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Safer by design: arc energy reduction techniques

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Strategies to protect electrical systems during maintenance and during on-going operation

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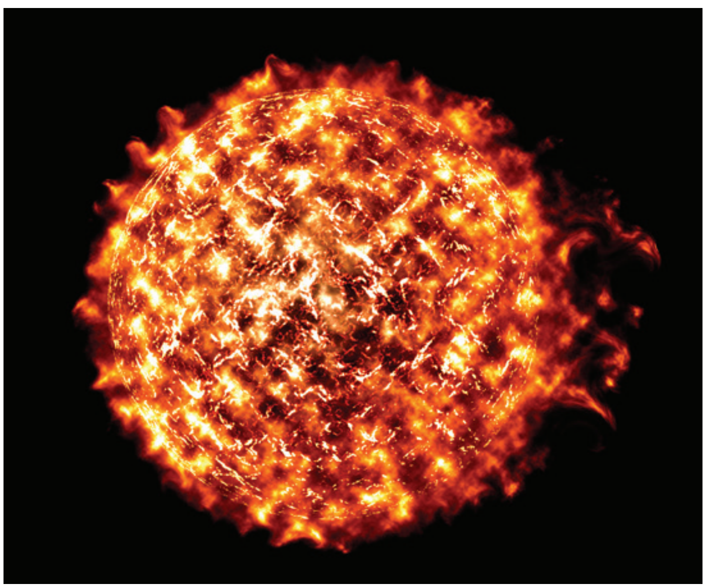
Arc flash safety matters

There are inherent risks associated with working with energized electrical equipment. Even inspecting electrical equipment can expose employees to shock and other risks. To enhance safety, work on electrical systems should be performed when those systems are de-energized. Unfortunately, that approach is simply not practical or possible in a variety of applications. Additionally, the steps involved in confirming that an electrical circuit is de-energized can also put personnel at risk.

The hazards of working on energized electrical equipment are clear. The U.S. Bureau of Labor Statistics indicates there were nearly 6,000 fatal electrical injuries to workers in the U.S. between 1992 and 2013. Non-fatal injuries between 2003 and 2012 reached 24,100. These incidents reached across industries and impacted workers at all experience levels and a variety of ages. Arcing events contribute to these incidents and the exposure to the flash is arguably one of the most critical safety issues in electrical power distribution applications.

Overcurrent protective devices interrupt current flow after a fault is detected. Designing for the fastest possible operation of overcurrent protective devices once a fault is detected is an effective approach to protect against damage resulting from an arcing event.

An alternative is the application of an arc quenching device to reduce the incident energy even further. This technology will be discussed later in this paper.



Hazards of an arc flash event at a glance:

- Arc flash events create an arc-plasma fireball which is like an explosion within the electrical equipment
- Temperatures exceed 36,000 degrees Fahrenheit, which is four times hotter than the sun
- Detected sound levels of 141.5 decibels
- Rapid expansion due to heat and vaporization of metals create pressure levels of up to 2,160 pounds per square foot

Safety standards apply

Given the dangers, arc flash safety requires serious attention and there are a host of standards by the Occupational Safety and Health Administration (OSHA), Institute of Electrical and Electronics Engineers (IEEE), the National Fire Protection Association (NFPA) and the National Electrical Code® (NEC) that apply. These standards and guidelines continue to evolve and have helped employers and employees to evaluate and improve their electrical systems and safety practices to reduce electrical shock and arc flash hazards.

In brief, OSHA enforces safety practices that are based on NFPA 70 and 70E, which help protect people and property from electrical hazards. NFPA 70 and 70E are the standards for safe electrical design, installation and inspection and address electrical safety work practices. The basic requirements for NFPA 70E include a safety program with defined responsibilities, calculations for the level of arc flash hazard, warning labels on electrical equipment, personal protective equipment (PPE), tools for safe work and training.

