ARC-RESISTANT EQUIPMENT – A RISK CONTROL PERSPECTIVE

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Abstract – Arc-Resistant Equipment has gained popularity in North America since the late 90's. Arc-resistant equipment tested per the IEEE C37.20.7 protocol can provide an improved level of risk control associated with electrical hazards, specifically, arc flash. However, it does not eliminate the hazard, nor does it provide risk control under all circumstances. Like other capabilities of electrical equipment and risk control mechanisms, it provides value when properly applied, maintained, and used, but its value limited if otherwise. The capabilities and limitations of arc-resistant equipment could be considered from the perspective of the intended risk control. This paper will attempt to further such an understanding.

Index Terms — Arc Resistant, Arc Flash, Arcing Current, Risk Management, Risk Controls, Clearing Time, Crowbar.

I. INTRODUCTION

Many technologies are available to deal with arcing faults in switchgear. They may be considered active or passive and proactive or reactive. Arc-resistant (AR) equipment, qualified per the IEEE C37.20.7-2017, IEEE Guide for Testing Switchgear Rated Up to 52 kV, for Internal Arcing Faults [1], is a widely used risk control. Usually, AR gear is considered a passive control, however, it does rely on active protection to varying degrees. In some cases that reliance may be to a specific device, setting and performance, more commonly only to a protection operating time which may be achieve in several ways.

The scope of IEEE C37.20.7-2017 states the following: "*This guide establishes methods by which equipment may be tested for resistance to the effects of an internal arcing fault.* … *Designs that meet the requirements of this guide will be referred to as arc-resistant*".

The document defines test protocols and how tests may be deemed successful, or not. The guide does not prescribe how AR equipment is to be built or arc resistance is to be achieved. Only how the test to have a claim is carried out and its result scrutinized so the equipment may be qualified as arc resistant.

Equipment arc classified per IEEE C37.20.7 is typically additionally identified by the manufacturer as arc rated per this IEEE Guide, however there are also IEC standards, IEC 62271-200 [2] for medium voltage and TR 61641 [3] which applies to IEC 61439-2 [4] low voltage equipment, that also define similar testing, which in IEC terminology is identified as internal arc classified (IAC) ratings. Though the documents have many similarities, there are also some differences, which may in some applications be important. The description "arc proof" is not used or defined within IEEE, IEC, UL or NEMA standards, however, in the industry vernacular it has a different meaning intending to describe a portion or volume of equipment where an arc cannot initiate. Properly filled gas insulated switchgear (GIS) equipment might be an example of equipment that could be considered "arc proof".

In the 1970s, European standard writers became interested in assessing electrical equipment under internal arcing. This led to the IEC standard defining the requirements for ac metal-enclosed switchgear and control gear > 1 kV and ≤ 52 kV applicable to indoor and outdoor assemblies up to 60 Hz. The interest was exported to North America and used as a foundation for EEMAC-G14, Procedure for Testing the Resistance of Metal-Clad Switchgear Under Conditions of Arcing [5], now superseded by IEEE C37.20.7.

The 2017 version of the IEEE guide covers various types of IEEE standard defined equipment; C37.20.1 metal-enclosed low-voltage switchgear [6], C37.20.2 metal-clad (MC) medium-voltage switchgear [7], C37.20.3 metal-enclosed interrupter (MEI) switchgear [8], C37.20.9 metal-enclosed switchgear assemblies incorporating gas insulating systems (GIS) [9], C37.23 metal-enclosed bus [10], and C37.04 metal-enclosed high-voltage air-insulated circuit breakers (CB) for outdoor application [11]. It also covers UL standard defined equipment; UL 347 medium-voltage ac controllers [12]; UL 845 motor control centers [13]; and UL 891 switchboards [14].

