Doors Wide Open: Safety Beyond the Standards

THE TESTING OF REAL-WORLD SCENARIOS

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FOR NEARLY THREE DECADES, ARC-RESISTANT, DETECTION, and quenching technologies have been in use and have continued to evolve together with changes to the associated global standards. These arc flash-related standards dictate hardware configurations and performance characteristics based on specific testing methods. However, they primarily focus on arc testing devices with equipment doors closed and latched, which offers only one basic protection scenario. Yet, many arc flash incidents occur when doors are open, especially during troubleshooting or equipment safety assessments. This raises questions about the validity of the testing sequences and results outlined in these standard procedures when one or more doors are open. This article aims to address this issue by proposing modifications to standard testing methods to better simulate real-world scenarios, where doors are often open during inspections and maintenance situations. Additionally, it will review the global standards for active arc fault mitigation, particularly focusing on regions adhering to IEC standards, where more rapid growth in deployment has been observed.

Introduction

Arc flash hazards present diverse safety challenges, influenced by factors such as the integrity of control mechanisms, site configurations, and environmental conditions. It is essential for electrical and safety engineers to strive to control, reduce, or eliminate these risks whenever feasible. Numerous articles have explored different aspects of arc fault events and reviewed various methods for personnel protection, including the use of arc-resistant equipment along with detection and mitigation strategies [1], [2], [3], [4], [5], [6], [17], [18].

In support of these arc protection technologies and methods, various recommended testing practices or standards have been developed and revised. The latest IEC related standards for arc detection and arc quenching devices (AQDs) [20], [24] provide a basis for utilization and unification of testing. Adapting these standards to equivalent North American versions for arc detection and quenching technologies could lead to better understanding and fewer misunderstandings, misguided beliefs, or inconsistent information for these important safety related technologies. On the other hand, the IEEE 1584 [14] standard has been widely utilized as the foundation or base for other international arc flash hazard standards created in many European countries.

These provide guidance surrounding the consistency of the testing methods and equipment configurations to provide uniform performance within the associated marketplaces. All of these standards and guides are useful in defining baseline protection characteristics, but most have made some fundamental assumptions that may not be in line with actual equipment use.

These include, perhaps, impractical real-world assumptions from the viewpoint that arc flash events only occur when the equipment doors are closed and latched, as defined in the IEEE C37.20.7 testing guide [7] and the arc test procedure portions contained in IEC 62271-200 [8], regarding prefabricated AC metal-enclosed switchgear and control gear. The internal arc fault testing is to be configured with the switchgear, motor control center, or control gear under its "normal operating conditions." This specified degree of protection is only provided by the enclosure with all the doors and covers closed, as should be the case under normal service conditions, and is independent of how these doors and covers are held in place. In [7], however, it does provide some clarity on internal arc testing required if any cover has to be removed and/or any door has to be opened to perform normal switching operations. In these cases, the internal arc test must be carried out with the cover and/or door removed.

Removing or replacing components (for example, power fuses or any other removable component) is not considered to be normal operation, nor are any tasks associated with carrying out maintenance work as outlined in NFPA 70B [10].

In both cases defined in [7] and [8], protection is only provided if the electrical equipment has been installed, operated, and completely maintained in accordance with the instructions of the manufacturer. Other standards such as NFPA 70E [9] and 70B [10] reinforce these requirements with the intent that there will be a lower probability that an internal arc fault will occur with better maintenance. However, this does not totally remove the risk of arcing faults, so they cannot be totally or completely disregarded.

When selecting new electrical equipment, a review of the possibility of the occurrence of internal arc faults, and any subsequent impacts, should be properly dealt with. There should always be an intent to provide an acceptable level of personnel protection to provide a level of acceptable risk for any task performed.

Achieving Acceptable Risk Levels

Acceptable residual risk is a fundamental concept integrated into various international safety standards and guidelines spanning equipment, products, processes, and systems. Recognizing that risk-related decisions are constant in real-world applications, achieving an acceptable risk or safety level yields significant benefits.

Determining the tolerable residual risk involves an iterative process of risk assessment and reduction for each identified hazard. While the term "acceptable risk" is common in global standards, safety professionals often refrain from labeling risks as "safe."

Reluctance to use terms like "safe" may stem from a lack of understanding about the job or task's nature, as well as concerns about biased judgments due to inherent uncertainties in risk assessments. Additionally, limited statistical data may hinder precise risk evaluations. Moreover, insufficient experience in more hazardous environments where risks are routinely accepted contributes to this aversion.

