Current-Limiting Arc Flash Quenching System for Improved Incident Energy Reduction

Robert J. Burns, *Member, IEEE*, Adams D. Baker, *Member, IEEE*, and Dan E. Hrncir, *Senior Member, IEEE*

***Abstract*—In response to a growing concern to mitigate arc flash incident energy hazards, the latest edition of the National Electric Code NFPA70-2017 includes requirements for reducing clearing time of overcurrent protective devices with a continuous current rating of 1200 A or higher. Section 240.87 lists seven options for reducing arc fault energy. This paper focuses on Method 4: energy-reducing active arc flash mitigation systems.**

***Index Terms*—Arc energy, arc flash, arc mitigation, arc quenching, current limiting, incident energy, low-voltage switchgear, UL 2748.**

I. Introduction

As electrical workplace safety continues to rise up the list of industry priorities, increased attention is being focused on arc energy reduction. The National Electric Code (NEC) section 240.87 was developed specifically with the following goal in mind: to provide the industry with a list of methods designed to reduce the arc energy in systems "where the highest continuous current trip setting for which the actual overcurrent device installed in a circuit breaker is rated or can be adjusted is 1200 A or higher" [1].

This list includes the following methods as of the 2017 NEC edition:

1) zone-selective interlocking;
2) differential relaying;
3) energy-reducing maintenance switching with a local status indicator;
4) energy-reducing active arc flash mitigation systems;
5) an instantaneous trip setting that is less than the available arcing current;
6) an instantaneous override that is less than the available arcing current;
7) an approved equivalent means.

Arguably, the broadest and least-defined of these methods is Method 4: "energy-reducing active arc flash mitigation systems." This method is not encompassed by a single product, technology, or breaker trip setting like the other methods. Instead, it encompasses a fairly broad array of existing, emerging, and yet-to-be-developed technologies. The purpose of this paper is to expand upon this method and to describe ground-breaking development that is resulting in innovative ways to reduce arc flash risk and satisfies NEC section 240.87.

II. Energy-Reducing Active Arc Flash Mitigation Systems

The aforementioned methods all have a limiting factor in common that sets a lower bound for the arc energy reduction that they can achieve. That limiting factor is the clearing time of the main overcurrent protective device. In the case of power circuit breakers (PCBs), the clearing time can be as high as four cycles, or about 67 ms. Since arc energy, and ultimately incident energy, is directly proportional to clearing time, the aforementioned methods may be unable to sufficiently reduce the incident energy in systems with high available fault current to protect personnel and equipment from an arc flash event. Incident energy above 1.2 cal/cm^2 requires personal protective equipment. Furthermore, according to testing performed, incident energy above 1.9 cal/cm^2 will often damage or destroy the equipment [2].

At the most basic level, arc flash relays that simply send a trip signal to the upstream circuit breaker fall into the category of "energy-reducing active arc flash mitigation systems." However, as with the other methods included in NEC section 240.87, the incident energy reduction possible with this implementation of Method 4 is limited by the clearing time of the upstream overcurrent protective device.

However, there are systems that fall under this method for reducing arc flash energy that do not rely upon the clearing time of the upstream overcurrent protective device to limit the incident energy. As described in the new UL Standard for Arcing Fault Quenching Equipment, these systems function by "creating a lower impedance current path, located within a controlled compartment, to cause the arcing fault to transfer to the new current path" [3].

These systems, referred to as arcing fault quenching equipment, typically work in conjunction with an arc flash relay to detect the ignition of an arcing fault. Upon detection of an arcing fault, the arc flash relay simultaneously sends a trip signal to the main circuit breaker and a trigger signal to the arc fault quenching equipment. Upon receipt of a trigger signal, most arcing fault quenching equipment can extinguish the arcing fault in

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The authors are with Eaton Corporation, Arden, NC 28704 USA (e-mail: robertjburns@eaton.com; adamsdbaker@eaton.com; danehrncir@eaton.com).