National Electrical Code and incident energy

The first technology to enter the NEC with an eye on reducing the incidents of arc flash events was ground-fault protection of equipment (GFPE) as part of the 1971 version of the NEC. Section 230.95, "Ground-Fault Protection of Equipment", was introduced because of the number of burn downs occurring at service entrance equipment. This section has expanded over the years focusing on solidly grounded wye systems of more than 150 volts to ground but not exceeding 1000 volts phase-to-phase for each service disconnect rated 1000 amperes or more. The language of this section would later be used as part of changes to section 240.87 during the 2014 cycle of the NEC.

In 2011, the NEC introduced Section 240.87 to enhance safety and help protect electrical workers from arc flash hazards. During the 2014 cycle of the NEC, NEC public inputs sought to address the fact that this section only addressed circuit breakers without an instantaneous trip; only "power circuit breakers" where instantaneous can be shut off.

The 2014 NEC expanded arc energy reduction requirements to circuit breakers. The language of Section 230.95 was used to identify the conditions under which this section is applied. Section 240.87 now applied to circuits breakers where the highest continuous current trip setting for which the actual overcurrent device installed in the circuit breaker is rated or can be adjusted is 1200 amps or higher. NEC 2014 provided the following approved methods for arc energy reduction:

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 approved equivalent means.

The 2017 edition of the code added two more methodologies to reduce clearing times and maintained the "approved equivalent means" to ensure new technologies are considered:

6. An instantaneous trip setting that is less than the available arcing current
7. An instantaneous override that is less than the available arcing current
8. An approved equivalent means

Arc flash mitigation during maintenance

The NFPA 70E outlines six risk control methods, including both preventative and protective risk control, using the following hierarchy: elimination, substitution, engineering controls, awareness, administrative controls and personal protective equipment. This paper will focus on the engineering controls that can be designed into the system.

The three factors that impact the severity of an arcing event are:

1. Power of the arc (i.e. the available fault current)
2. Distance to the arc
3. Duration

While in many applications it is difficult to change the available fault current or the proximity of the unknown event to the maintenance worker, the duration of the event can be greatly reduced. This, ultimately, lowers the arc incident energy. The basic techniques to shorten arc flash events by reducing clearing times that will be reviewed in detail in this paper and that are listed as options in Section 240.87 are as follows:

- Zone selective interlocking, which is active 24x7
- Enabling an energy-reducing maintenance switch like the Arcflash Reduction Maintenance System™ technology, in order to shorten the duration, and is only active when enabled
- Using the instantaneous trip capabilities of a circuit breaker
- Energy-reducing active arc flash mitigation systems

Differential relaying is not addressed in detail in this paper, as it is more complex and expensive than other methods. Further, it is typically applied in medium-voltage equipment (over 1000V), which is not regulated by 240.87. In fact, zone-selective interlocking was developed for low voltage assemblies to provide similar protection as bus differential without the heavy expense associated with the separate CT's and relays. Differential relaying is similar to zone-selective interlocking and recognizes faults through current transformers within a defined zone of protection. Arc flash energy is reduced due to the reduced clearing times through the use of a differential relay. Although differential relaying is an effective arc energy reduction method, it is typically only 1 to 2 cycles faster than zone-selective interlocking, and is usually impractical to apply in low-voltage systems due to expense and physical space required. Further, this scheme trips all the circuit breakers in the zone and would require many more relays and current transformer pairs to provide protection for other zones and downstream equipment.