Safety standards like NFPA-70E [9] aim to reduce hazardous conditions, but they acknowledge that achieving zero risk is improbable. While zero risk remains the ultimate goal for safety professionals, its practical attainment is sometimes rare.

In the realm of arc flash protection, can emerging technologies alter perspectives on acceptable risk levels?

Table 1. Comparison of arc containment and mitigation techniques

Technology	Considerations
Arc-resistant switchgear/MCC	• Dependent on enclosure integrity • Arc by-products exhaust point
Remote control/operation	• No impact on equipment protection • Only a reduction of close personnel interactions and exposure
Fuses	• Dependent on current limiting/interruption abilities (curves), arc impedance may lead to longer operation time or no operation
Current-limiting CBs	• Relies on current limiting, arc impedance may lead to longer operation time or no operation • Interruption based on curves
CB combined with an instantaneous trip unit	• Relies on current limiting, arc impedance may lead to longer operation time or no operation • Interruption based on fastest mechanical clearing time of the CB
Temporary reduction of overcurrent settings (maintenance switch)	• Temporarily faster and more sensitive than breaker trip settings • Relies on operator actions • Interruption based on fastest mechanical clearing time of the CB
Arc detection relaying	• Fastest detection method requires light sensor installation in protected gear • Final arc clearing time depends on upstream CB opening time
AQD (often referred as high-speed switches or crowbar system in North America)	• Requires a detection relay as a trigger device • Utilizes optical and/or current sensing • Extremely fast detection and arc clearing
Triggered current limiters	• Combinations of pyrotechnically triggered devices in parallel with fuses
Zone selective interlocking	• Requires more sophisticated relaying and application practices
Bus differential scheme	• Requires sophisticated relaying, dedicated CTs and application practices • Still depends on upstream switching device for clearing the arc • Very challenging on LV systems

MCC: motor control center; CB: circuit breaker; CT: current transformer; LV: low voltage.

Exploring testing methodologies becomes crucial to redefine safety achievements beyond current criteria.

How can industries further mitigate risks associated with routine tasks prone to arc flash incidents? Continued exploration and adoption of innovative technologies alongside refined testing methodologies are key avenues for risk reduction.

Evaluating Arc Flash Mitigation Techniques

There have been several excellent articles written regarding the use of arc flash and detection technologies and methodologies [2], [3], [4], [17], [18]. These include various techniques and technologies, which are summarized in Table 1. Each of these various techniques or methods, listed in Table 1, has individual pros and cons in relationship to its impact on the level of arc flash risk control, the level of personnel safety, and its impact on the electrical system.

Characteristics of Arc Flash Detection

When an electrical arc flash event occurs, the characteristics of the event are generally always very similar in nature. Each characteristic may vary in size or intensity, but the components will exist in all cases. This makes the use of various technologies, to measure or monitor these characteristics, rather straightforward.

These characteristics include

- fault current above full load
- intense light energy
- increase in air pressure around the fault (pressure wave)
- various negative impacts to the system voltage.

Arc flash detection relay systems, whether utilized individually or in combination, are commonly employed for sensing various arc fault attributes. These systems, available in different types, detect arcing fault phenomena. Early systems relied solely on detecting intense light energy associated with large arc faults, leading to false detections from external light sources. The introduction of fault current monitoring enhanced the reliability, sensitivity, and selectability. Detection methods combining light energy and high current trigger a relay to indicate an arc fault, which then issues a trip signal to disconnect the circuit. Pressure sensing technology further enhances detection algorithms, especially in systems lacking means to measure fault current. Regardless of the detection method, these relays can only issue a trip command to remove the fault condition upstream.

As noted in an article by Kay, Arvola, and Kumpulainen [3], fault protection systems inherently involve additive latencies. For instance, power circuit breakers (CBs), whether using air or vacuum technology, have mechanical opening and arcing times. Therefore, despite rapid arc detection processes (typically 2–5 ms), the upstream device's opening and fault current clearing time are significantly longer (e.g., >50 ms). These additive latencies, essential for protection coordination to maintain selective overcurrent protection, result in a total latency of over 300–400 ms, as depicted in Figure 1.

