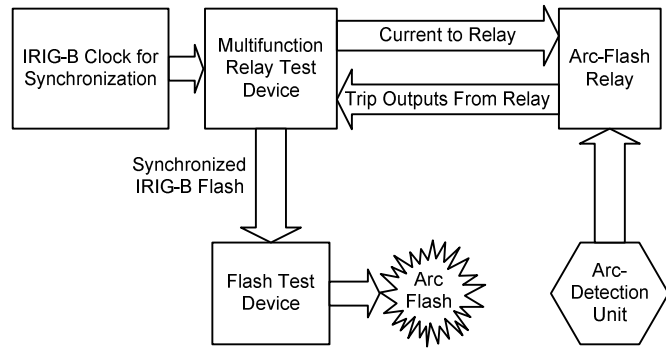


Fig. 4. Test system block diagram

In setting up the tests, a multifunction test set was used to provide current output, IRIG-B synchronization, high-speed binary/analog inputs to measure the contact response time, and binary outputs to control the IRIG-B signal to the flash. The test set also provided a dc power supply to the relays that needed power. A single-phase test set current output was connected to the current input of the relay. The high-speed output contact of the relay was connected to the test set. The high-speed outputs required a wetting voltage and load, so a dc relay was used as the load and 110 Vdc was applied. This required that the test set inputs be configured to trigger on a wetted contact.

The tests were set up using a state sequencer program. Prefault, fault, and post-fault states were used. The flash was synchronized so that it was applied with the current at the start of the fault state. A current value above the pickup level was used for the tests that evaluated current supervision. After the first tests, it was found that the flash generator would flash with each IRIG-B pulse. This led to misoperations, so a binary output contact from the test set was inserted in the IRIG-B signal to the flash generator. This caused a delay in the activation of the flash generator, so a two-pulse delay state was inserted before the fault state.

The first test performed was an overcurrent surge test or normal overcurrent event. This test included a prefault state, an IRIG-B starting state, a fault state that included the fault current, and a post-fault state for timing purposes. This test did not produce a flash when the current was applied. The second test was a flash without current. In this test sequence, the same setup was used but no current was applied to the relay. The third test performed was a flash and overcurrent fault applied to the relay using the same test sequences. Finally, a test was performed with nominal load current, 1 A secondary, and a flash to confirm the security of the relay with current supervision.

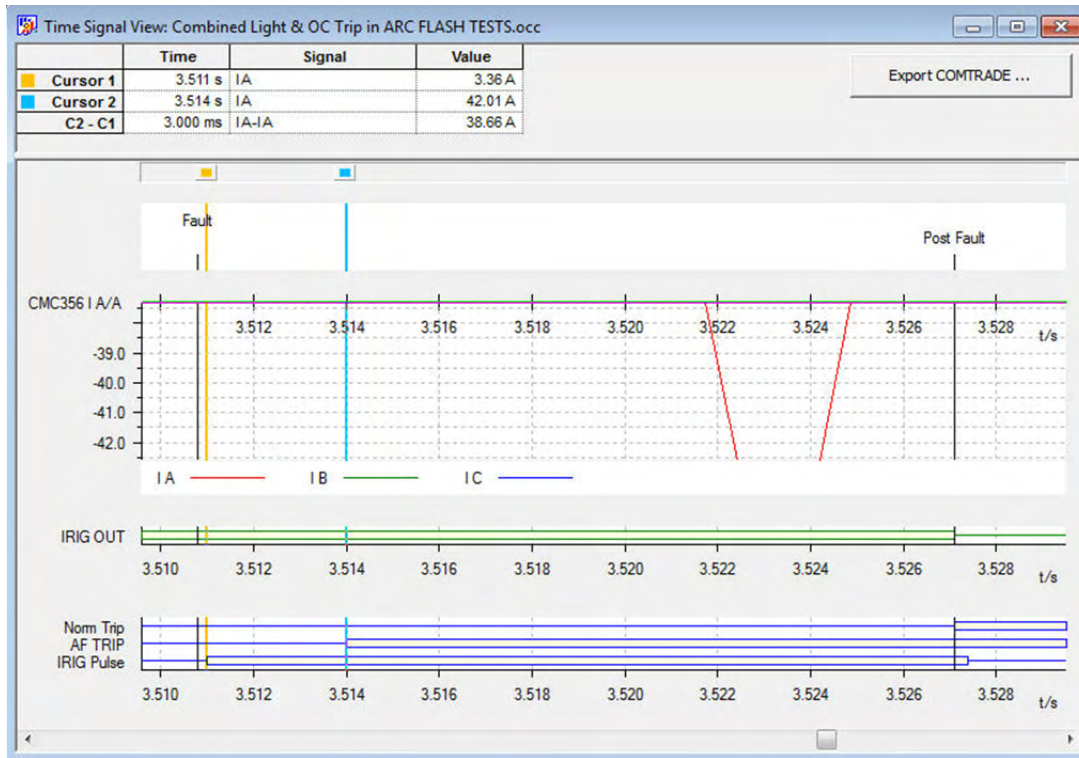


Fig. 5. Typical test screen showing fault initiation and time to trip

The same setup was used for all the relays in the study. The timing was evaluated using the time signal view of the test set software. The beginning of the IRIG-B pulse to the initiation of the output contact was measured, and the results are shown in Fig. 5 and in Table II.