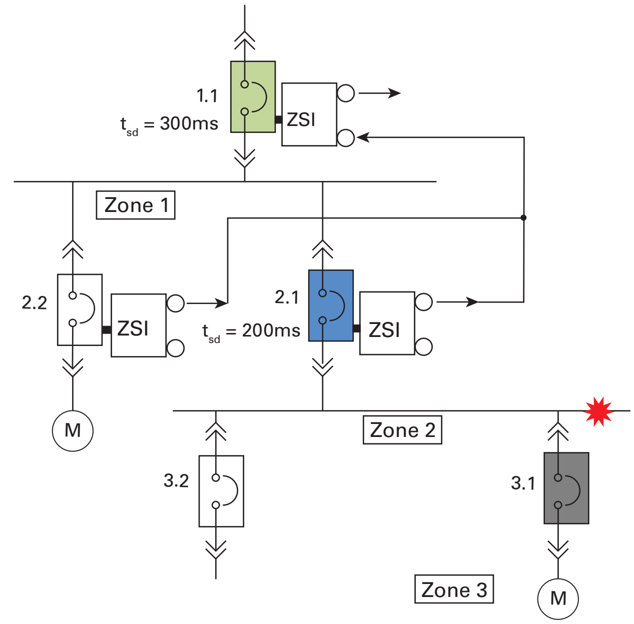
Zone-selective interlocking (ZSI)

The method:

ZSI is designed to reduce thermal and mechanical stress on electrical distribution equipment during short-circuit or ground-fault that occur within the zone of protection.

ZSI enables the nearest upstream circuit breaker to a short-circuit or ground-fault to override any of the delays programmed for coordination. This protection scheme helps reduce arc flash energy by tripping the breakers faster than the programmed settings.

The ZSI scheme uses a "restraining" signal transmitted from downstream breakers that see a fault to the next breaker upstream. The upstream breaker sees both the fault current and the restraining signal and thus keeps its programmed delays, allowing the downstream breaker to clear the fault. Should a fault occur between the downstream and upstream breaker, the downstream feeder doesn't



see the fault or send a restraining signal to the upstream breaker – causing the upstream breaker to bypass any of its programmed time delay settings and trip, significantly reducing arc flash incident energy.

In the example system shown in the diagram above, the Zone 1 breaker is programmed with a 300msec delay and the Zone 2 breaker is programmed with a 200msec delay to provide selectivity. A fault has occurred between the Zone 2 and Zone 3 breakers. In this case, the Zone 2 breaker will see the fault and will send a signal to the upstream Zone 1 breaker. This tells the Zone 1 breaker to continue with its programmed 300msec delay. The Zone 2 breaker will **NOT** receive a signal from the Zone 3 breaker because the fault is upstream of the Zone 3 breaker. Therefore, the Zone 2 breaker will override its programmed 200msec delay and will trip more quickly reducing arc flash energy and equipment damage.

Because the ZSI scheme requires the breakers to always check for a restraining signal first, the breaker tripping closest to the fault will have a 1 – 2 cycle delay in tripping when compared to instantaneous tripping. In other words, ZSI clearing times are longer than instantaneous, which is defined as short circuit protection without an intentional time delay.

Benefits, challenges and key considerations:

ZSI provides nearly the equivalent protection of differential relaying schemes at a significantly lower cost. As with differential relaying schemes, ZSI is always active and does not require user intervention.

Other benefits of ZSI include the availability with a wide range of trip units and the elimination of nuisance tripping concerns. ZSI can also be applied to medium-voltage systems, low voltage systems, across substation transformers, etc... to provide a cost-effective way to reduce clearing time and meet NEC Section 240.87 requirements.

While ZSI can be an effective approach, historically the biggest challenge with this method has been the complexity of wiring, and testing, and the lack of visual indication to provide confirmation that ZSI is engaged and active.

The new Power Xpert Release (PXR) electronic trip units provide an enhanced level of ZSI capability. When the ZSI function is enabled in PXR trip units with a display, the letters "ZSI" will appear on the LCD display. This is the confirmation that the trip unit understands that ZSI protection is active. The PXR trip units also show a √ 'check mark' on the display to acknowledge that the trip unit received a ZSI restraint signal. This mark will stay on the display as long as there is auxiliary power to the trip unit. The check mark can then be reset and cleared from the display by pressing the reset pushbutton. When testing ZSI in a group of interlocked PXR trip units, the check marks are all reset to their normal cleared state. Then, a test current above the rated short time or ground fault pick-up setting is injected into a downstream breaker. Each of the PXR trip units are then inspected to see if the they should or should not have a check mark according to the ZSI wiring diagram. Generally, upstream breakers should have a check mark while other breakers in the same zone should not. This provides a very simple and effective means to fully test the complete ZSI system. It also provides a visible indication and event log of ZSI operation after an actual fault event.