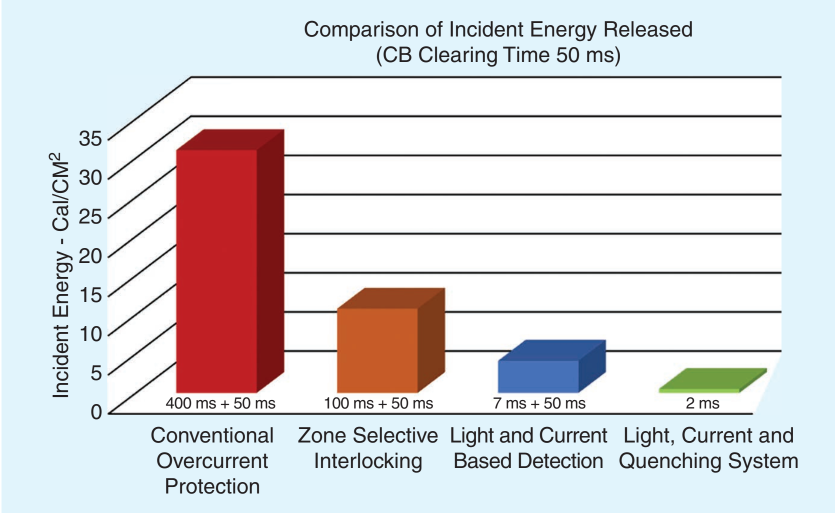

FIGURE 1. A comparison of incident energy of different protection methods at 480 V, 65 kA, gap of 32 mm, working distance of 610 mm, grounded [2].

Arc quenching systems were introduced to eliminate much of the latency associated with traditional fault detection and removal methods, where the upstream switching device was eventually tripped to remove the incident energy release. These quenching systems removed most of the latency. However, the protection system configuration remains in parallel to ensure selective protection for faults other than arcing.

Variations in Arc Quenching Techniques

As mentioned earlier, arc quenching systems have a long history of service worldwide, with ongoing enhancements in design and capabilities to improve speed, reliability, and reusability. These systems establish a low-impedance path for all three phases to ground or facilitate connection of all three phases.

The core principles of arc quenching systems are straightforward. Collaborating with arc flash detection devices, such as relays or sensors, they swiftly identify arc fault ignitions. Upon detection, the arc flash relay typically sends two signals: one to trip the source circuit-breaking device(s) and the other to activate the AQD. For a basic example, see Figure 2.

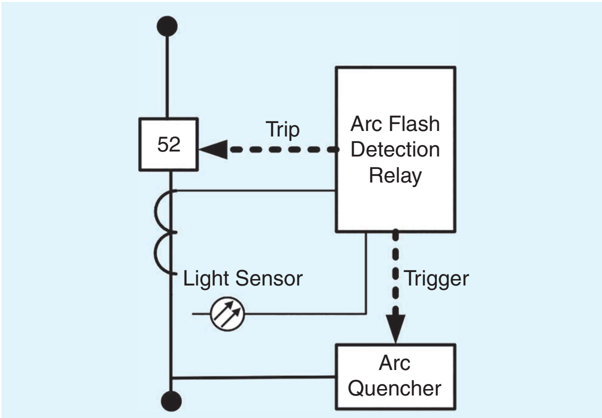

FIGURE 2. The arc detection relay with a light and current-based quenching system.

Low-Voltage System Applications

The first-generation LV (low voltage) quenchers were typically single-use devices limited to system voltages up to 600 V. These units employed explosive charges to create a shorted connection to each phase, requiring replacement after operation. Some products still utilize variations of this method. For example, Figures 3–5 showcase a present-generation resettable arc quencher and its associated system.

FIGURE 3. A typical resettable LV AQD.

Newer quenching systems offer various techniques or topologies to enhance quenching capabilities. These technologies may include creating parallel arcing within containment vessels; incorporating parallel fusing and explosive charges; or utilizing high-speed, resettable electromagnetic coil assemblies for direct shorting of faulted phases. Customized solutions, combined with other circuit influencing devices, provide tailored performance characteristics.

