Living with Arc Flash Mitigation

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***Abstract* – Developing an optimal arc flash protection strategy for a given facility can be difficult due to the number of solutions and system variables involved. Effective arc flash hazard reduction is best achieved by establishing an overall system protection strategy that accounts for safety and operational requirements as well as system reliability and availability. An overview of available solution categories and application guidance based on experience in a wide variety of facility types is presented in order to assist engineers trying to implement "safety by design" principles to help deal with arc flash hazards. The approach provided addresses the complexities of the trade-offs between competing priorities and provides tools that help users develop effective protection strategies for the unique circumstances in a given facility.**

Index Terms – accident prevention, electrical safety, risk analysis, occupational safety, arc flash

I. INTRODUCTION

NFPA 70E [1] defines the arc flash hazard as "a dangerous condition associated with the possible release of energy caused by an electric arc." High-energy arcing faults can cause significant damage to electrical equipment as well as significant injury to workers exposed to such an event. Industry awareness of the issue has increased significantly over the past 10-15 years, led by industry standards such as NFPA 70E and IEEE 1584 [2].

Typical responses to arc flash hazards include analysis to estimate the arc flash incident energy level, installation of warning labels on equipment, training employees on risk assessment and risk control methods, and use of proper arc rated personal protective equipment (PPE). NFPA 70E requires that equipment be placed in an electrically safe work condition before most work is done. However, there are exceptions to this rule (e.g., testing/troubleshooting) that could result in exposure. In addition, the act of testing to verify equipment de-energized during the lockout/tagout process may result in workers being exposed to arc flash hazards.

While many think first of arc rated PPE as the primary defense against arc flash hazards, the use of PPE is only one way to manage the risk of electrical injury. In fact, it may be the least effective way of doing so. ANSI Z10 [3] defines a hierarchy of risk control methods, ranked from most to least effective:

1. Elimination
2. Substitution
3. Engineering Controls
4. Awareness
5. Administrative Controls
6. PPE

Eliminating a hazard altogether or substituting something less hazardous is often impractical in the context of electrical safety – after all, electrical loads will always need an electrical power distribution system to supply them. PPE is an important part of a safety program, but as a last line of defense, not as a primary risk control method. Awareness and Administrative Controls seek to modify employee behavior but do not directly affect the source of the risk. Engineering controls involving product or design solutions that help reduce the magnitude of the hazard and/or the risk to the worker occupy a "sweet spot" where arc flash mitigation is concerned. Even if they cannot totally eliminate the hazard, proper application of engineering controls can actually reduce the available incident energy in the system, or at the least, reduce a worker's exposure to that energy.

There may be several reasons to pursue arc flash mitigation solutions through application of engineering controls, including:

- *Code requirements*. Beginning with the 2014 edition of the National Electrical Code (NEC), [4] section 240.87 now requires engineering controls intended to reduce arcing energy at any low-voltage circuit breaker sized 1200A or larger. Similar requirements for fused circuits were added in 2017, to become effective on Jan. 1, 2020.
- *PPE reduction*. Possible when the available incident energy is lowered sufficiently.
- *Internal Policies*. Certain employers have implemented policies to reduce the arc flash levels throughout their facilities to provide a safer work environment.
- *Reliability / Availability*. The relationship between incident energy levels and equipment damage is difficult to quantitatively assess, since there are no objective guidelines that link the two. However, the idea that "more energy" likely results in "more damage" is somewhat intuitive.

Whatever the motivation behind arc flash mitigation, it is better to consider it early in the project design process rather than trying to later retrofit solutions into existing facilities. Using principles of "safety by design," where required safety parameters are defined early in the project lifecycle and then are reflected in specifications and design documents, will ultimately be the best way to mitigate arc flash levels in the system, in terms of both effectiveness and cost. Many solutions may also be retrofit in existing facilities, though this may require additional downtime, costly field modifications, or replacement of otherwise functional equipment to accomplish.