Note: ZSI schemes should incorporate technology from one manufacturer; ZSI wiring, signaling, application, etc. varies and would not be compatible between different manufacturers.

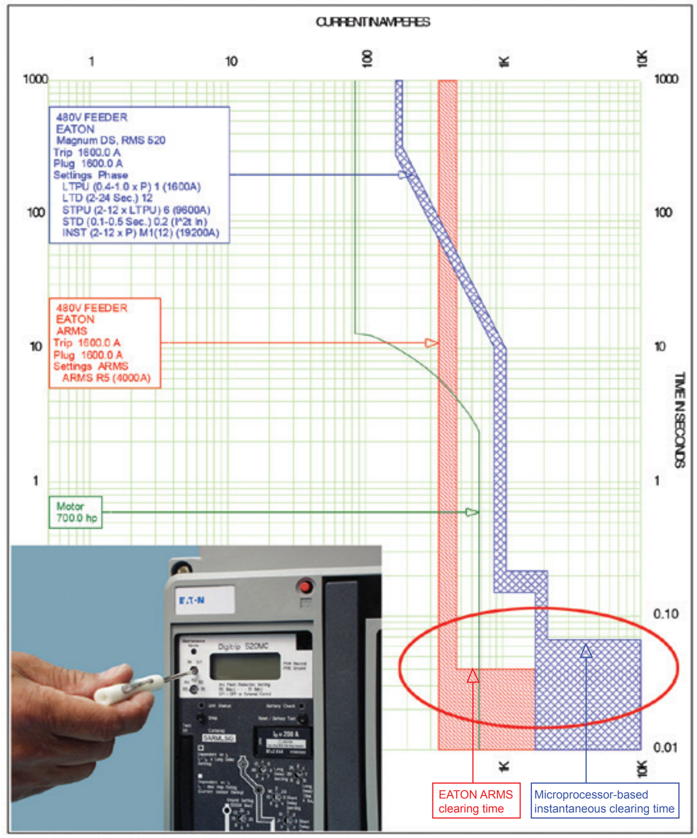
Enhanced safety during maintenance – Eaton's Arcflash Reduction Maintenance System™ Technology

The method:

Eaton's Arcflash Reduction Maintenance System uses a separate bypass path that is strictly analog, bypassing the electronic trip unit to save critical milliseconds over using instantaneous trip settings. This provides the fastest possible breaker clearing time which results in the lowest arc energy exposure to the worker. This is a dedicated, fast-acting method of tripping that is engaged during maintenance operations that includes a visual indication feedback that the enhanced protection is active. The optimum pick-up settings to provide the maximum arc energy reduction without causing nuisance tripping are based on system analysis.

This technology is designed to be used by personnel when they are required to perform work on energized electrical equipment, as allowed by the NFPA 70E Standard. It is intended to be used only during the time that a worker is exposed to the arc flash hazard and can be used in addition to all the other appropriate traditional solutions for arc flash reduction to provide further reduction in the arc energy hazard. This technology can reduce the arc energy by over 60 percent.

Energy-reducing maintenance switch protection can shorten the duration of the faults beyond ZSI or the standard instantaneous tripping function of a microprocessor-based trip unit. It is important to note that microprocessor-based instantaneous devices require power up and processing time, resulting in delays compared to analog devices. Boot up time, A/D conversion rate and code execution time add milliseconds of delay time. Exact trip times for energy-reducing maintenance switching varies among manufacturers, and while some may be slower or the same as instantaneous, Eaton's Arcflash Reduction Maintenance System offers total clearing times that are faster than instantaneous. The shorter duration reduces the level of arc fault energy to downstream personnel and equipment, helping enhance safety for personnel and reduce arc hazards.