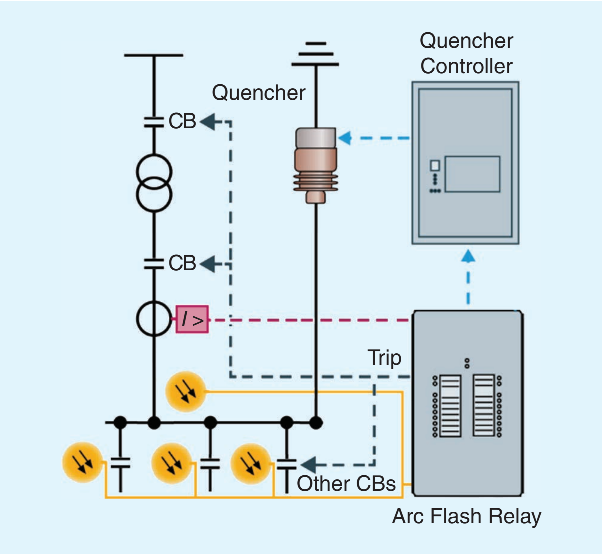

FIGURE 4. A typical basic medium-voltage (MV) quenching system.

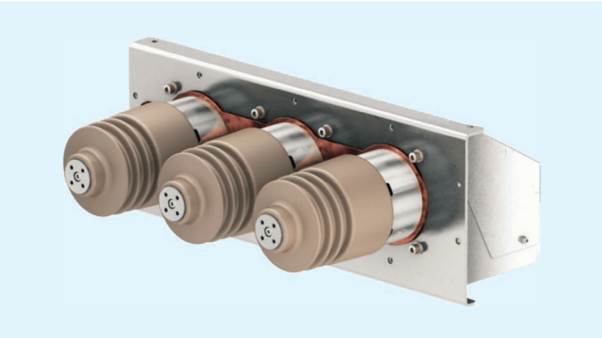

FIGURE 5. A typical resettable MV AQD. (Source: Siemens)

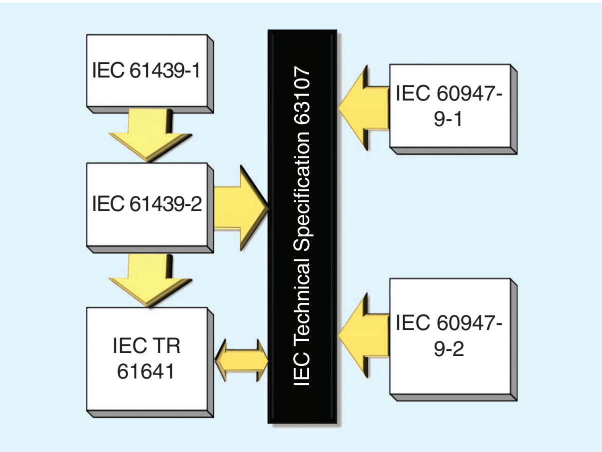

FIGURE 6. The IEC 63107 related group of standards.

Medium-Voltage System Applications

Earlier generations of medium-voltage (MV) quenchers used either resettable/reusable devices or single-use devices activated explosively. Both methods introduced a low-impedance path, with some systems using explosives while others relied on high-speed contact closures. Despite the differences, both technologies had similar closure times.

Figure 4 illustrates a basic MV system configuration, including an arc detection relay and the associated quencher and controller. Today's arc detection systems and associated quenching control units are highly optimized for fast and reliable removal of arc fault dangers. By utilizing multiple arc fault characteristic inputs, false tripping of the quenching unit is nearly eliminated, addressing concerns from earlier technologies. Unlike first-generation devices, modern units are resettable, minimizing equipment downtime caused by false trips. Additionally, they enable multiple engagements during commissioning, allowing for accurate protection setting verification and comprehensive system timing tests. Validated results from these tests can be reliably used in incident energy release calculations. Figure 5 depicts a multiuse, resettable MV quencher.

Review of Applicable Standards

Arc fault risks remain a significant concern, necessitating performance assurances for any protection methods employed. To ensure consistent performance of arc fault sensing and mitigation devices, the IEC introduced a new standard, IEC 60947-9-2 [20]. This standard focuses on internal arc fault control devices and sensor technologies used in conjunction with mitigation devices to detect arc fault optical effects. Compliance with the standard's requirements is ensured through various testing methods and test reports. Alongside IEC 60947-9-1 [19], 61439-1 [21], 61439-2 [22], and TR 61641 [23], this standard forms part of the IEC Technical Specification 61307 [24], depicted in Figure 6.

The purpose of Specification 63107 is to define requirements for integrating arc fault mitigation systems into power switchgear and control gear assemblies. It guides original manufacturers to fulfill assembly requirements and verify internal arc fault mitigation system operation.