II. IT IS ABOUT RISK CONTROL

The C37.20.7 guide includes Annex B which is an application guide intended to address typical considerations for the application and installation of equipment covered in the AR testing guide. The purpose of the annex is to assist the user in determining the appropriate installation conditions for the equipment. The Annex addresses factors important in determining installation conditions for the equipment including:

- Physical constraints of the site
- Coordination of the electrical protective scheme
- Base level of structural consistency for the building
- Installation site requirements on equipment ratings
- Where internal arcing faults are more likely to occur

The annex also states: "*It cannot be assumed that the presence of arc-resistant switchgear eliminates all conditions that may constitute a risk to the operator*." It also states: "*This guide (Annex B) does not cover all effects and conditions which may constitute a risk*." a risk control. In clause 1.2.2 it states: *"… does not ensure total protection under all circumstances that may exist at the time of an internal arc fault. Does not provide additional degree of protection to operating personnel who in the normal performance of their duties later equipment condition. Does not ensure total protection to persons in the general vicinity of the equipment in the event of an internal arc fault."* More specifically in clause 1.2.3 it states*: "The guide does not cover all effects that may constitute a risk to personnel such as the release of toxic material and excessive sound pressure."*

It is important that the user of AR equipment understand how the AR rating may impact electrical hazard risk control during the expected operation and maintenance of the equipment. One way to consider it is as PPE (personal protective equipment) protecting personnel that is worn by the equipment, not the personnel. Like PPE an AR rating must be properly selected and properly worn. Like PPE it has limitations on what it can accomplish. When PPE is properly selected, worn, maintained, and used within its capabilities, it is very effective. Similarly, the AR properties of equipment are dependent on proper maintenance, proper operating procedures, proper installation considerations, as well as proper engineering considerations for the power distribution system.

A. How Does AR/IAC Testing Correspond to Personnel Injury?

Both IEC and IEEE standards evaluate the equipment using ignition of cloth indicators at a specified distance as a sign of excessive energy release from the enclosure. While AR equipment (and to some degree non-AR equipment) mitigate other effects, these are not specifically evaluated:

- Cal/cm^2 burns severity vs. indicator ignition
- Peak pressure to audio dB vs. AR or non-AR risk impact
- Ejected components < 60 g a risk
- Toxic smoke a risk.

B. Containing an Electrical Explosion

Electrical equipment is designed to withstand the mechanical forces between conductors, and conductors and structure, which may occur when a short circuit (a.k.a., bolted fault) occurs on the load side of the of the equipment. What is normally referred to as a “through fault” because it flows through the equipment. In switchgear defined by the relevant IEEE C37 documents, there are tests that ensure the capability of the equipment to withstand test currents for 30 cycles or more. Equipment such as UL 891 listed switchboards may only be tested to withstand a through-fault current for only the time that feeder circuit breakers or fuses may be expected to need to interrupt such a fault, typically 3 cycles though longer is allowed by standard. All equipment standards include test protocols to ensure the fault current can be successfully interrupted by the overcurrent devices expected to be mounted in the equipment. No equipment standard stipulates how the equipment is to withstand or survive a fault within the equipment structure itself.

The internal electrical explosions that all equipment must withstand successfully are those that occur within interrupting devices such as circuit breakers. These are not trivial events; however, they involve less released thermal energy than a 3-phase arc between conductors that are 10s of millimeters apart and last 6 or more cycles. The impact of an internal arcing fault is only tested per IEEE C37.20.7, or the applicable IEC documents for IEC equipment. The impact of an arcing fault within non-AR equipment is unpredictable and may present significant risk to nearby workers due to arc flash related heat as well as ejected debris and other hazards.

The test protocols in the IEEE guide prove the ability to keep arc energy away from personnel immediately around the equipment. However, this may require the energy be exhausted in a controlled manner by, usually, exhausting energy via a plenum outside the switchgear outdoors, or out the top or rear of the gear, or more rarely, fully contain the energy within the gear. This is the risk control the AR qualification provides; the ability to contain the explosion within the equipment if the explosion happens, for a defined number of cycles or milliseconds, or less, at a specific voltage, or less, for a specific available fault current, or less. Parameters normally associated with arc flash calculations per IEEE 1584, Guide for Arc Flash Calculations [15] such as arcing current (I_a), or the arcing gap (G), or the electrode orientation are not identified for the IEEE C37.20.7 test protocol. There is no quantification of incident energy (E_i), as defined in IEEE 1584. The IEEE C37.20.7 guide has preferred values for the available prospective short circuit current (I_{bf}), the voltage (V_{oc}), and the time the test current must last, or be available, however, the actual values are up to the manufacturer.