Eaton's Arcflash Reduction Maintenance System can be enabled by three methods:

- Directly on the face of the trip unit, which may require maintenance personnel to dress in appropriate PPE to engage the system
- Via a remote switch with an indicating light. The switch and light can be mounted locally on the gear, or remotely. (If located outside of the arc flash boundary, no PPE required for this remote operation)
- Remotely through communications (again, no PPE is required for this remote operation)

All methods can be verified by the indicating light providing positive feedback that the maintenance mode is engaged

All trip unit protective functions are still active even when the energy-reducing maintenance protection is active, but the faster acting protection is dominant. The other protective functions act as back-up protection.

Benefits, challenges and key considerations

This methodology has been proven and well-studied for more than a decade. Eaton's Arcflash Reduction Maintenance System technology was first introduced in 2005 and is available on trip units for insulated case and power circuit breakers. It is also offered as an option on electronic trip units for molded case circuit breakers 400A through 2500A frames. Additionally, Eaton's Arcflash Reduction Maintenance System is available on medium voltage breakers and protective relays.

The main advantage is that this method enables the fastest available response from the trip unit when an arcing fault is present, which provides the greatest reduction of arc flash energy. This means that it is faster than the standard instantaneous settings on the circuit breaker.

Beyond being fast, energy-reducing maintenance switching has a host of additional benefits. It is an economical way to meet the NEC requirement. It also, importantly, incorporates a characteristic local, blue indicating light, so that personnel know when and if the system is engaged. There is no inter-wiring between breakers required and the technology can be easily applied in assemblies. It can be easily tested and integrated into lockout / tagout safety procedures without additional hardware beyond a remote selector switch / remote pilot light (if applicable).

Further, because the Arcflash Reduction Maintenance System reduces the tripping time of an upstream circuit breaker, it helps reduce the arc flash hazard to personnel working on downstream equipment. This may allow personnel to wear lower rated and less cumbersome PPE. This allows the work to be completed more quickly, shortening the duration of the risk, as worker dexterity is not impeded by the PPE.

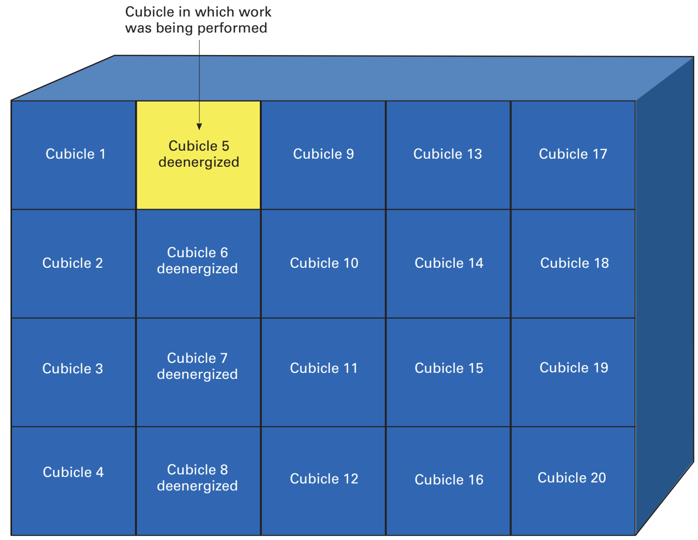
The main disadvantage of using Arcflash Maintenance System technology is that in a similar manner to working de-energized and having to turn a switch or circuit breaker to the off position, it too requires personnel to interact and put it in maintenance mode prior to doing "justified energized work," unless an automatic means (like an occupancy sensor) is used to activate it; and requires personnel to deactivate it when maintenance is complete. NFPA 70E "lockout/tagout" procedures should be followed for engaging / disengaging the energy reducing maintenance function to ensure enhanced safety during maintenance and return to normal once maintenance is completed.

Examples: Energy-reducing maintenance switching

To see the impact and benefit of reducing clearing times and resulting fault current, it may be helpful to look at an example.