In North America, UL2748 [12] and UL2748A [13] offer basic information on arcing fault quenching equipment and arc fault interrupting devices. UL2748 covers equipment creating a lower-impedance current path to quench arcing faults. UL2748A addresses fast-operating devices interrupting currents associated with arcing faults. Unlike IEC standards, these UL standards have limited requirements for arc detection relays or sensors, triggering devices, or quenching equipment. They lack requirements for testing entire arc mitigation systems, including arc sensors, relays, quenching equipment, and integration within protected equipment.

Pushing Beyond the Testing Guides and Standards for Arc Flash Protection

The main aim of arc flash protection techniques is to minimize incident energy to prevent significant injuries to personnel working near the equipment. Like arc-resistant technologies, the objective is to limit skin damage to a treatable second-degree burn. Personal protective equipment (PPE) is chosen based on expected arc flash energies to offer the best possible protection, although minor burns, typically first or second degree, may still occur.

In sections 240.67 and 240.87 of the 2020 National Electric Code (NEC) [11], the NFPA has listed methods that can be used to reduce the arc energy at various points of an electrical system where CBs and fuses are being applied.

The 2020 NEC code-making panel determined that large fuses (>1,200 A) should have a clearing time of 0.07 s or less at the available arcing current. If they do not, then the various means of decreasing the arc time, such as those options listed in 240.67, should be used. This same guidance for clearing time was also arbitrarily selected for large CBs, where the highest continuous current trip setting for which the actual overcurrent device installed in a CB is rated or can be adjusted, is 1,200 A or higher [26].

These same fundamental techniques, as outlined in the NEC sections listed above, can be applied in various points within any electrical system:

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

Informational Note No. 2, added by the code-making panel, states that an energy-reducing active arc flash mitigation system helps in reducing arcing duration in the electrical distribution system. No change in the CB or the settings of other devices is required during maintenance when a worker is working within an arc flash boundary as defined in NFPA 70E-2021, Standard for Electrical Safety in the Workplace [9].

The suggested technique, "energy-reducing active arc flash mitigation systems," is a very broad statement that is not supported by the incorporation of just a single product, unlike the other items, methods, or techniques listed above.

So, if this is taken one step farther, a review of the aspects of equipment certification or validation of an arc-resistant rating is required. Using the IEEE testing guide, C37.20.7 [7], for example, the intent of the testing is to provide validation or verification of these four critical and foundational pass/fail criteria:

- Properly latched or secured doors, covers, and so on did not open during the arc test.
- No fragments were expelled from the enclosure within the time specified for the test.
- There are no burn-through locations on the enclosure under test.
- None of the burn indicators, placed around the exterior of the unit under arc test, were ignited as a result of escaping arc gases.

Arc flash incidents often occur during equipment interaction, prompting standards like C37.20.7 to introduce type 2B accessibility for enhanced protection in LV control compartments. However, arc flash events can still happen when MV compartment doors are open during setup, emergencies, or routine maintenance. Differing employer requirements and situations lead to varying perspectives on working with energized power buses. Despite "dead front" cells, internal equipment portions may not prevent arc flash energy propagation in adjacent cells or bus compartments. Do current testing guides support industry practices and requirements? Changes in the C37.20.7 guide aim to address arc flash risk control during LV compartment access, driven by industry demand. However, this does not cover all necessary accessibility. Updated testing methods aim to reflect realistic equipment use scenarios, but workers may still face arc flash risks during the verification of electrically safe conditions, necessitating appropriate PPE for worst-case scenarios.

Testing Beyond the Standards

Both the arc-resistant testing guides, C37.20.7 [7] and IEC 62271-200 [8], share similar pass/fail criteria, emphasizing closed and secured doors according to the manufacturer's instructions. Some equipment vendors have shown that certain arc quenching systems can reduce incident energy levels to the extent that traditional safety measures like arc gas ducts or heavily reinforced enclosures are unnecessary.

The concern arises regarding the standards' focus on closed-door scenarios. Should not standards also address worker protection when enclosure doors are opened? Based on reviewed data, arcing fault events with no worker interaction pose minimal injury risk. However, when interactions occur, the arc flash risk is higher. Ensuring worker safety when doors are open remains a challenge, even for qualified workers.

Looking Beyond the Rhetoric

Well-designed electrical systems must account for occasional short circuit events. Protection involves integrating various overcurrent protective devices like intelligent electronic devices, CBs, or fuses to detect or isolate faults. Components such as cables, busways, power buses, and disconnecting switches must withstand mechanical and thermal stresses from maximum short circuit currents (SCCs).