The risk being controlled, to personnel, is the risk of the impact of the electrical explosion exiting the enclosure if the driving voltage, available fault current and the time the arc lasts is equal or less than the AR qualification identifies, and the equipment is installed and operating at the same conditions it was tested. This means all required panels and doors are closed, the equipment grounded, and the equipment is in good condition. If any of these parameters are not followed, the AR performance may be compromised. Similarly, if the thermal rating of PPE is exceeded by the received E_i the PPE may not provide adequate protection.

Since the explosion is internal to the gear there should be, in a successful test, no impact outside the enclosure that could be described in arc flash terms. The application of AR equipment has no impact on arc-flash risk analysis from the perspective of determining the potential value of E_i. It may, however, have an impact on whether certain tasks performed around the exterior of the equipment require, or do not require, arc-flash PPE. However, the equipment should not impact the rating of PPE worn, if PPE is deemed necessary by the site safety policy established by appropriate authority for the considered task.

Equipment standards which include testing, strive to test the performance of the equipment versus the future worst case needs of the intended application. It is usually impractical to test every possible permutation of the equipment and usage conditions. Hence, the testing is designed to test worst-case conditions and stress the equipment as much, or more than actual expected events or use. For electrical equipment that means testing at equal or higher voltage than it is applied at, at equal or higher fault current than may be expected in the application and for equal or longer time than may be expected during an event. It is important than when equipment is in service it is within the maximums that were used in the testing.

C. What Kind of Risk Control?

Risk controls may be classified as fitting within a six-level hierarchy as defined in NFPA 70E [16], Annex F. The levels, from most effective to least effective are:

1. Elimination
2. Substitution
3. Engineering Control
4. Warnings
5. Administrative Controls
6. Personal Protective Equipment (PPE)

Is AR equipment a “Substitution” or an “Engineered Control”? It may seem a substitution because it substitutes non-AR equipment with AR equipment. However, it does not replace one lesser hazard in lieu of a greater hazard, as the hazard is the energy, and the energy is still there. The AR rating is simply additional performance that requires maintenance and operational considerations as do most engineering controls. The performance is dependent on.

- Proper application of the equipment within its AR rating,
- Proper operating procedures that keep panels and doors closed and always appropriately secured,
- Protective devices with the required sensitivity and speed for the I_a range that may be expected,
- Proper maintenance of the equipment and all devices,
- No equipment interaction disallowed by the AR rating.

Based on these dependencies it is appropriate to consider AR equipment an "engineered control" and when compared to other potential risk-control investments it may be appropriate to consider it as similar to those, with respect to the hierarchy of risk controls, because of the need for maintenance, correct application and specific operating procedures. Proper operation in the context of such maintenance is like automation or protection performance relied upon for risk control needs to be considered, both of which are classified as engineered solutions.

A way to look at overall risk control for a facility over time is to look at the total exposure in some measurable way such as manhours, evaluate events probability during the exposure in a way that it can be ranked and to also consider the potential severity terms of measurable potential injury, and one may consider economic impact as well. See "Assessing Solutions to Electrical Hazards" [17] for a discussion of such a methodology. AR equipment may impact the hours of exposure for personnel but does not necessarily lower the probability off an event or the potential severity of the event should it occur during certain tasks and does not lower the impact of the event on the need for repair or replacement of the equipment.

III. ASSESSMENT, APPLICATION PERSPECTIVE

AR equipment is an effective risk control; however, it may not be optimal for all situations and requires understanding its merits and drawbacks as well as alternatives to select and apply optimally. A potential buyer or specifier following a prevention through design (PtD) philosophy [www.cdc.gov/niosh/topics/ptd/default.html] may consider some questions before deciding to invest in AR equipment, such as:

- Will having AR classification impact whether PPE is worn by personnel for planned tasks near this equipment?
  - What tasks are impacted, can tasks be done differently or prevented so that risk is equally or better controlled?
  - What is potential injury being prevented? Is residual risk too much or can other risk controls address it.
  - Does AR classification benefit all planned tasks?
- What are operating and maintenance procedures needed to ensure the AR performance remains valid and reliable?
  - Can they be reliably implemented?
  - Do they impose additional complexity or risk?
- How will the electrical room differ and does using AR equipment impact location for the AR gear, or other gear?
- Does AR equipment incur more cost or consequences?
- Are overcurrent protective devices (OCPD) fast enough for AR classification?
  - Can OCPD be set as needed without selectivity loss?
  - Will maintenance be able to keep them reliable?
  - Are all portions of the equipment suitably protected?
- Is the power system like the one used to test the gear?
- Is AR gear worth it? Can other controls be more effective?