II. ALIGNING SAFETY OBJECTIVES AND MITIGATION STRATEGY

An important part of a successful safety by design strategy is establishing appropriate, specific design criteria rather than designing with only a vague idea of "safety" or "products" in mind. Since hazard and risk can rarely be totally eliminated, consideration should be given to what "safety" actually means for an organization, facility, equipment, or process. For example, if the goal of an arc flash mitigation program is to reduce the incident energy level in the system, what level of incident energy is acceptable? Different solutions may affect the level of incident energy to a greater or lesser degree, so the design criteria can have a significant impact on mitigation strategies used and on the final design of the power system.

One basic criterion is to simply impose a limit on the maximum allowable arc flash incident energy in the system. While arc rated PPE is available with ratings exceeding 100 cal/cm^2, many employers have adopted 40 cal/cm^2 as an upper threshold above which no energized work is allowed, making it an obvious mitigation target. Reducing the incident energy levels further, e.g., to the 8-12 cal/cm^2 range, may allow for the use of less bulky arc-rated PPE (e.g., treated cotton or lighter-weight arc-rated synthetics), and the face and head protection may also be reduced. See Fig. 1 for typical examples of 8 cal/cm^2 and 40 cal/cm^2 rated PPE.

Fig. 1. PPE rated 8 cal/cm^2 (L) & 40 cal/cm^2 (R). Photos courtesy of Oberon.

How does selecting an 8 cal/cm^2 threshold rather than a 40 cal/cm^2 threshold affect the type of solution that must be applied to reduce the incident energy levels? IEEE 1584 defines the arc flash incident energy as

$$E = 4.184 C_f E_n \left(\frac{t}{0.2}\right)\left(\frac{610^x}{D^x}\right) \text{ (J/cm}^2\text{)}. \quad (1)$$

Equation (1) shows that the incident energy is directly proportional to the clearing time t of the arc – i.e., the time it takes a circuit breaker or fuse to operate and clear the fault from the system.

All other variables being equal, to reduce the incident energy at a given location from 40 to 8 cal/cm^2, the arc duration must be reduced by 80%. What if even lower levels are desired? As an example, a 480V switchboard with 42kA available fault current and arcing duration of 500ms will result in an incident energy of ~40 cal/cm^2 at the standard 18” working distance. To reduce the incident energy to below 1.2 cal/cm^2, the level below which arc rated PPE is no longer required, the upstream overcurrent protective device must operate in 15ms, or slightly less than one 60Hz cycle. If the upstream OCPD is a medium-voltage breaker or large LV circuit breaker or fuse, this speed of operation may be difficult or impossible to achieve. Care must be taken in setting goals to ensure appropriate design criteria may be established for the specific operating environment.

The overall project budget may become a constraint as well, particularly when retrofit solutions in existing facilities are considered. In such cases, prioritizing the mitigation tasks becomes important. One way to do this is to consider not only the incident energy level but also the potential for exposure, as the two factors combine to determine the actual risk that workers may face. In many facilities, the highest incident energy levels will be found at the service entrance equipment, fed directly by the utility source. However, if workers rarely have to interact with this equipment, their actual exposure to elevated incident energy levels is infrequent. It may be more desirable to first focus on minimizing incident energy levels at locations where worker exposure is more frequent, even if that leaves the incident energy at a few locations above an otherwise undesirable threshold or limit.

In other instances, it may be possible to address worker exposure to certain tasks by using solutions that help remove workers from the “line of fire” rather than directly affecting the incident energy. These can include remote operation of switching devices, remote racking of withdrawable breakers, and installation of infrared windows or embedded thermal monitors to allow for some maintenance activities to be performed without requiring workers to be directly exposed to arc flash or shock hazards. Effectively, this allows for prioritization of “risk” vs. “hazard” reduction.

III. MITIGATION SOLUTIONS CATEGORIES

A number of different engineering controls for arc flash hazards are available, and more are developed and introduced to the market on a regular basis. Regardless of the solution type or type of system (MV/HV vs. LV, industrial vs. commercial, etc.), they can be grouped into one of four main categories: prevention, reduction, avoidance, and containment. More detail on the relative performance of each solution category is given below. A summary of the key characteristics of several common mitigation types/strategies are shown in Table I in the Appendix.

A. Prevention

The solutions in this category include product design techniques that make arcing faults less likely to occur, thereby reducing the risk to workers. Not all of the prevention solutions would also reduce the degree of the hazard (i.e., the incident energy level) as well, so the level of PPE required at a given location might not change. Regardless, reducing risk by reducing the likelihood of an arcing fault occurring at all provides an obvious benefit to workers.