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subcycle times, some systems in less than 3 ms. This quenching time is an order of magnitude faster than the clearing time of a PCB and results in a considerable reduction in incident energy.

Arc-quenching systems fall into following two categories: systems that create a lower impedance current path by applying a bolted fault to the equipment and systems that create a lower impedance current path by applying a controlled arcing fault to the equipment. Bolted fault systems will draw maximum peak fault current when they are triggered. Drawing maximum peak fault current will place large stresses on cable terminations, bus bracing, and the windings of the upstream transformer and could cause damage to such components that have aged or have already undergone multiple short circuit events. Since bolted fault systems are marketed primarily for equipment protection, users have to weigh the risks of an arc flash damaging their equipment without the bolted fault system against the risks of the bolted fault system potentially damaging their upstream equipment when it operates.

The latest evolution of arc-quenching systems, however, produce a lower impedance current path by creating an alternate controlled *arcing fault* path in the equipment. The controlled arcing fault path presents a lower impedance than that of the original arcing fault, but a higher impedance than that of a bolted fault. This design still causes the arcing fault to transfer to a controlled compartment, but it results in significantly reduced peak fault current, at least 25% less. Since electromagnetic force is related by the square of the current, such systems can reduce the induced electromagnetic forces during an arc-quenching operation by at least 44%. The result is dramatically less stress on the upstream equipment but with a reduction in incident energy, which is equivalent or better than a bolted fault system.

III. UL 2748 Standard for Arcing Fault Quenching Equipment

Regardless of the method used to create the lower impedance current path, devices must pass through the following performance tests to comply with UL 2748 [3]:

1) continuous current tests (if the device carries main-circuit current under normal conditions);
2) power–frequency withstand tests;
3) maximum current withstand tests;
4) internal arcing fault tests;
5) arc transfer tests.

The first three tests are typically performed on low-voltage metal-enclosed switchgear per ANSI/NEMA C37.51 and are conducted again with the arc fault quenching equipment installed and operating in the switchgear. The tests result in a continuous current and withstand rating specifically for the arc-quenching device.

The fourth test involves performing IEEE C37.20.7 arc fault testing to "demonstrate that the quenching device does not create an arc fault hazard during the quenching operation" [3]. While this proves that an arc-quenching device does not create an additional arc fault hazard during operation, it does not mean that the switchgear is arc-resistant when an arc-quenching device is installed. However, some manufacturers have done further testing to prove that the arc-quenching device, when used in conjunction with a suitable arc detection system, can reduce incident energy to such a low level that the standard switchgear, with an otherwise nonarc-resistant construction, can pass the C37.20.7 test guide to attain an arc-resistant rating (see Section VI for further discussion).

The fifth test is very specific to UL 2748 and determines the "maximum time for an arcing fault to transfer to the intended lower impedance fault" [3]. In other words, this test determines the time between when the arc-quenching device receives a signal to operate and when the unintended arcing actually ceases. This time can be combined with the time to detect the arcing fault (typically the speed of the arc detection relay) and used to calculate the incident energy of the switchgear with the arc fault quenching equipment installed.

IV. Current-Limiting Arc-Quenching Devices

The latest arc-quenching systems comply with UL 2748 and, as mentioned above, limit the peak fault current during operation to reduce the stress on the upstream power distribution equipment. Such systems are called current-limiting arc-quenching devices and their operation can be broken down into the following three major parts:

1) arc detection;
2) arc transfer;
3) arc containment.

A. Arc Detection

All arc flashes have standard characteristics that make them detectable. Arc flash detection relay systems sense any individual, or a combination of more than one of the following characteristics:

1) high current;
2) intense light;
3) erratic voltage;
4) pressure wave.

The most common characteristics of arcing faults are high current and light. If current is monitored without light, the relay may incorrectly identify a downstream short circuit fault as an internal arcing fault, causing the main breaker to trip without coordinating with the downstream devices. If light is used without current, the relay may be prone to false tripping from ambient light or camera flashes. If light and current are registered by the relay simultaneously, this would be designated as an arcing fault, and the relay would send a trip signal to the overcurrent protective device, such as a main breaker. However, circuit breakers that interrupt in air, and some fuses, pose a problem with this method of arc flash detection.