A. AR Classification as One of Several Risk Controls

Remote racking, powerful electronic devices for control, metering or diagnostic that are remote mounted, permanent thermal monitoring or infrared windows are mutually exclusive with an AR gear classification. All can be implemented simultaneously. However, when resources are limited and tradeoffs evaluated the value of each with respect to risk control, installed or operational cost and plant reliability may need to be considered.

The function of the AR classification is to contain the impact of the internal arc within the equipment and hence mitigate the risk of injury to personnel as if personnel were wearing equivalent PPE. It may be valuable to consider what that the activity is, how much of it may transpire, how much risk is controlled, and can other investment create better results?

Activity near equipment may include:

1. Operation of control switches to open or close circuit breakers, switches, parallel, or turn generation on or off.
2. Operation of controls for diagnostic or metering functions.
3. Verification of absence of voltage.
4. Performing infrared surveys or similar
5. Maintenance measurements or maintenance activity.
6. Racking circuit breakers, or moving starter units, out or in.

A question may be; can risk associated with these activities be controlled or minimized in some other manner with better results, lower cost or other additional benefits? The following text offers some thoughts on this.

1) Remote Control, Metering, and Monitoring Panels

In equipment with traditional analog meters, it was common to implement phase switches and other mechanical switching devices to connect expensive meters in various ways to obtain a broad range of metering functions from one meter. However, in modern equipment a broad range of parameters can be measured and monitored from a limited number of sensors connected to digital metering displayed on instrument screens or computer screens that can be located remote from the equipment. Such systems, if remotely located, are both outside the arc flash boundary and provide expanded metering and diagnostics without the need to approach the equipment. If modern digital metering is located on the equipment and within the arc flash boundary a potential risk control has ignored.

In modern equipment it is not complex or particularly expensive to locate most if not all equipment controls in remote dedicated panels that do not need high energy buses within the panels. Control wiring, often in the form of a limited number of low voltage conductors for serial communications and a limited number of small gauge signal wires, can provide all the needed communications and information for all needed controls and metering outside of the arc flash boundary surrounding high energy equipment. Operating controls in a remote panel would usually have limited need, if any, for PPE by operating personnel.

2) Diagnostics and Troubleshooting

Diagnostics, troubleshooting or measurements of devices or wiring within panels may be needed during the life of equipment. However, is an equipment arc-resistant classification valuable in providing risk control during such activity? If the activity requires opening of panels or doors in the equipment the AR classification may no longer be applicable. The IEEE C37.20.7 Guide allows a 2B supplemental classification when the equipment has compartments intended to enclose low voltage or low energy circuits which are tested with their doors open while an arcing fault is caused within proximate closed equipment. This is intended to prove that a worker in front of that open compartment is protected from an arc in an adjacent compartment within the equipment lineup. Relays, meters, and instrumentation may be housed in such a compartment. High energy conductors capable of significant AF energy are not located within those compartments. Normal equipment can also include similar compartments that, though not arc resistant, can only include devices operating at 120V or below with only a few limited gauge conductors carrying higher voltage that are protected from accidental contact. This would minimize the possibility of accidental contact creating an arc flash event within the compartment though it would not preclude arc flash risk should an arcing fault occur in a proximate compartment. Proper engineering design should also limit the possibility of shock whether in AR equipment or not.

