CURRENT LIMITING ARC FLASH QUENCHING SYSTEM FOR IMPROVED INCIDENT ENERGY REDUCTION

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Paper No. ESW2018-07

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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 1200A or higher. Section 240.87 lists seven options for reducing arc fault energy. This paper will briefly review the defined methods of reducing incident energy as outlined in the Standard, with focus on option 4: energy-reducing arc flash mitigation systems.

Index Terms – arc flash, incident energy, current limiting, arc quenching, arc mitigation, arc energy, low voltage switchgear

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 NEC section 240.87 was developed specifically with this 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 Local Status Indicator
4. Energy-Reducing Active Arc Flash Mitigation System
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

Many papers have been published that describe these first three methods in depth, but a brief review of them is useful in order to provide context for the advancements that have been recently made in the realm of the "Energy-Reducing Active Arc Flash Mitigation System."

II. ZONE-SELECTIVE INTERLOCKING

Zone-Selective Interlocking (ZSI) is a technology that has been applied in power distribution systems for decades. ZSI was originally developed as a more cost-effective alternative to differential relaying [2]. There are two fault scenarios that must be considered in order to understand how ZSI is designed to function. When a fault occurs downstream of a feeder breaker both the feeder breaker and main breaker trip units will see the rise in current. In a system utilizing ZSI, the feeder breaker trip unit will send a blocking signal to the main breaker telling it to trip per its time delay trip settings. This enables the feeder breaker to attempt to clear the fault without the main breaker clearing and taking the entire switchgear offline. If, however, the fault occurs inside the switchgear, upstream of the feeder breaker but downstream of the main breaker, the feeder breaker will not send a blocking signal to the main breaker and the main breaker will instead reduce its tripping time delay to 2 cycles. An intentional delay of 2 cycles is used to reduce the risk of nuisance tripping.

ZSI is a very cost-effective system, and often comes built in to circuit breaker trip units, needing only proper control wiring within the switchgear to enable its functionality. However, this method does have a few drawbacks. First of all, many implementations of ZSI do not have a way of indicating if the system is not functional, for example, due to a loose or missing control wire. The arc energy reduction benefits of ZSI are also limited by the speed that the main circuit breaker can clear the fault plus the intentional 2 cycle delay. This can result in up to a 6 cycle clearing time for power circuit breakers and only provides higher speed clearing for faults between the main and branch breakers.

III. DIFFERENTIAL RELAYING

Differential Relaying is a more complex, expensive and space-intensive method of reducing arc energy that is more often found in medium and high voltage equipment. Differential relaying requires three additional CTs per circuit breaker and a relay with an ANSI/IEEE 87 feature. It functions by measuring the current flowing into and out of the electrical equipment. Under normal operating conditions, the currents should be equal. If there is a fault inside the equipment, either phase-to-phase or phase-to-ground, the current flowing into the equipment will no longer equal the current flowing out of the equipment and the relay will send a signal to the main overcurrent protective device to trip.

Differential relaying is a relatively expensive system due to the need for high-accuracy CTs and the 87 relay. In some cases, differential relaying can cause the equipment to increase in size in order to accommodate all of the large high-accuracy CTs. And, as with ZSI, its ability to reduce arc fault energy is limited by the clearing time of the main circuit breaker, which can be 3 to 4 cycles, and provides for no increased protection for faults external to the zone of protection. This leaves cable terminations, for example, unprotected.

IV. ENERGY-REDUCING MAINTENANCE SWITCHING WITH LOCAL STATUS INDICATOR

"Energy-Reducing Maintenance Switching With Local Status Indicator" is a relatively inexpensive and very effective method for reducing arc fault energy. Maintenance Switching comes as a standard feature of many trip units and can be retrofit into existing equipment. The system consists of a switch, which when closed, overrides the delays that have been programmed into the relay or trip unit. When an overcurrent fault is detected, the trip unit or relay causes the breaker to clear without any intentional delay. This method reduces the incident energy for any connected equipment downstream of a breaker equipped with Maintenance Switching.

In certain trip units, Maintenance Switching can bypass the digital trip unit circuitry and trip the breaker using an analog trip circuit thereby allowing the breaker to clear faster than the instantaneous trip setting. Such configurations can reduce the fault clearing time in low voltage power breakers to about 2 cycles. However, Maintenance Switching adds a layer of administrative controls which are considered to have a low level of effectiveness according to OSHA's Hierarchy of Controls [3]. In other words, this method will not function unless maintenance personnel remember to activate the system at the start of maintenance activities and deactivate it after activities have been completed. Since Maintenance Switching removes the coordination delays for the circuit breaker, it should not be left activated or nuisance tripping could occur. This system also only provides for protection downstream of the device in which the maintenance switch is installed.