An air circuit breaker creates temporary arcing in open air between the parting internal contacts when interrupting high currents. This arcing creates a bright flash of light that is released from the breaker's arc chutes. If the breaker is performing as designed and clearing a fault external to the power distribution equipment, the arc flash detection relay may trip by sensing

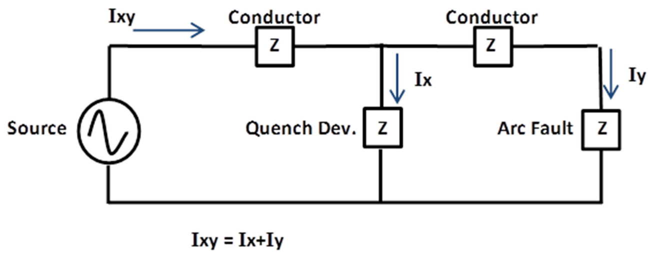

Fig. 1. Current division with arc fault downstream of the arc-quenching device.

light emitted from the breaker's arc chamber and high current, causing errant operation of the arc flash mitigation system.

One solution to this problem is to filter the light entering the arc detection relay's light sensors. Arc flashes have been measured to be in the 200 kLux range for 600-V class equipment at about 6 ft from the arc. Light intensity increases as the distance to the light source is decreased. In other words, it is possible to place light sensors farther away from a PCB's arc chutes, or add some light shielding between the arc chutes and nearby light sensors. However, given the construction method used in metal enclosed electrical equipment, most compartments are perforated in multiple locations for heat venting, wiring, etc. This makes isolating light sensors from arc chutes very difficult while also not isolating light from areas around the breaker that are more prone to arc faults, such as the primary disconnects.

A better solution to prevent falsely identifying a low-voltage PCB opening operation as an arc flash event is by interlocking the PCB's opening operation with the arc detection relay. If the PCB can generate an output signal to the arc detection relay before the PCB's primary contacts open, then the relay can block a trip signal long enough for the PCB to finish its opening operation. The arc detection relay's trip blocking feature only starts when the PCB is already beginning to open. The trip blocking duration can therefore be reduced to the maximum amount of time it may take for the parting contacts to clear the fault current. For low-voltage PCB switchgear, this is the ideal solution for preventing false arc-quenching system activation, and to minimize the time the equipment is unprotected by the system when a PCB is performing overcurrent protection.

With this technique for protecting against nuisance tripping, the arc detection relay system can be left on continuously, and all portions of the equipment are protected. Paired with an arc-quenching device, this approach ensures continuous and complete equipment and personnel protection all of the time, not just during maintenance operations.

B. Arc Transfer

Current-limiting arc-quenching devices operate on the principle of Kirchoff's current law, just like bolted fault quenching devices. If a current path with lower impedance is introduced to the faulted circuit in parallel, then current divides (see Fig. 1). If the impedance of the added branch (Quench Dev.) is low enough, the voltage in the arc fault circuit is reduced to the point that the arc fault extinguishes.

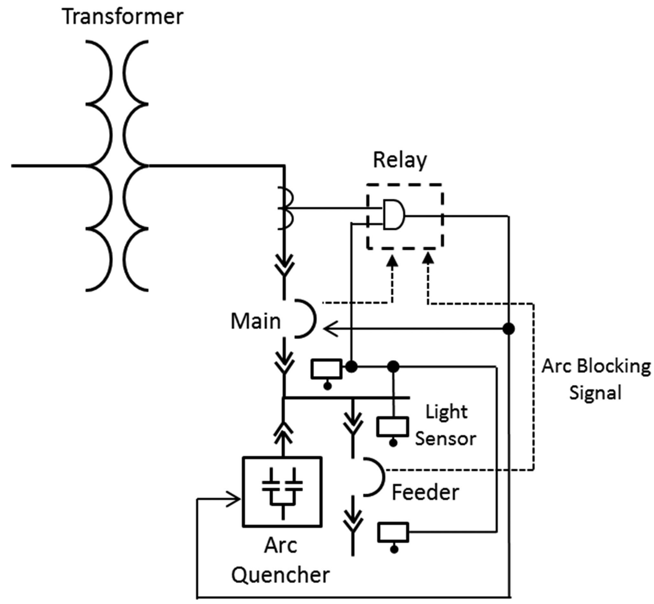

Fig. 2. One-line diagram with the arc-quenching device on the load side of the main breaker.