There is no equivalent to IEEE AR type 2B within the IEC IAC system; all doors, even on low voltage compartments must be closed for the IAC rating to apply. However, to minimize the possibility of arcs initiating, IEC equipment includes partition class “PM” in which earthed metal barriers surround de-energized high-voltage compartments so that if opened, the electric fields in the adjacent energized compartments cannot be disturbed, nor can energized conductors be inadvertently contacted. In low-voltage equipment arcs are assumed to start when there is contact, but in higher voltages electric fields may be strong enough that if sufficiently disturbed the dielectric properties of air around energized conductors may be compromised and an arc can initiate over air. This is intended to reduce the probability (ostensibly to zero) of an arc flash in the still energized adjacent higher-voltage compartment, although the consequences are considered unmitigated as the intervening metallic barrier is not intended to withstand the energy released should an arc occur. Using modern communicating devices with data processing capabilities can minimize the number of devices used such as sensing devices, meters, relays, control components, etc. Digital communicating devices can simplify wiring and minimize potential failure points and provide watchdog functionality, monitoring functionality and other functions that enhance the ability to troubleshoot and diagnose problems remotely. Even activity such as IR scans used to monitor for high impedance connections, loss of connection integrity or contact deterioration can be replaced, supplanted or aided with permanently mounted thermal sensors, IR windows, intelligent algorithms and other mechanisms that monitor or calculate for the above listed potential failure points minimizing the need for manual thermal monitoring of energized equipment through open doors, which if opened, would violate the AR classification of the equipment.

3) Verification of Absence of Voltage

Verification of absence of voltage can be accomplished using permanently installed instrumentation that can detect for absence of voltage in a manner consistent with safety standards such as NFPA 70E and CSA Z462 [18]. Specifically designed devices listed per UL 1436 [19] are available for the purpose.

4) Temperature Monitoring: Infrared Surveys

Temperature monitoring of electrical equipment, particularly connections between conductors and equipment as well as within equipment and within devices is one of the most common maintenance activities. Generally, equipment must be energized and loaded which means fully operational. This means when the activity is manually accomplished it is done at the time of highest exposure to the worker and highest risk to the process should an incident cause and uncontrolled shutdown. Even in the case where the best protection is implemented and works as intended, regardless the fact that injury to a worker may have been averted, injury to the process was not.

However, methods exist to provide continuous temperature monitoring that can be combined with other operational information. Continuous thermal monitoring can minimize the need for manual temperature monitoring, provide better temperature information, minimizes risk to the process and achieve lower costs of ownership as well as reduce risk to personnel. Such methods are entirely consistent with the use of AR gear as they are fully operational with all equipment doors closed, but do not require the use of AR equipment either.

5) Maintenance Activity

Preventive electrical equipment maintenance consists, in many cases, of implementing, periodically, various measurements such as circuit breaker response to excessive current, mechanism timing, dielectric testing to verify integrity of insulating materials and similar. Implementing condition-based maintenance that relies on tracking device activity, measurements of key parameters such as CB speed during controlled operations, partial discharge, operating temperature, and other parameters can provide information that may be used to transition from calendar-based maintenance to a more condition-based maintenance. This can reduce the need to shut down equipment and implement manual control and maintenance activities that may reduce exposure to electrical risks as well as reduce the need for system shutdowns and other expensive activities. Condition based maintenance requires careful planning and implementation of the right measurement devices and systems but can provide a return in both risk controls and operational efficiency.

6) Circuit Breaker Racking

Racking a circuit breaker to or from a connected position is considered a high-risk activity. It involves mechanical movement of energized (line side) components. The risk is particularly acute during the racking operations which follow maintenance. If AR equipment is selected to mitigate this risk, it may be beneficial if equipment is capable of closed-door racking.

The C37 guide, clause 5.4.2 requires testing with the circuit breaker in an intermediate position (at the point of contact with the primary circuit) and with the door removed. This requirement is not in IEC 62271-200, but 6.102.2 requires that doors to HV compartments not be able to be opened unless the CB is in the disconnected position with shutters closed. Consequently. within IEC, closed door racking is mandatory in MV equipment.

An alternative to AR equipment that can mitigate this risk is remote racking for most modern circuit breakers. Since such racking is “mechanized” implementing controlled torque control or protection against excessive force, or misalignment, it may be that it is also more reliable than to do it manually. The remote capability may provide similar risk control, or better, than AR equipment, even with closed door racking capability, as well as improving procedure reliability, adding risk control for other injury modes that AR does not target. It certainly can complement AR equipment as well. Some AR switchgear may not allow closed door racking and hence remote racking may be needed regardless, see Table II for a visual demonstration on how risk controls for CB racking compare.