V. AN INSTANTANEOUS TRIP SETTING THAT IS LESS THAN THE AVAILABLE ARCING CURRENT

"An instantaneous trip setting that is less than the available arcing current" is a new addition to the NEC section 240.87 as of the 2017 edition. To utilize this method, an arc flash study or other means must be used to determine the available arcing current for the equipment downstream of the protective device being considered. The instantaneous trip setting of the trip unit or relay of the protective device must then be set to trip below this calculated arcing current. This method requires no additional equipment beyond a relay or trip unit with a programmable instantaneous trip. However, in some electrical systems, selective coordination will not be achieved if the instantaneous trip setting is too low. And as with the aforementioned methods, the reduction in arc fault energy that can be achieved using this method will be limited by the clearing time of the overcurrent protective device.

VI. AN INSTANTANEOUS OVERRIDE THAT IS LESS THAN THE AVAILABLE ARCING CURRENT

"An instantaneous override that is less than the available arcing current" is also a new addition to the 2017 NEC. The "instantaneous override setting" is very similar to the "instantaneous trip setting" method described above but it is typically found in molded case circuit breakers that do not have an adjustable instantaneous trip setting. The override feature protects against fault currents above the withstand capability of the breaker. It is built in to override any adjustment that has been made to the electronic trip unit once the current reaches a preset level.

The aforementioned methods all have a limiting factor in common which 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, the clearing time can be as high as 4 cycles, or about 67 milliseconds. 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 (PPE). Furthermore, according to testing performed, incident energy above 1.9 cal/cm^2 will often damage or destroy the equipment.

As a result, there are compelling reasons to explore alternate methods that are not limited by the clearing time of the main overcurrent protective device. Some of these faster methods are encompassed in the "Energy-Reducing Active Arc Flash Mitigation Systems" category of the NEC section 240.87.

VII. ENERGY-REDUCING ACTIVE ARC FLASH MITIGATION SYSTEMS

At the most basic level, arc flash relays fall into the category of "Energy-Reducing Active Arc Flash Mitigation Systems". But as with the aforementioned systems, the incident energy reduction possible with this implementation of the "Energy-Reducing Active Arc Flash Mitigation Systems" method 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. 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.

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 commutate the arcing fault in sub-cycle times, some systems in less than 3 milliseconds. This arc transfer time is an order of magnitude faster than the clearing time of a power circuit breaker and results in considerable reduction in incident energy.

Arc quenching systems fall into 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 can damage cable terminations, bus bracing and the windings of the upstream transformer. Since these 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 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 the original arcing fault, but a higher impedance than 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. The result is dramatically less stress on the upstream equipment, but with an equivalent reduction in incident energy.

VIII. CURRENT LIMITING ARC QUENCHING DEVICES

The operation of this type of current limiting arc quenching system can be broken down into 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 be prone to falsely identifying a short circuit fault as an arcing fault. 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. However, circuit breakers which 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 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 feet from the arc. Light intensity increases as 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 power circuit breaker (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 power circuit breaker 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. See Figs. 1 and 2 for timing diagrams.

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.