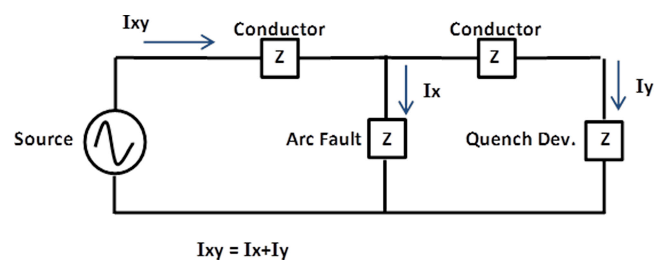

Fig. 3. Current division with arc fault upstream of the arc-quenching device.

Arc fault circuit impedance depends upon the following two variables:

1) length of the conductor between the arcing fault and the source;
2) gap between conductors across which the arc is sustained.

Current-limiting arc-quenching devices take advantage of both of these variables.

1) Distance From Source: A typical one-line of an arc-quenching device applied in low-voltage equipment is shown in Fig. 2. In this example, the quenching device is located as close to the source as possible while still remaining downstream of the main low-voltage overcurrent protective device. Therefore, all locations where the arc flash is most likely to initiate are downstream from the quenching device and have a longer length of conductor between them and the power source. This placement would give the arc-quenching device an obvious advantage of lower impedance.

However, testing has demonstrated that even when the arc fault is within a reasonable distance upstream of the arc-quenching device, it is able to commutate the arc because of the lower impedance arcing fault inside the quenching device (see Figs. 3 and 4). Testing also demonstrated that even with a source-side fault on a main breaker and a quenching device

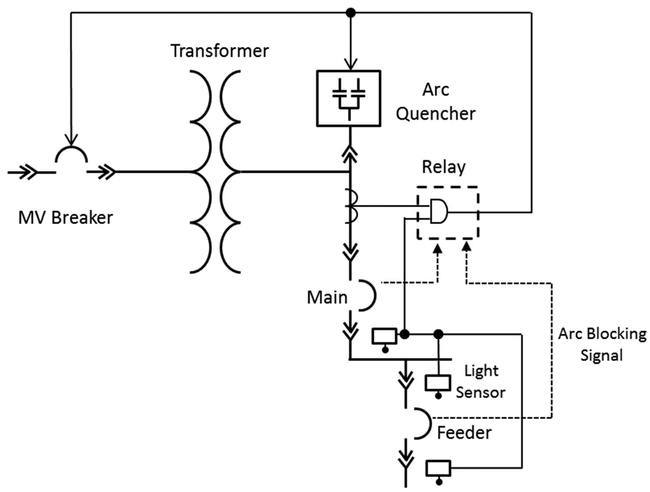

Fig. 4. One-line diagram with the arc-quenching device on the line side of the main breaker.