An example of a Prevention solution is equipment constructed with additional barriers or compartmentalization. Such barriers could be designed to make it more difficult for workers to cause faults through accidental contact with energized parts. Barriers between phases can make it more difficult to establish a phase-to-phase arcing fault, further reducing the risk of a harmful event occurring. A good example of this is the system of barriers applied in low-voltage breaker cubicles as described in [5], intended to help prevent arcing faults between phases or from phase to ground, and then to help extinguish any arcing faults that do occur. See Fig. 2 for examples.

Fig. 2. Example of Shielding Barriers in LV Switchgear.

IEC levels of Ingress Protection (IP) and Forms of Internal Separation provide a convenient way to quantify the level of protection provided by barriers or guarding of live parts. "Finger safe" equipment meeting IP2x requirements as defined in ANSI/IEC 60259 [6] protects live parts from contact by a worker's hands/fingers, but may not protect against contact from tools or wires. Barriers inside IEC equipment are classified according to the Forms defined in IEC 61439-2 [7], from Form 1 (no internal separation) to Form 4b (significant internal separation of functional units). Due to differences in construction, it is difficult to assign typical ANSI/UL equipment a corresponding IEC "Form", though there are definite variations. For example, low-voltage ANSI switchgear is typically much more compartmentalized than a UL-listed switchboard. In any case, it is important to note that while these barriers and compartments inside the equipment may reduce the chances of inadvertent contact, they often do not protect against intentional contact (e.g., voltage testing), nor do they necessarily prevent arc flash events from occurring. Ultimately, like other "prevention" solutions, they may reduce the risk without eliminating the hazard.

High Resistance Grounding (HRG) is an example of a *system* solution that affects risk without reducing the calculated level of hazard. In an HRG system, a resistor is placed between a transformer's secondary neutral point and ground in order to limit the available ground fault current in the system, typically to 5A or less. Since the majority of faults originate as single-line-to-ground (SLG) faults, the limited energy in such faults occurring on an HRG system helps to prevent arcing SLG faults from escalating to potentially more damaging three-phase faults. However, HRG systems do not prevent phase-phase or three-phase faults from occurring. Since arc rated PPE (when required) is selected based on potential exposure, not probability of occurrence, the HRG system does not reduce the level of PPE required. The reduction of risk is certainly a benefit, but if the goal is to reduce the level of required PPE for workers, other solutions may need to be considered in lieu of or in addition to the HRG system.

B. Reduction

Energy – whether produced by an arc flash event or otherwise – can be calculated in electrical terms as the product of *voltage*, *current*, and *time*. In a given system, the *voltage* is fixed – 480V loads are going to require a 480V supply, arc flash concerns notwithstanding. Steps can be taken to modify the available fault *current* levels in a system, but doing so can be counterproductive – if the fault current is reduced and the opening time of the upstream overcurrent protective device is increased as a result, the incident energy level in the system may rise. The best way to reduce incident energy levels in the system is to affect the *time* by reducing the arcing duration – i.e., clear the arcing fault from the system more quickly.

There are a number of ways to accomplish this. The simplest and most straightforward is making sure arc flash levels are considered when the coordination study for the facility is being performed, as recommended in IEEE 1584.1 [8]. In some cases, breaker or relay settings can be chosen to minimize arc flash levels without sacrificing selective coordination. In other cases, the study may identify opportunities to upgrade devices (e.g., to replace a thermal-magnetic circuit breaker with one having an electronic trip unit, or to use an alternative fuse with a faster clearing time) to achieve the desired level of incident energy reduction.

In other instances, supplemental protection may be required to bring about faster clearing times while still maintaining acceptable levels of selective coordination between protective devices. Fortunately, a number of solutions to help address these problems are available, including zone-selective interlocking (ZSI), arc-flash maintenance switches, high-speed shorting switches, and relaying schemes such as a "transfer trip" configuration (referred to as the "virtual main" in [9]) or optical relaying systems.