A 480-volt distribution system required extensive work and the last portion of the project included the removal of a three-conductor cable from energized gear. The area where the work would be performed was de-energized and the upstream circuit breaker used Eaton Arcflash Reduction Maintenance System technology.

The physical layout of the situation is important to understand the sequence of events that occurred.

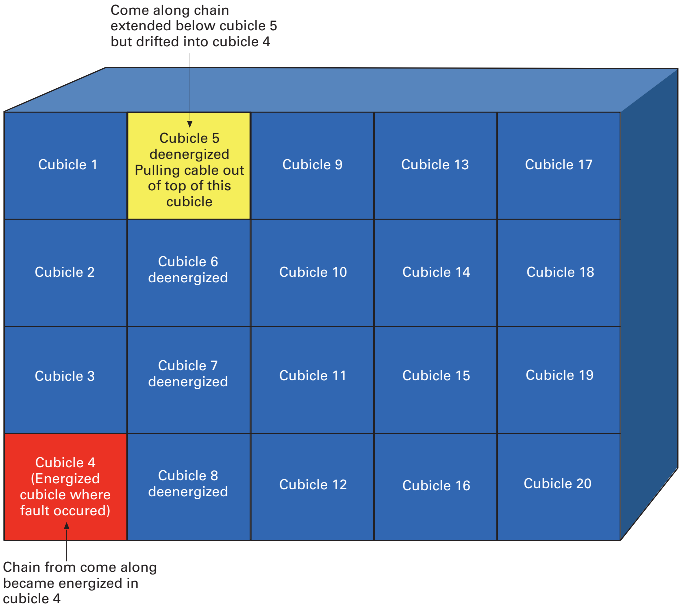


In this situation, there was a 1,000 kVA transformer upstream and the available fault current was 21,000 amperes. Without arc reducing technology, the incident energy available would be 17.7 Cal/cm2. With arc reducing technology, the incident energy was lowered to 2.9 Cal/cm2. The PPE used was for an arc rating of 8 Cal/cm2.

Without arc energy reduction, higher rated and cumbersome PPE as shown, is often required.

It is important to note that the project involved extensive pre-planning and a review of the safety plan, which was based on NFPA 70E. This meant that a shock and arc flash work hazard analysis was performed; complex lockout and safety work permitting was required and obtained; the project plan overview was conducted before the work was performed, and the cable was removed from the cable tray exiting the switchgear before the work on the switchgear commenced.

The rope method was not working and the team secured a come-along hoist. However, this tool was conductive and was not an approved tool per the work permit. The chain from the new tool drifted into an energized cubicle causing an arc flash event.



Thanks to the Eaton Arcflash Reduction Maintenance System, this event did not result in the loss of life or injury, nor was any equipment lost due to the event. While the plant did need to be shut down, the overall damage was minimal and the equipment was re-energized quickly. While the event was not anticipated or desired, the minimal impact to personnel and equipment was a relief. It was the Arcflash Reduction Maintenance System technology employed in the upstream breaker that helped reduce the incident energy available and minimize the impact of the event.

Instantaneous trip and instantaneous override

The method:

This methodology involves first calculating arcing currents at the equipment and then ensuring that current is in the instantaneous trip region of the circuit breaker by leveraging the Time Current Characteristic (TCC) curve of the circuit breaker.

The requirements of options 5 and 6 of NEC 2017 are such that comparing the arcing current with the final setting of the instantaneous trip determines whether or not additional arc energy reduction techniques are required. It is not the intent that the instantaneous trip be adjusted to a lower setting while a worker is working on the equipment, and then adjusted back to the desired setting after work is complete.

Benefits, challenges and key considerations:

Keeping in mind that the goal is to reduce the exposure to hazards for personnel, this method poses a host of challenges and introduces new risks, even though it can be applied across many circuit breaker models.