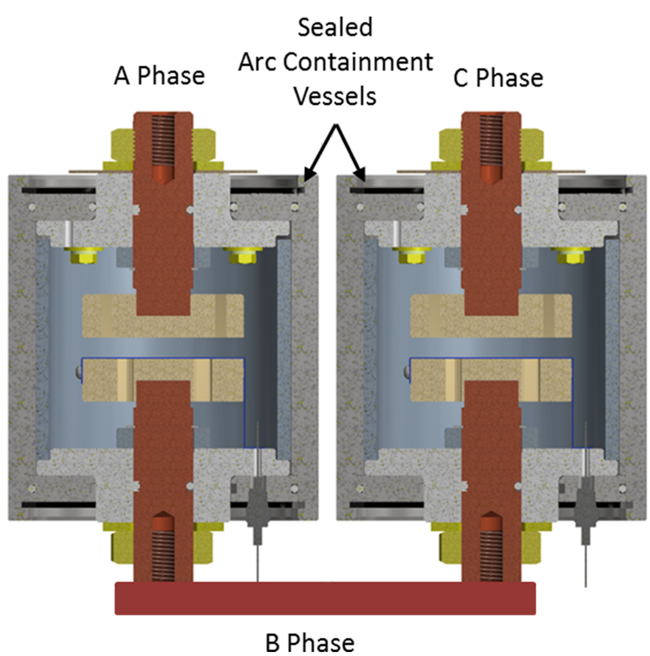

Fig. 5. Arc containment vessels in a three-phase system.

on the load side, the source-side fault did not restrike after the circuit breaker opened, even though the source-side remained energized after the breaker opened. Devices applied in this manner must have a maximum allowable ac impedance upstream of the quenching device as listed, as required by UL 2748, Section 19.3 [3].

2) Arc Gaps: A current-limiting arc-quenching device designed for use in metal-enclosed low-voltage switchgear has arc gaps that are smaller than the allowable spacing between conductors set forth in Table 12.1 of UL 1558 [4].

For a typical 480 Vac system, the minimum through-air distance between conductors of opposite polarity is 25.4 mm (1 in). However, the volume inside each arc-quenching device's arc containment vessels can be classified as a Pollution Degree 2 Microenvironment, as defined in UL 2748 [3] (see Fig. 5).

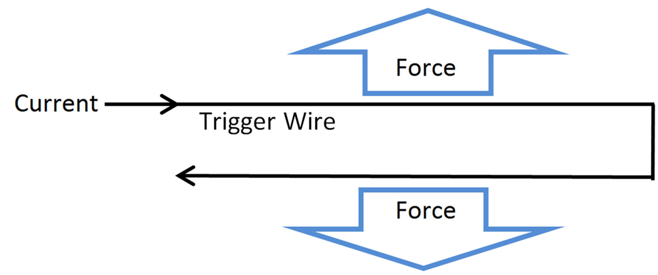

Fig. 6. Lorentz force.

Section 11.3 permits conductors of opposite polarity to be spaced as close together as is needed if they are inside a Pollution Degree 2 Microenvironment. The device must also still pass a Power-Frequency Withstand Voltage Test as described in ANSI/IEEE C37.51 [5]. Testing has shown that a conductor gap of 9.5 mm (3/8 in) is ideal to keep the impedance of the arc-quenching device low, and still easily maintain a 2.2 kVac dielectric withstand rating.

When an arc is initiated inside the arc containment vessels, the 2.2-kV dielectric barrier is eliminated. As the arc within the containment vessel erodes more conductive material, it produces ionized gas, which is highly conductive. If the ionized gas can be contained close to the arc gap, it further improves the sustainability of the arc.

Unintended arc faults starting inside low-voltage switchgear are somewhat enclosed, but the switchgear, by design, has venting and large spacings between conductors. An arc in this environment will be much more easily extinguished than one inside the hermetically sealed environment of an arc containment vessel.

Arcs consist of conductive material in the plasma phase. When a small wire, for instance, is placed across two electrodes with opposing electric potential, and the available current is higher than the ampacity of the wire, the wire will melt. If the amount of available energy is high enough, the wire will turn to liquid and then to gas. In the presence of a magnetic field, the atoms and molecules of this gas lose and gain electrons, making the gas ionized. Ionization of the gas is the transition to a plasma—the highest energy state of matter.

One method to start an arc inside an arc-quenching device is with a small copper wire, as previously described. When the arc-quenching device is triggered, this wire must be moved to short out the internal contacts at opposite electric potential. In order to rapidly move the wire, an electromagnetic force (Lorentz force) can be used. When conductors are physically parallel to one another and current is passed through them in opposite directions, the Lorentz force is developed and the conductors magnetically repel each other. This principle is used to move the arc trigger wire so that it shorts out the contacts in the arc-quenching device. Fig. 6 shows forces developed in a conductor with a physically parallel current path.