TABLE II: RISK CONTROL IN CB RACKING

Risk controls for CB racking	Compartment open	Compartment Closed
Operator in front of compartment (near)	PPE required	Engineered Controls
Operator at distance from compartment (remote racking)	Administrative Procedure	Engineered Controls & Administrative Procedure

Less risk

More control

B. Procedures to Keep AR Equipment AR

When potentially energized circuits are approached it is standard practice per standards such as NFPA 70E, to implement administrative controls (procedures) to ensure conductors are de-energized and remain so during the task, such as using visible disconnection assurance, lockout-tagout and grounding of buses or sources as well. When an AR classification is part of the risk control that determines whether other risk control is used it may be wise to also determine if the AR classification can be relied upon. For example, by assuring, prior to the exposure, if:

- All doors and panels are securely latched, handles in the correct position and bolts all in place and properly secured. Handle position may be easy to verify, bolt torque may not. See NFPA 70, Table 12.3.1-10 and Annex 12.3.1.
- All vents have closing flaps in place and ready to operate for sudden pressure inside. (i. e. spring mechanisms verifiable without creating risk?).
- That the procedure being planned is doable while maintain the AR classification (e.g., not all AR gear allows CBs to be racked with compartment doors closed).
- If the procedure requires access to LV components and are those components in 2B rated compartments?
- Is the protection the AR classification requires to operate in good maintenance condition? Is it set properly?
- If power system changes invalidate the AR classification? (Closed tie, extra generator, Automatic reclosing?)
- Required venting out of the room, is room egress impaired, is the venting or egress area clear, is PPE proper for the residual risk caused by that venting?

The fundamental question being, do tasks that rely on the AR classification include risk control steps to manage all possible risks including ensuring that the AR gear is truly AR at the time the task is executed, in the manner it is intended to be executed?

NFPA 70E requires arc-flash studies be revisited every five years or when changes impacting in the power distribution system are made to ensure they are still valid. Similarly, the AR rating should be evaluated to ensure it remains valid if power system changes occurred or adequate maintenance is lacking.

C. AR Equipment Installation Considerations

AR equipment requires specific installation considerations. Internal arcing fault byproducts are rarely fully contained within the equipment and usually need to exit the equipment. A common method is via top or rear mounted flues that exit the room and exhaust the gases and effluent outdoors. The required provision will vary based on product, manufacturer, and other considerations, however, in all cases, the manufacturer will provide specific requirements that must be followed. The flue connection may provide a direct connection from the equipment to the outside and could impact humidity and temperature in the equipment. The exhaust point of this venting should not create a hazard for personnel or other equipment and must be properly located and protected. The flue may require flaps or similar features to prevent fire from entering the building.

In some applications, energy may be routed under the equipment. When that is intended it is important that the volume that will receive and channel the gases does not contain any materials not allowed to be located within that volume. Care should be exercised that that pressure does not impact floor structures if downward venting is possible. If rails or similar are required, the equipment will have been tested with the recommended rails and manufacturer installation instruction must be followed. If equipment is located above an opening and it is not expected to route gas out the bottom an appropriate floor must be provided per manufacturer instructions.

If the equipment vents out the top into the immediate space the vents which are usually a pressure operated flap which must not be blocked, nor should materials not specifically approved be installed close to the vent opening where they can impact vent flow or be damaged by the high temperature gases. Adjacent equipment can be impacted by the pressure, heat. and fumes.

Where the equipment vents out the top or rear into the room where personnel may be located, egress should be available, though the best egress may not be enough to provide adequate risk control from the impact of smoke, noise and falling debris, etc. Though equipment may be AR classified and tasks may not require PPE, it may be advisable for personnel not needed for the task to not be in the room potentially impacted by and arc-flash event if they do not need to run that risk. The following considerations are important for installation of equipment that vents into the room from the top of the gear:

- A minimum clear distance above the equipment as recommended by the manufacturer. This space should have no obstructions. The space helps to avoid the reflection of hot gases into the area specified in the accessibility type rating.
- A minimum distance from the equipment to nearby walls is usually recommended. This may avoid reflecting and channeling hot gases to where personnel may be.
- Wireways, lighting, conduit, piping, and duct work in the path of the pressure relief vent, even if installed beyond the distance specified by the equipment manufacturer, may be exposed to the pressure wave and high temperature of the hot gases. Such items should be evaluated for the impact of the effluent and if possible, located elsewhere.
- Components near the overpressure vents should be evaluated to verify that they will not be damaged by an escaping pressure wave and not fall into the equipment or an exposed aisle.
- Elevated walkways, platforms, and movable equipment could locate personnel where equipment pressure-relief vents and may create a hidden risk for workers.