- It requires that personnel know the exact arcing current at the location maintenance is to be performed.
- The correct arcing current must be compared with the instantaneous pickup of the upstream circuit breaker, including all of the worst-case tolerances.
- The value of arcing current compared to the breaker instantaneous response has to be considered down the entire span of the circuit being protected. For example, the magnitude of arcing current for a fault occurring at the end of 100 foot cable run would be much lower than that for a fault occurring right at the breaker loadside terminals. The instantaneous pick-up response may be higher than the arcing current for arcing faults that occur farther down the protected circuit path which would leave part of the protected circuit without arc energy reduction protection. It is imperative that the arcing current anywhere along the protected circuit always be above the worst-case instantaneous pick-up to ensure operation with no time delay.
- Instantaneous / Instantaneous Override should only be used to meet the requirements of NEC 240.87 if the calculated value of arcing current is always above the instantaneous override or maximum adjustable instantaneous pick-up setting. This ensures that the required arc energy reduction is present regardless of coordination settings or any field adjustments made to the device.

It is not the intent of the NEC requirement that the instantaneous setting be adjusted to a lower level during times of maintenance. In addition to there being no local indication that a change has been made, there is no way to confirm that settings get returned to the normal state. Electrical Inspectors are also not accepting the approach that requires changing the instantaneous pick-up setting during times of maintenance as meeting the requirements of NEC 240.87.

Failure to comply with any of these regulatory, or non-regulatory requirements could have hazardous, and potentially fatal consequences.

The advantages of ZSI + Arcflash Reduction Maintenance System technology

Designers of electrical power systems need to conduct short circuit analysis, selective coordination studies of over-current protective devices and arc flash studies to determine the levels of arc flash hazards in an electrical system. With data from those studies, an assessment of hazards and how to enhance safety for personnel and to protect equipment can occur.

ZSI can provide enhanced protection to a power distribution system that has already been selectively coordinated, without compromising coordination; the ZSI scheme, once properly installed is always active and acts to provide faster trip times and lower arc flash energies – resulting in reduced stresses on the electrical system and reduced arc flash hazards to personnel that may be working nearby.

Ultimately, time matters. The fastest way to clear the fault helps reduce the arc flash energy, minimizing the related hazards and enhancing safety. Eaton's Arcflash Reduction Maintenance Switch technology provides the fastest available breaker clearing times during maintenance operations, but requires intervention to activate the protection. ZSI has the advantage of being active all the time, but doesn't offer the same level of arc energy reduction as Eaton's Arcflash Reduction Maintenance Switch technology. Utilizing combinations of both technologies can help provide the best level of protection for a given application.

Enhancing safety to protect personnel and reduce equipment damage

The best way to work on electrical equipment is when it is de-energized. Unfortunately, that is not always possible or practical. It is important to understand the six risk control methods that include both preventative and protective risk control methods outlined by NFPA 70E to help reduce risks and protect personnel.

When working on energized equipment, the NEC Section 240.87 requires that one of several acceptable arc energy reducing technologies (i.e. engineering control methods) is implemented. Eaton's Arcflash Reduction Maintenance System acts faster than ZSI, differential protection, and even microprocessor-based instantaneous tripping. However, it does require intervention to activate / de-activate the protection. Utilizing this technology along with ZSI helps give the best of both worlds to provide arc energy reduction at all times and even further arc energy reduction during times of maintenance. No single solution will magically address safety when working on energized electrical equipment. But, reducing the total clearing time goes a long way to reducing hazards for personnel. The means to accomplish this are evolving and manufacturers are continuing to invest in safety technologies to help make systems safer by design. An example of one of these technologies, arc quenching switchgear, is discussed in the final section of this paper.

Arc Quenching Switchgear

The method:

Most methods for reducing arc energy, including those already discussed, rely on tripping an upstream circuit breaker to clear a fault. However, power circuit breakers can take 3-4 cycles to clear a fault after receiving a trip signal. Therefore, the total clearing time for an arcing fault includes the time to detect the fault, which can range from a matter of milliseconds up to 2 cycles, plus 3-4 cycles for the circuit breaker to trip. Since incident energy is directly related to clearing time, this creates a lower bound for the incident energy and may not provide adequate protection when there is high available fault current. In such instances, arc quenching switchgear is an alternative which can provide a substantial reduction in incident energy.