When a high current pulse is passed through the arc trigger wire, the top half of the wire, which is physically unconstrained, moves toward the other contact and shorts the two contacts out, as shown in Fig. 7.

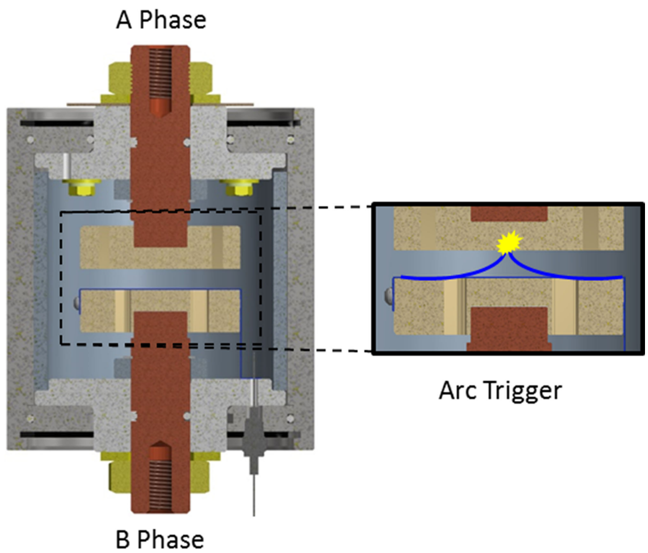

Fig. 7. Arc trigger.

When the trigger wire creates this short, the wire is vaporized and the dielectric barrier between the two contacts breaks down, plasma forms, and current starts flowing between the two contacts as an electric arc.

C. Arc Containment

Current-limiting arc-quenching devices maintain impedance higher than that of a bolted fault by creating an internal controlled arcing fault. This method poses a challenge to contain all of the energy in a desired area. Unlike bolted faults, arc faults release a tremendous amount of energy into free air. With a bolted fault, the energy remains harnessed electrically in the flow of current through the conductors and mechanically by conductor bracing. With arc faults, conductive material is first melted to a liquid, then vaporized into a gas, and then the gas becomes ionized to a plasma state. As the plasma erodes the contacts, the volume of ionized gas grows exponentially.

To contain the energy, the arc containment vessels of the arc-quenching device must be designed to handle the heat and pressure developed inside. The magnitude of pressure developed depends upon the mass of internal vaporized material, which depends upon the available fault current and the energy needed to vaporize the material. In areas most directly exposed to the arc, tungsten is used because it has the highest melting point of any known metal. Tungsten is the common material found in many electrical contacts for this reason.

The energy of the arc is absorbed by the arc containment vessels as material is vaporized and heat is absorbed into their thermal mass. The energy is gradually released from the arc containment vessels after the event by natural convection, conduction, and radiation. The pressure eventually drops back close to initial state after the arc inside the container is extinguished and materials re-solidify.

V. Arc Flash Quenching System Reliability

Arc flash detection relays and arc-quenching devices can employ real-time monitoring of all critical components and issue alerts or alarms if any component is not working properly. An arc detection relay employing current and light sensors, for instance, can monitor the connections of these sensors. If a sensor fails or becomes disconnected, the relay will issue an alert. The arc-quenching device can also monitor its connection to the relay and if the connection is lost or damaged, the arc-quenching device will issue an alert. Furthermore, an arc-quenching device will employ internal real-time monitoring of all critical circuits. This self-supervision of an arc flash quenching system, combined with good preventative maintenance, improves the reliability of the system.

VI. Timing and Incident Energy

IEEE 1584, Section 9.7 [6] states that incident energy is directly proportional to the duration of the arc fault. If the arc fault duration can be reduced, the incident energy is also reduced. Incident energy reduction not only reduces potential harm to personnel but also catastrophic damage to the equipment.