Although short circuit or arc fault events are unexpected, the inclusion of an AQD provides additional

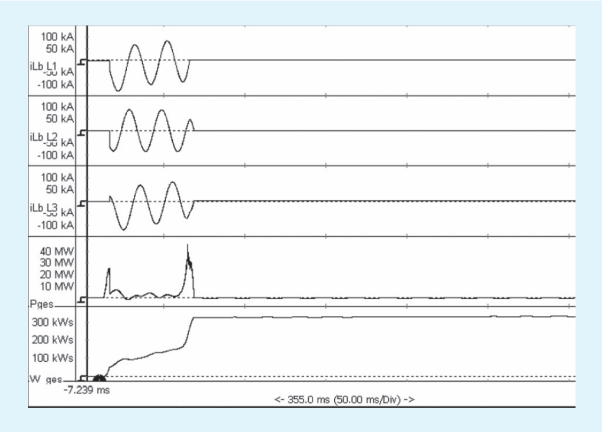

FIGURE 7. A 65-kA arc test with AQD engaged followed by the CB opening (refer to Figure 11).

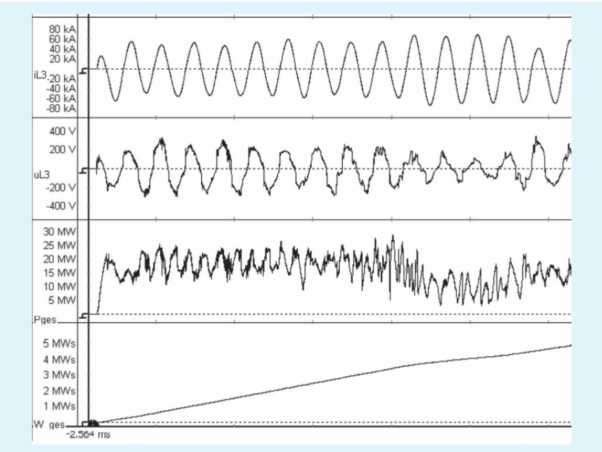

FIGURE 8. A 65-kA arc test with no current interruption (~250 ms) (refer to Figure 11).

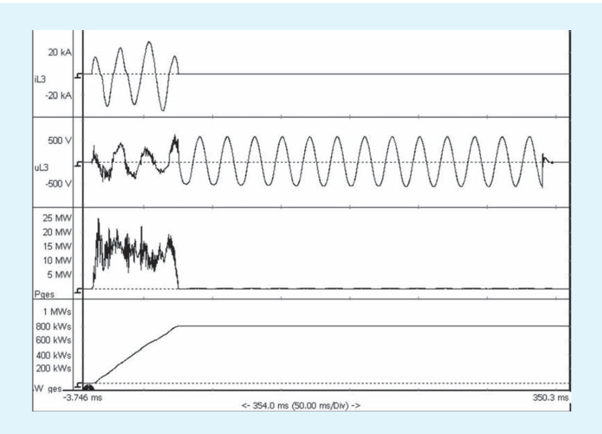

FIGURE 9. A 20-kA arc test with arc flash detection and CB opening approximately three cycles (refer to Figure 11).

protection and assurance for equipment and personnel. For system designers and protection engineers, the upstream transformer sets many protection requirements. Considerations include additional current contributions from circuits, including those from rotating machines like synchronous generators and motors. The current supplied to the fault by these rotating machines is controlled by impedance and circuit reactance, which influence system behavior during short circuits or AQD engagement.

AQD systems, described in NFPA 70 [11] and NFPA-70E [9], reduce arc flash energy without relying on upstream overcurrent protective devices' clearing time. Discussions also focus on introducing intentional low-impedance current paths into systems, with articles addressing actual system effects versus assumed impacts. Arc fault events in distribution systems affect various characteristics until cleared, impacting the network and connected loads. AQDs swiftly remove destructive characteristics during arcing faults (see Figure 1). The AQD's low impedance remains until the fault current is cleared by the upstream CB, tripped instantly by arc detection relays.

While high current stresses are a concern, AQDs offer safety benefits by potentially eliminating incident energy injuries and minimizing equipment damage. This rapid recovery is independent of traditional overcurrent coordination and motor contributions to internal arcing events. There is no need to modify switchgear rooms for arc ventilation or ducting, as required by traditional arc-resistant equipment.

In North American markets, concerns about peak currents from AQD activation have been prevalent. However, a comprehensive review of system application practices and resulting current characteristics is needed. Engineers must consider fundamental protection requirements and complete system protection despite incorporating overcurrent protection elements.