C. Avoidance

For a worker to be injured in an arc flash incident, physical presence near a location with high available incident energy is necessary. Solutions that can help avoid this situation are another alternative means to provide protection to workers. Remote racking systems, for example, allow workers to install/remove withdrawable circuit breakers while standing at a relatively safe distance from the actual equipment – preferably, outside the arc flash boundary. Remote operation of switching devices is also possible through a number of means, including remotely-mounted control panels, HMI screens, SCADA systems, etc. Infrared windows and embedded thermal or partial discharge sensors may allow for diagnostic information regarding equipment condition to be obtained without exposing workers to hazards. Finally, well-planned procedures and proper work practices can also help workers avoid electrical hazards.

D. Containment

Equipment specifically designed to contain the effects of an arcing fault can be used either as a safety enhancement or as a solution of last resort. Arc-resistant switchgear, which is designed and tested for compliance with IEEE Std. C37.20.7 [10], is intended to provide additional protection for workers during normal operating conditions. Practically speaking, the effects of the internal arcing fault (e.g., hot gases, radiated heat, etc.) are contained or redirected so that a worker within the protected perimeter of the arc-resistant equipment is not exposed to the arc flash hazard. Testing requirements include demonstrating that the internal arcing faults will not burn holes in the equipment or cause doors and covers to open, and also that cotton indicators (simulating non-arc rated clothing of workers) placed near the gear will not ignite from the heat released in the arc flash event. See Fig. 3 for an example of an arc resistant switchgear lineup under test.

Fig. 3. Medium-Voltage Arc Resistant Switchgear Under Test.

There are several application issues that must be carefully considered when applying arc resistant equipment, including making sure that the available arcing fault current and the maximum arcing duration does not exceed the ratings of the equipment. In addition, the arcing by-products, mainly the hot gases ejected from the gear (see again Fig. 3) must be properly contained or redirected to a secure location. When properly applied, though, arc-resistant equipment can be a valuable part of an overall arc flash protection strategy.

IV. PERFORMANCE CONSIDERATIONS

Selecting arc flash mitigation solutions for a large facility is a challenging task considering the numerous and often nuanced benefits of the available technologies. As a first step in selecting a technology, a mitigation strategy must be developed that takes into account both safety objectives and operational constraints. Naturally, there will be a tension between performance requirements and total cost of ownership that must be evaluated in order to select the best mitigation strategy. The approach outlined in this section has been developed based on industry best practices with the goal of aligning safety policies and operational constraints with an overall mitigation strategy – and ultimately with specific mitigation technologies.

A. Operational View of Arc Flash Solutions

As discussed in Section III, *prevention* and *avoidance* technologies generally do not reduce the available incident energy. They may be viewed like administrative procedures – while they do not reduce the energy levels (i.e., the severity of the *hazard*), they may significantly reduce the probability that an arc flash event will occur in the first place (the *risk*). These should be considered as a first-line defense, but do not protect against human error or intentional exposure, such as testing & troubleshooting.

Reduction solutions offer additional protection over passive technologies as they often offer protection for both incidental and intentional exposure. Active reduction solutions not only improve personnel safety; they may also minimize damage to equipment. However, these systems require periodic testing and maintenance to validate proper system operation.

Containment solutions require less maintenance and are ideal for environments where personnel are in close proximity to the equipment, either while operating it or when performing other duties. They do not protect against all types of intentional exposure when equipment doors and covers are open. Passive containment solutions (e.g., conventional arc-resistant switchgear) are simple and reliable, but may compromise footprint in order to create a safe space around the equipment.

B. Five Key Questions to Help in Developing an Arc Flash Mitigation Strategy

Based on experience with arc flash mitigation projects in a variety of facilities, we have developed a series of key questions that may be used in order to help develop an appropriate arc flash technology for a given project in a given facility. The questions are intended to align solution performance with both organizational goals and operational constraints.

1. *What are the arc flash incident energy reduction goals for each level of distribution equipment?* These could be based on minimizing worker PPE levels, safety policy objectives, frequency of exposure, or standard operating procedures.

2. *Which operations & maintenance procedures/tasks require protection?* This may require consideration of incidental vs. intentional exposure, as discussed above. A proper arc flash risk assessment, as outlined in NFPA 70E, can help evaluate the potential for exposure based on given work tasks.