Because current-limiting arc-quenching devices do not have moving parts of significant mass, their operational time is much faster than PCBs. PCBs can take up to four cycles to clear a fault. For a typical arc fault with 85 kA prospective fault, four cycles is more than enough time to rupture the distribution equipment enclosure, seriously injure personnel and for the distribution equipment to sustain substantial damage. A current-liming arc-quenching device, however, can quench an arc event in as little as 3–4 ms.

It has been demonstrated through testing that certain arc-quenching systems reduce the incident energy to a level low enough that the system can pass the IEEE C37.20.7 [7] for internal arcing faults without the need for ducts, plenums, special construction, or venting into the room. Traditional arc-resistant equipment is typically constructed using thicker-gage steel, multipoint latches, reinforced hinges, and special construction methods to create a more robust enclosure. The equipment is only effective at protecting personnel from arc flash events when all panels are correctly installed and doors are closed and completely latched so the energy can be contained and directed away from the operator. The most advanced arc-quenching systems, on the other hand, are able to exceed the C37.20.7 test guide by providing the same level of personnel protection, but with doors open and/or panels removed.

Arc-quenching systems that do not rely upon special enclosure construction and reduce the incident energy enough to pass the C37.20.7 test guide will also suffer minimal to no damage from an arc fault event. This stands in marked contrast to traditional arc-resistant equipment that, while providing excellent personnel protection, often suffers catastrophic internal damage in the event of an arc fault. If such damage can be minimized or prevented altogether by an arc-quenching system, process downtime is drastically decreased due to the time to repair being reduced to a matter of hours versus weeks or months spent waiting for parts or new equipment to arrive and repairs to be made.

VII. Conclusion

The emphasis on improving personnel safety, protecting expensive electrical equipment from arc flash damage, and reducing the downtime of critical processes continues to grow in nearly every industry. NEC section 240.87 describes methods to reduce arc energy that help industry achieve these three important goals. However, the most common methods of arc energy reduction described in this NEC section, when applied to low-voltage equipment, rely upon the clearing time of the upstream circuit breaker. Unfortunately, PCBs in particular have significant mechanical inertia that limits their clearing time and creates a minimum threshold for arc energy reduction. To achieve further reductions in arc energy, alternate methods for capturing and containing the energy must be explored. Current-limiting arc-quenching devices represent the most significant advancement in arc flash safety in recent years. These devices provide superior personnel protection, advanced equipment protection, and significant reductions in downtime in the event of an arc flash. Additionally, by applying antinuisance trip features for overcurrent protective devices that interrupt in air, total equipment protection can be provided.

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Robert J. Burns (M’14) received the B.S.E. degree with mechatronics concentration from North Carolina State University, Raleigh, NC, USA, in 2006.

He is a Lead Design Engineer at Eaton Corporation, Arden, NC, USA for the Low-Voltage Switchgear product line. He has worked as an Engineering Consultant at Western NC and Upstate SC, as a Product Engineer at Eaton, and most recently as a New Product Development Engineer at Eaton.

Mr. Burns is a Registered Professional Engineer in the states of North Carolina and South Carolina.

Adams D. Baker (M’17) received the B.S.M.E. degree and the M.E.M. degree from Dartmouth College, Hanover, NH, USA, in 2006 and 2008, respectively.

He is a Product Manager at Eaton Corporation, Arden, NC, US for the Low-Voltage Switchgear product line. He has been involved with industrial new product development for over a decade in a variety of capacities including design engineering, manufacturing, sales, and marketing.

Dan E. Hrncir (SM’08) received the B.S. degree in mechanical engineering from Texas Tech University, Lubbock, TX, USA, in 1996.

He manages the New Product Development team at Eaton Corporation, Arden, NC, US for the Low-Voltage Switchgear business. He has 20 years of experience in designing electrical distribution equipment for Eaton. He has been the Chairman of several C37 series standard revisions. He holds several US Patents, all in the field of electrical distribution equipment.

Mr. Hrncir is a Registered Professional Engineer in the state of North Carolina.