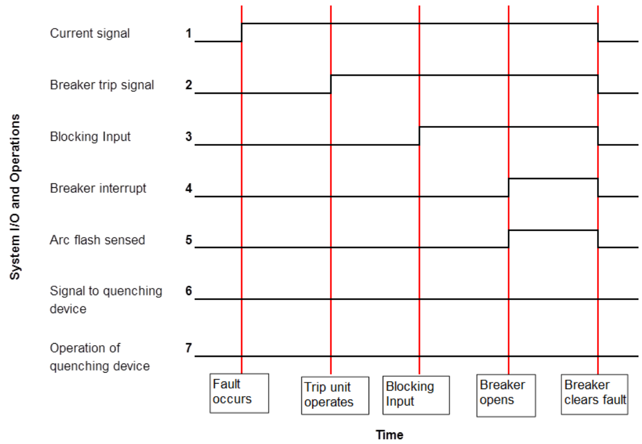

Fig. 1 Fault External to Equipment

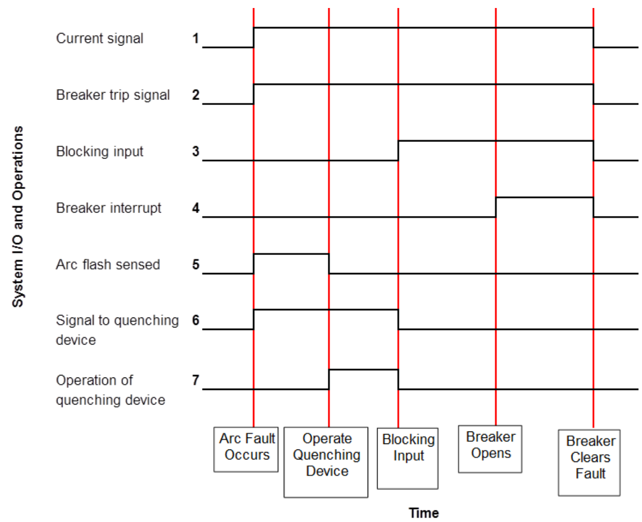

Fig. 2 Fault Internal to Equipment

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. 3. 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.

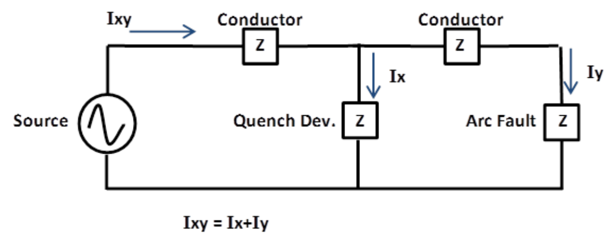

Fig. 3 Current Division With Arc Fault Downstream of Arc Quenching Device

Arc Fault circuit Impedance depends upon two variables:

1. Length of conductor from 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. 4. 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.

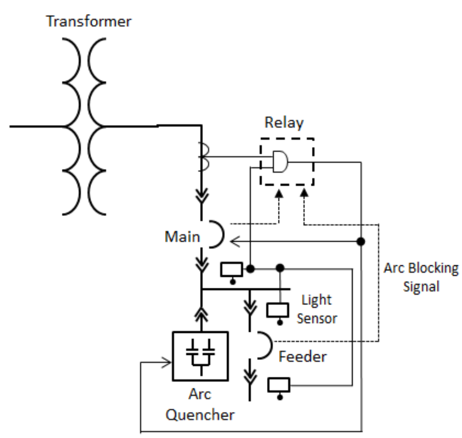

Fig. 4 One Line Diagram With Arc Quenching Device On Load Side of Main Breaker

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 (Figs. 5 and 6). Testing also demonstrated that even with a source-side fault on a main breaker and a quenching device 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 14.3 [4].

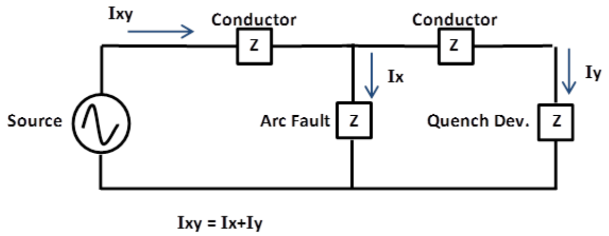

Fig. 5 Current Division With Arc Fault Upstream of Arc Quenching Device

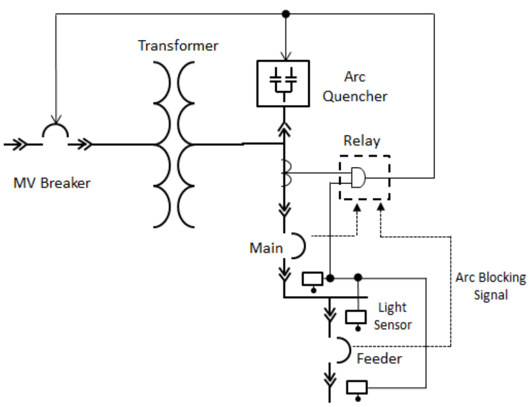

Fig. 6 One Line Diagram With Arc Quenching Device On Line Side of Main Breaker

2) Arc Gaps

A 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 [5].

For a typical 480 Vac system, the minimum through-air distance between conductors of opposite polarity is 25.4 mm (1"). 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 [4]. 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 [6]. Testing has shown that a conductor gap of 9.5 mm (3/8") 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.