3. *What is the prevention and avoidance strategy for mitigating risk?* How are prevention technologies evaluated and, when present, how will they be considered in the risk assessment? Can some mitigation technologies introduce risk (e.g., operational risk related to proper/improper operation of a maintenance switch)?

4. *Is there a specific requirement for equipment survivability or mean-time-to-repair (MTTR)?* As discussed above, quantifying the effect of mitigation technology on equipment damage is difficult; nevertheless, there is a logical connection between the two. Critical equipment may need to be evaluated for the potential need for greater degrees of mitigation.

5. *What are the other limiting factors?* These could include equipment footprint, capital expenditure (CAPEX, or installed costs) vs. operational expenditure (OPEX, or ongoing costs, including maintenance), maintainability (of complex equipment or relaying schemes), and reliability, including selective coordination.

Once these questions have been answered, an arc flash mitigation strategy and performance criteria can be written to assist in selecting the best technology for the application and performance objectives. One example of a solution matrix is shown in Table II in the Appendix.

C. Critical Power Applications

Critical power environments, whether in process industries, hospitals, or data centers, create a natural conflict between system uptime and incident energy exposure. As an example, selective coordination of protective devices can extend fault clearing times as one moves upstream in the system. In data centers, for example, these extended clearing times are often the cause of high levels of incident energy at the UPS level and above. A common recommendation is to use communication aided tripping schemes (e.g., ZSI or transfer trip) and optical detection as they reduce incident energy through an accelerated response to an arc flash event.

On the opposite end of the spectrum, low fault currents found further down in the power system may not provide enough current to trigger operation in the instantaneous trip range of the breaker. Slow operation of the protective device creates arc flash high incident energy that is often seen downstream of PDU transformers or when running on an emergency generator source. Maintenance switches, communication aided tripping, and administrative controls are recommended for these applications.

The arc flash mitigation strategy must include performance requirements for each level of the electrical distribution system. This is a crucial requirement as available incident energy, equipment construction, and risks associated with typical work tasks are very different at each level of the system.

In data center environments, for example, five areas are of particular interest: low-voltage service-entrance equipment, UPS input/output switchgear, PDU secondary buses, generator paralleling equipment, and MV distribution equipment. Table III below provides typical recommendations as an example.

TABLE III
SOLUTIONS FOR KEY LOCATIONS IN DATA CENTERS

System Location	Issue	Recommendations
LV service entrance equipment	Protection on HV side of transformer does not quickly respond to LV faults	Transfer trip or transformer differential protection, along with Zone-Selective Interlocking
UPS input/output switchboards	Selectivity requirements lead to extended clearing times	ZSI or optical detection
PDU secondary (480-208/120V)	Low fault levels at the PDU combined with transformer inrush current extend arc clearing times	Maintenance switch, compartmentalized PDU construction, administrative controls
Generator paralleling equipment	Low fault levels combined with multiple sources extend arc clearing times	Bus differential or optical detection, adaptive settings of relays
Medium-voltage distribution equipment	Multiple utility sources and/or generator sources result in high available fault current	High-speed shorting switch, bus differential, and/or optical relaying

V. CASE STUDY

To illustrate the application of the procedure, a case study is examined involving a 480V switchgear lineup fed from a 2500kVA stepdown transformer, and farther upstream, a MV circuit breaker with electromechanical overcurrent relay. An arc flash study shows that the available incident energy at the incoming terminals of the LV switchgear is > 40 cal/cm^2, and the settings of the existing MV relay cannot be reduced enough to lower incident energy levels without risking tripping on transformer inrush current.

In this case, the goal is to reduce the incident energy exposure of the worker to less than 8 cal/cm^2 (Question #1). The switchgear feeds a critical process at the facility, so a "reduction" solution that may help limit equipment damage during an event is preferable to an "avoidance" solution such as Remote Racking that could reduce worker exposure but not affect the available incident energy level (Question #4). "Prevention" and "containment" solutions are also given a lower priority for the same reason. Ideally, the solution would protect for all work tasks (Question #2).