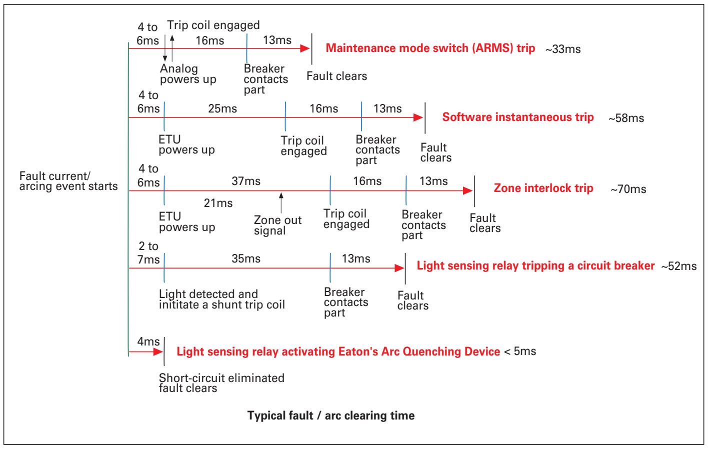
Arc Quenching Switchgear, which falls under method 4 of the NEC Section 240.87 "Energy-reducing active arc flash mitigation system," consists of two main parts: The Eaton Arc Flash Relay (EAFR) and the Arc Quenching Device (AQD). When the EAFR detects an arc fault inside the switchgear, it sends a trigger signal to the AQD. The AQD then produces a lower impedance arc fully-contained inside arc containment vessels located in the AQD. The lower impedance arc collapses the voltage and immediately extinguishes the unintended arcing fault as the current begins to flow into the AQD. This quenching operation occurs in less than 4 ms or about one quarter of a cycle; an order of magnitude faster than the aforementioned technologies. The arcing continues safely contained inside the AQD until the upstream power circuit breaker trips. Since the AQD creates a current-limited lower impedance path, it dramatically reduces the peak fault current when compared to a bolted fault solution.

Benefits, challenges, and key considerations:

Arc Quenching Switchgear reduces the incident energy to such a low level that it is able to provide ANSI/IEEE C37.20.7 arc-resistant protection without the need for ducts, plenums, venting into the room or special enclosure construction. It can even provide arc-resistant protection with doors open or circuit breakers removed. Since the incident energy is so low, damage to the switchgear from an arc flash event is minimized or completely eliminated which dramatically reduces equipment downtime.

The arc quenching system is always on and does not require any administrative controls to provide protection. The system performs complete system self-supervision with health status communicated via dry contacts and MODBUS communications as well as a white light mounted above the AQD which indicates overall system health. Furthermore, Arc Quenching Switchgear does not affect the selective coordination of the system and it can be used in conjunction with ARMS and ZSI, if desired.

Arc Quenching Switchgear is a more costly solution than ARMS and ZSI and it is currently only available for low-voltage metal enclosed switchgear. The AQD is a single-use device that must be replaced after it quenches an arcing fault.



About Eaton

Eaton delivers a range of innovative and reliable indoor and outdoor lighting solutions, as well as controls products specifically designed to maximize performance, energy efficiency and cost savings. Eaton lighting solutions serve customers in the commercial, industrial, retail, institutional, residential, utility and other markets.

Eaton's electrical business is a global leader with expertise in power distribution and circuit protection; backup power protection; control and automation; lighting and security; structural solutions and wiring devices; solutions for harsh and hazardous environments; and engineering services. Eaton is positioned through its global solutions to answer today's most critical electrical power management challenges.

Eaton is a power management company with 2017 sales of $20.4B. Eaton provides energy-efficient solutions that help our customers effectively manage electrical, hydraulic and mechanical power more efficiently, safely and sustainably. Eaton has approximately 95,000 employees and sells products to customers in more than 175 countries. For more information, visit www.eaton.com

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Authors

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