For instance, designers still need to account for all possible fault conditions in the distribution system, ensuring that maximum SCCs do not exceed equipment ratings. Calculations for worst-case SCCs assume zero impedance with no current-limiting effect, although actual short circuits often involve arcing, which can reduce current magnitudes.

Analytical studies show widely varying sustained arcing SCCs, with IEEE standards suggesting values as low as 0.5. In MV systems, per unit values approach the system bolted fault current as voltage increases (refer to Figure 10).

When comparing system stress from arcing currents to AQD's low-impedance currents, attention should be paid to the asymmetry of arcing fault current versus the symmetry of AQD current. AQD's symmetrical low-impedance current causes a single power peak, whereas CB opening leads to a larger peak, as depicted in Figure 7 for AQD and CB peak megawatts during a 65-kA/700-volt test.

The asymmetrical arcing current, if allowed to burn for a longer time, causes continuous power peaks and high total power being pulled from the transformer during test, as seen in Figure 8 with the similar 65-kA fault current at 700 volts.

When an AQD is inserted into the system, the symmetrical current, from the very low impedance, introduces a lower-power peak. Since the current is symmetrical, the electromechanical stress is lower than those of uncontrolled asymmetrical currents associated with uncontrolled arcing or when a CB removes the arc energy from the system (refer to Figure 7).

Figure 9 illustrates the current, voltage, and energy profile after the CB is triggered to trip by an arc detection relay. In this case the breaker opens in approximately three cycles.

Often, arcing faults start as a single-phase fault, and depending on the type of system grounding, the fault current in such a case may be low. Therefore, it is important to consider whether a single-phase fault shall trigger the AQD, or it shall be only tripped by the arc detection relays and associated CBs. Today's modern arc detection relays are capable of distinguishing between single or multiphase faults and initiating different actions based on the fault type.

Figure 10 illustrates an example of the variance between system bolted fault current versus the associated arcing fault current, in MV systems. This difference is attributed to the voltage drop at the arc fault itself. This arcing fault current profile will vary since the arc can be very unstable.

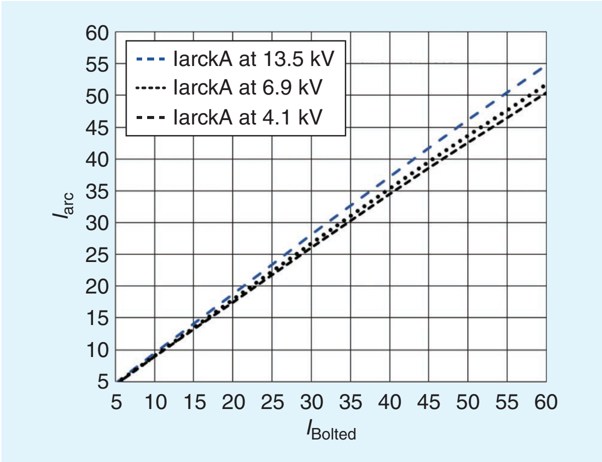

FIGURE 10. Perspective arcing current compared with bolted fault current.

Incident Energy Reduction

Standards like NFPA-70E [9] and IEEE 1584 [14] have extensively documented that incident energy levels in arc faults directly correlate with the duration of the event. Thus, reducing the duration of an arc fault can lead to a decrease in incident energy. IEEE 1584 [14] has served as a foundation for many European national standards, such as Germany's DGUV-I 203-077 [25], as well as standards in Sweden and Italy.

This is where AQDs excel. Most LV and MV quenching units can quench arcs within 2–4 ms, significantly faster than the fault clearing time of LV and MV breakers, which ranges from three to five power cycles (50–85 ms). This delay can allow internal arc pressures to breach enclosures, causing serious injury to personnel and substantial damage to equipment. Table 2 compares various arc detection and protection configurations, detailing their arc detection time, resulting arcing durations, total arc detection and quench time, and total energy released.

Testing Results and Observations

Continual testing conducted by different equipment vendors has demonstrated that when arc quenching is applied correctly, incident energy levels in the protected system are significantly reduced. In the lead-up to this article, extensive testing cycles were conducted to offer more clarity and validation of the performance capabilities of these systems, even when enclosure doors are open. Figure 11 illustrates the straightforward configuration of the test circuit.