Replacing the electromechanical relay with a digital multifunction relay offering better flexibility of settings may help provide incident energy reduction as well as other benefits (e.g., event recording, etc.). A coordination analysis and subsequent arc flash calculation shows that selecting settings sufficient to allow the relay to ride through the inrush current will reduce the incident energy level at the LV switchgear, but not to less than 8 cal/cm^2. Adding a Maintenance Switch to the relay is an option if workers are adequately trained in its proper operation (Question #3). However, since the potential for equipment damage is a consideration, a Maintenance Switch is not preferable since it only provides the highest level of protection when set to Maintenance Mode (Question #4).

This still leaves several options, including Zone-Selective Interlocking between the LV breaker and the MV relay, implementation of a Transfer Trip scheme, or Optical+Current relaying. These solutions can be evaluated based on relative performance as well as installed cost (Question #5). In this case, it is determined that it is possible to use the existing LV breaker in a ZSI scheme with the proposed MV relay (also Question #5), so Zone-Selective Interlocking is chosen as the most cost-effective scheme that meets the performance requirements.

Note that the use of one solution does not necessarily preclude the use of others – for example, remote racking could still be added to further reduce exposure during specific tasks. Different sets of constraints (e.g., performance criteria, equipment compatibility, etc.) can lead to different conclusions, but working through the process as outlined should aid in systematically identifying feasible solutions for any situation.

VI. CONCLUSIONS

The variety of arc flash mitigation solutions now available can be both a blessing and a curse – while they give more options for helping manage incident energy levels in a power system, design engineers have a more difficult job than ever trying to identify the optimal set of solutions for a given facility. Using a systematic approach will help to streamline the process:

- *Perform an arc flash study and revise it as the project progresses.* Once the system layout is defined, a preliminary study can identify "hot spots" requiring attention. Mitigation solutions should always be validated with calculations. Finally, an "as built" study defines the final arc flash values to be used when generating warning labels for the equipment.
- *Develop a protection strategy.* What level of incident energy is acceptable at various locations? Are solutions that require worker intervention (e.g., maintenance switches) acceptable? Should energy levels be reduced everywhere that it is feasible to do so, or are avoidance solutions acceptable in some locations? The answers can help develop a set of guiding principles for the system design.
- *Specify performance instead of technology.* Every available solution has its own unique strengths and weaknesses, and there are some situations where one specific mitigation technique is better suited than others. Specifying arc flash performance requirements rather than specific solution technologies allows engineers and vendors the freedom to apply the best solution that may be available for a given set of circumstances.
- *Allow for, and even seek out, input from engineers familiar with the varied aspects of arc flash mitigation.* In many cases, these may be application engineers employed by equipment vendors. In any event, engineers familiar with the mitigation process that are willing to consider application of several different solutions should be able to help in identifying optimal solution strategies, especially on projects involving upgrades to existing equipment.