One of the variables in setting up the testing procedure was the use of analog adjustment knobs (shown in Fig. 6) on some of the arc-flash detection systems. Modern relays avoid this subjectivity by using digital settings to exactly program the sensitivity. The adjustment knobs on some of the systems made the sensitivity setting inexact and nonrepeatable.



Fig. 6. Arc protection analog setting knob

#### IV. TESTING RESULTS

The response times from the tests are shown in Table II. Overall, the systems tested matched the actual performance with published specifications from the manufacturers. Each system was tested for possible false trips by subjecting the systems to flashes of light without the corresponding current, as well as current without light.

TABLE II  
ARC-FLASH RELAY TESTING RESULTS

| Device | Detection Technology           | Published Response Time | Actual Response Time |
|--------|--------------------------------|-------------------------|----------------------|
| A      | Light only                     | <2.5 ms                 | 0.6 ms               |
| A      | Current only, instantaneous    | No overcurrent element  | NA                   |
| A      | Light with current supervision | <2.5 ms                 | 0.7 ms               |
| A      | Load current and flash         | No trip                 | No trip              |
| B      | Light only                     | <1 ms                   | 1.3 ms               |
| B      | Current only, instantaneous    | <1 ms                   | Did not trip         |
| B      | Light and overcurrent          | <1 ms                   | 1.2 ms               |
| B      | Load current and flash         | No trip                 | Tripped              |
| C      | Light only                     | 2 to 5 ms               | 3.3 ms               |
| C      | Current only, instantaneous    | 24 ms                   | 22 ms                |
| C      | Light and overcurrent          | 2 to 5 ms               | 3.0 ms               |
| C      | Load current and flash         | No trip                 | No trip              |
| D      | Light only                     | <1 ms                   | 0.9 ms               |
| D      | Current only, instantaneous    | <1 ms                   | 6.5 ms               |
| D      | Light with current supervision | <1 ms                   | 1.5 to 2 ms          |
| D      | Load current and flash         | No trip                 | No trip              |

Relay A has no separate overcurrent output, so the overcurrent element could not be evaluated. Relay B would trip with light only. Relay B has an overcurrent unit that provides a blocking signal when an overcurrent event occurs; this function did not work on the relay used in this study.

## V. CONCLUSION

Personnel safety while working around energized electrical equipment depends on the proper performance of several key devices. Personal protective equipment is specified based on published performance specifications from the equipment manufacturers. New technology has enabled the testing of arc-flash detection systems, including trip response times. While this paper was only able to evaluate four arc-flash detection systems, it does reflect well that the arc-detection equipment performs as expected. The authors of this paper are continuing to test available arc-flash detection systems and will update this paper with the results.

All the arc-detection relays were able to detect and signal a trip within the published interval. Evaluation of an arc-detection system should be based on the quality, reliability, sensitivity, security, and usability of the system. Fast trip times do not necessarily make the best overall protection system. Security against false trips from electrical or light noise can be as important as the speed of the system.

When selecting arc-hazard mitigation schemes, engineers need to understand the pros and cons of each technology. The fastest detection and trip times are accomplished with arc-flash light detection systems. These systems can use light only or can be made more secure with the addition of current supervision or best with overcurrent detection. Systems using either light or current alone are not as secure as the combination of both technologies. Systems using current alone, such as instantaneous trip maintenance systems, have the difficult task of balancing security and sensitivity, along with the variation in trip times encountered from different fault levels and manufacturer variations.

## VI. REFERENCES

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## VII. BIOGRAPHIES

**William Knappek** is the Technical Support and Training Manager for OMICRON Electronics Corp. USA. He holds a BS from East Carolina University and an AS from Western Kentucky University, both in Industrial Technology. He retired from the U.S. Army as a Chief Warrant Officer after 20 years of service, of which 15 were in the power field. Will has been active in the testing field since 1995, and he owned and operated a testing company for 10 years. He is certified as a Senior NICET Technician, Certified Plant Engineer, and a former NETA Level IV technician. Will is also a member of IEEE.

**Mark Zeller** received his BS from the University of Idaho in 1985. He has broad experience in industrial power system maintenance, operations, and protection. He worked over 15 years in the paper industry, working in engineering and maintenance with responsibility for power system protection and engineering. Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2003, he was employed by Fluor to provide engineering and consulting services. He has held positions in research and development, marketing, and business development. Mark has authored several technical papers and has patents pending through SEL. He has been a member of IEEE since 1985.