Arcs 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. 7 shows forces developed in a conductor with a physically parallel current path.

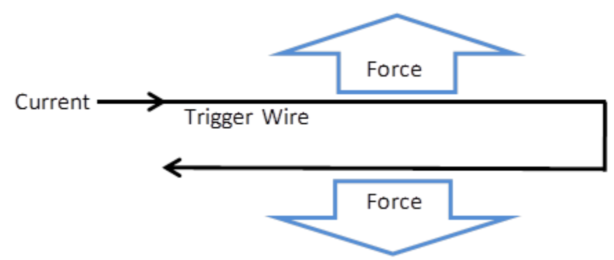

Fig. 7 Lorentz Force

When a high current pulse is passed through the arc trigger wire, the top half of the wire, which is physically unconstrained, moves towards the other contact and shorts the two contacts out as shown in Fig. 8.

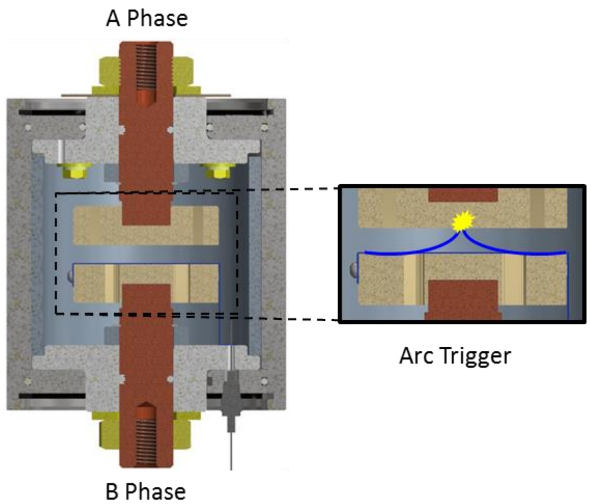

Fig. 8 Arc Trigger

When the trigger wire creates this short, it 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 currently on the market maintain impedance higher than 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. Fig. 9 shows the construction of an arc containment vessel. 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 vessel as material is vaporized and heat is absorbed into its 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.

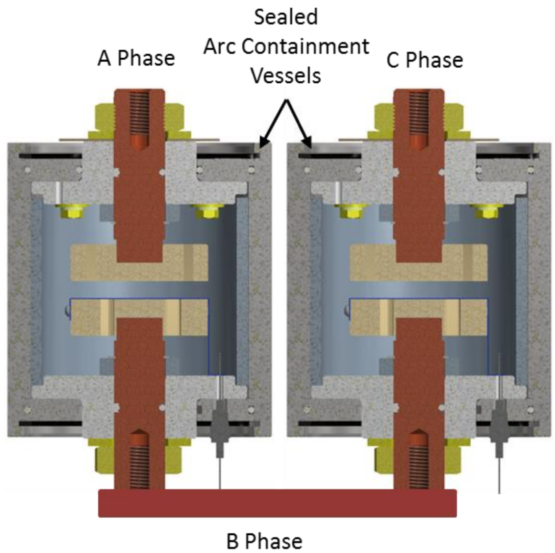

Fig. 9 Arc Containment Vessels

IX. 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.

X. TIMING AND INCIDENT ENERGY

IEEE 1584, Section 9.7 [7] 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 with a great deal of mass, their operational time is much faster than that of a power circuit breaker. Power circuit breakers can take up to 4 cycles to clear a fault. For a typical arc fault with 85 kA prospective fault, 4 cycles is more than enough time to rupture the 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 [8] 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, multi-point 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, should be able to exceed the C37.20.7 test guide by providing the same level of personnel protection, but with doors open 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.

XI. CONCLUSIONS

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 which 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, power circuit breakers 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 anti nuisance trip features for over current protective devices which interrupt in air, total equipment protection can be provided.

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[7] IEEE 1584 Guide for Performing Arc-Flash Hazard Calculations

[8] IEEE C37.20.7 Guide for Testing Metal-Enclosed Switchgear Rated Up to 38 kV

XIII. VITAE

Mr. Robert Burns is Lead Design Engineer for Eaton’s Low Voltage Switchgear product line. He has a BSE, Mechatronics Concentration, from North Carolina State University. He has worked as an engineering consultant in Western NC and Upstate SC, as a product engineer for Eaton, and most recently as a new product development engineer for Eaton. Mr. Burns is a registered professional engineer in the states of North Carolina and South Carolina.

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Document number: WP019003EN