VII. REFERENCES

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VIII. BIOGRAPHIES

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VIII. APPENDIX

TABLE I
EXAMPLES OF PROTECTION SOLUTIONS

Mitigation	Type	Pros	Cons	Recommendation
Compartmentalization IEC type 4b or ANSI equivalent barriers & boots	Prevention	Reduces the likelihood of arc flash by compartmentalizing equipment and insulating energized parts.	Equivalent to a “guard” on a saw; hazard is still present. Maintenance & testing may require exposure to energized parts.	While this does not reduce the available energy available, it does reduce the probability of a fault. Compartmentalization does not address requirements of NEC 240.87 or change incident energy calculation.
Arc Resistant	Containment (Passive)	Protects the personnel by directing energy away from the worker when required covers are on. Tested per IEEE C37.20.7	Maintenance & testing may require removal of covers. Equipment is exposed to damage. Larger footprint. May require second mitigation means to stay within rated arcing duration, esp. at LV.	This solution offers protection to the worker for specific tasks, but does not reduce the available energy. This solution is recommended where active mitigation methods are not acceptable.
High-speed Shorting Switch	Active Reduction	Fights “fire” with “fire”. Re-directs arc flash energy back into the bus by creating an intentional bolted-fault; may use optical, differential and current waveform recognition.	Unconventional solution that is not well understood by the market. Requires additional section of equipment.	May qualify as Arc Resistant per IEEEC37.20.7. Needs robust control system to minimize chances of nuisance operation.
Zone Selective Interlocking (Blocking Schemes)	Active Reduction	Communication aided transfer trip scheme that reduces breaker trip time and amount of energy released during an arcing fault.	Requires communication wiring between breakers. Trip units or relays must be installed with ZSI capability.	This solution is recommended for LV. Also available with some MV relays.
Transfer Trip (“Virtual Main” system)	Active Reduction	Reduces most common arc flash “hot-spot” by opening transformer primary device for faults between the transformer and LV breaker.	Requires additional CTs, relay and wiring to upstream device. Requires dedicated MV device for each transformer.	This solution is recommended for equipment connected to transformer secondary. (~750kVA+)
Optical Detection	Active Reduction	Reduces trip time by detecting light associated with arc flash in addition to current signature	Additional devices and sensors required. First generation technology may false trip for normal light emitted from LV arc chutes.	Viable solution in LV when other mitigation methods are not feasible.
Differential Relay	Active Reduction	Quickly detects faults by summing all currents in and out of a zone. Clears zone when currents do not equal; all devices are tripped.	Requires additional relays, CTs and wiring. Zone of protection may not include all connections/compartments in switchgear.	Recommendation for MV when other mitigation methods are not feasible. Often cost prohibitive at LV.
Maintenance Switch	Reduction	Reduces trip time by changing protective device settings.	Only works if used by staff. Causes temporary mis-coordination.	Recommended when a 24-7 mitigation solution is not feasible.
Remote Operation	Avoidance	Removes worker from arc flash boundary through remote control/indication/racking devices.	Reduces only personnel risk when properly coordinated with maintenance procedures. Additional control panels and equipment required.	Recommended for personnel protection when switchgear automation is used or when energized breaker racking is required.

TABLE II
SAMPLE ARC FLASH SOLUTION MATRIX

AF Mitigation Technology	Incremental Commissioning Complexity	Protection for Intentional Exposure	Protection for Incidental Exposure	Footprint	CAPEX	OPEX	Equipment Survivability	AFIE Reduction	Typical Application
Prevention									
Barriers	Low	Limited	Limited	No change	Low	Low	+	None	LV Switchgear/ Switchboard
ANSI Compartmentalization	Low	Limited	Limited	No change	Low	Low	+	None	LV Switchgear/ Switchboard
IEC Form 4b Compartmentalization	Low	Limited	Limited	No change	Low	Low	+	None	LV Switchgear/ Switchboard
High Resistance Grounding	High	Limited	Limited	Increased	Med	Low	+	SLG-fault only	480V – 5kV Systems
Shielding Barriers [5]	Low	Limited	Limited	No change	Low	Low		None	LV Arc Resistant Switchgear
Administrative Controls	NA	Limited	Limited	No change	Low	Low		None	All; Increased training requirement
Containment									
Arc Resistant	Low	No	Yes	Increased	High	Low		None	LV/MV Switchgear
Solid Dielectric Bus	Med	Yes	Yes	No change	Low	Low	+	None	MV Switchgear
Reduction									
Differential Protection	High	Yes	Yes	No change	High	Med	+	Significant ^{1}	LV/MV Switchgear
Zone Selective Interlocking	Med	Yes	Yes	No change	Low	Med	+	Significant ^{1}	LV Switchgear/Switchboard
Transfer Trip scheme (aka “virtual main”)	High	Yes	Yes	Increased	High	Med	+	Significant ^{2}	LV Switchgear fed from ~750kVA or larger transformer
High-speed Shorting Switch	Med	Yes	Yes	Increased	Med	Med	++	Significant ^{1}	MV Switchgear
Adaptive settings	Med	Limited	Limited	No change	Low	Med		Moderate ^{3}	MV Relays
Optical detection	High	Yes	Yes	No change	Med	Med	+	Significant ^{1}	MV Switchgear and specific LV applications
Maintenance Switch (Alternate Settings)	Med	Limited	No	No change	Low	Med		Moderate^3	LV Switchgear/switchboard, some MV applications
Avoidance									
Remote operating panels	Med	Limited	No	Additional Panel	High	Med		None	Complex
Remote operation (racking, umbilical cords)	Low	Limited	No	No change	Low	Med		None	All

Notes:
1. Typically less than 4 cal/cm2
2. Typically less than 8 cal/cm2
3. Typically less than 8 cal/cm2 – deliberate activation of alternate settings is required
+ Moderate impact
++ Significant impact