Table 2. Test resultsa comparing arc durations and arc energy

Configuration	Doors Open/ Closed	Test SCC (A)	Arc Duration	Arc Detection Time	Total Arc Detection and Quench Time	Arc Energy
No arc protection relay[b]	Closed	30 kA	310 ms	1.5 ms	308 ms*	27.16 cal/cm^2
Arc protection relay and AQD	Closed	30 kA	5.8 ms	1.43 ms	4.4 ms	0.35 cal/cm^2
Arc protection relay and AQD	Open	65 kA	3.7 ms	0.77 ms	2.97 ms	0.68 cal/cm^2
Arc protection relay and AQD	Open	100 kA	3.53 ms	0.54 ms	2.99 ms	1.2 cal/cm^2

[a]Basic test configuration shown in Figure 11.
[b]Current removed by opening upstream CB.
*Timing with test breaker.

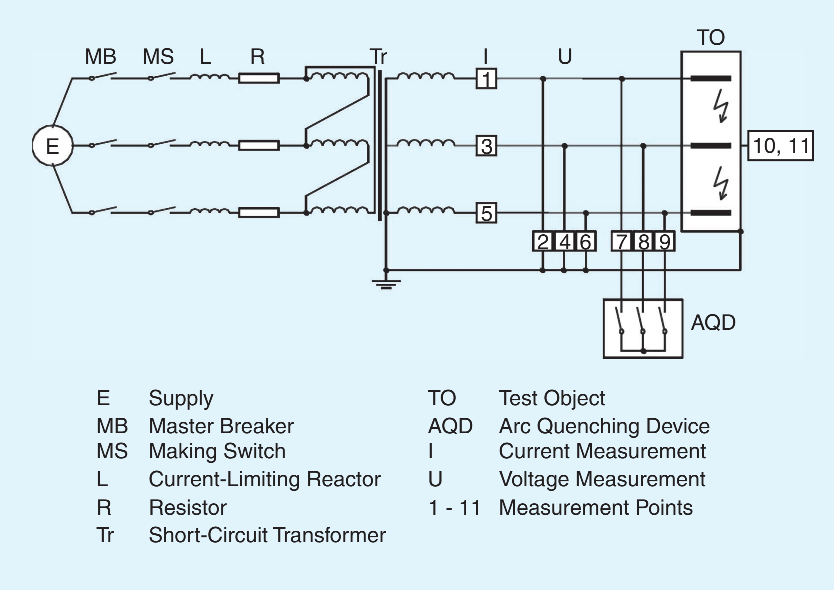

FIGURE 11. The AQD system test configuration.

FIGURE 12. The cabinet after the 63 kA test after AQD engaged.

FIGURE 13. The arc initiation wire (shorting).

All the testing illustrated that very little incident energy is released anywhere in a system protected using the quenching methods employed for these tests. Also observed was the very small amount of subsequent damage to the protected system. In most cases, it was difficult to find any significant equipment damage.

A typical example of the limited resultant arc damage, when the AQD was employed, is shown in Figure 12. The prior-to-testing state is shown in Figure 13. It can be observed from this photographic evidence that there is almost no distinguishable damage associated with the arcing fault when an AQD is employed. In this example, with a quick visual inspection and light cleaning of the equipment, followed by the appropriate tests, this equipment could be quickly placed back into service.

Conclusions

Ensuring personnel safety and protecting valuable electrical assets from arc flash damage are top priorities across industries. While arc-resistant equipment offers personnel protection when installed and operated as per standards, it lacks the ability to safeguard equipment from arc fault damage. Additionally, its personnel protection is compromised when used outside defined conditions, such as during maintenance.

Incorporating arc quenching systems into electrical distribution setups provides significant advantages. These systems not only protect personnel but also drastically reduce equipment damage during internal arc faults. When combined with traditional circuit protection methods, arc quenching systems offer superior safety and equipment protection under routine operating and maintenance conditions compared with arc-resistant products.

New standards in both European and North American electrical engineering communities harmonize equipment testing requirements, leading to better application and understanding of arc quenching technologies. Further testing has demonstrated that these technologies can greatly enhance arc hazard protection and minimize catastrophic internal damage, thereby reducing repair and downtime.

These very fast arc quenching solutions, with typical total arcing times of 4–5 ms, exceed the present safety requirements and required results associated with the arc testing guides and standards. Whether equipment doors are open or closed, these new solutions swiftly reduce arcing current, minimizing incident energies and providing greater protection for the equipment and for personnel when the appropriate PPE is worn.

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