The installation may require some important steps not associated with installation of standard equipment. Installation instructions may require

- Sealing the gap between the equipment structure and cement floor using an approved grout.
- Ensuring that movable flap covers are properly installed, not blocked, and able to move when needed.
- Ensuring that baffles and ducts to direct the flow of exhaust gases are installed as required.
- Ensuring fittings or cable penetrations are rated for pressure as specified by the switchgear manufacturer.
- Ensuring areas required above and around the switchgear to allow proper venting during an internal arcing are clear.
- Ensuring the room size is equal to or greater than needed to withstand the potential pressure of an arcing event.
- All the extra structures, considerations, and requirements unique to an AR equipment installation may also become additional maintenance considerations during the life of the equipment. Spaces ensure to be clear at the time of installation must remain so, grout installed to seal a gap must remain in good condition, etc. This adds to maintenance complexity.

D. Protective Devices, Time, Type, and Location

An important AR classification parameter is time. The equipment has been tested for a determined length of time to contain the arc inside the enclosure. The larger an enclosure the easier it is to withstand the pressure spike of an internal arc. The amount of time available in the market varies by type of equipment and manufacturer. Generally smaller low voltage (LV) equipment such as LV motor control centers (MCC) will have shorter ratings, possibly 6 cycles (minimum preferred rating in IEEE C37.20.7) or less. LV switchgear is typically rated for 30 cycles and medium voltage (MV) switchgear may offer a second or more. Several preferred ratings are suggested in the guide; however, different longer, or shorter ratings may be available.

The time of interest is the clearing or interruption time the device will need to clear the arcing fault at the expected range (minimum to maximum) I_a. It is important that the rating implemented allow enough time for device to operate as desired within the system as the system may need for reliable operation, i.e., selectively. For example, an MCC may be obtained with a 3 or 6 cycle AR rating, however, if the feeder to that MCC must clear in more than 12 cycles to maintain selectivity with motor protection in the MCC, then the AR classification is not sufficient and should extend to 12 cycles, or more. Alternatively, the user must accept a non-selective MCC which may be undesirable.

It is good engineering practice to perform a short circuit study and coordination study during system design. An arc flash analysis is also good practice to ensure that incident energy levels are acceptable without sacrificing desired system reliability. Similarly, if AR equipment is to be selected the coordination study serves to evaluate that protection is sufficient to support the AR equipment selection and the arc flash study may determine the need for the AR equipment selection and where it may be more valuable. These steps could be considered part of a PtD system design philosophy.

1) Device Limited AR Classifications

The rated arc duration is the time equipment can successfully experience an internal arcing fault. However, both IEEE and IEC standards for low-voltage equipment also allow AR classifications based on protection by a specific protective device expected to act very quickly such as fuses or arc quenching devices (AQD). AQD are outside of scope for MV IEC switchgear but are discussed at length in Cigré technical brochure 686 *Mitigating the Effects of Arcs in M.V. Switchgear* [20]. UL has also published ANSI/UL 2748 *Standard for Arcing Fault Quenching Equipment* and ANSI/UL 2748A *Arcing Fault Interrupting Devices* [21]. Within IEEE, where device-limited classifications apply the protective device must be identified on the equipment nameplate, not the time the arc is allowed to last. The maximum prospective fault current the equipment was tested and the maximum fault current that can flow without the device operating in its current limiting range must be verified via test. As the 2017 IEEE guide is written, there is no explicit mention of fast protection provided by other than current limiting fuses or circuit breakers. The marking requirements reflect the operating mechanics of current limiting overcurrent devices. However, there is no specific exclusion of other types of devices such as AQD. These devices may be called crowbars colloquially but are properly referred to as arc quenching devices. Generally, they are deployed using light detection as the primary arcing detection mechanism, but may use current for confirmation, or other methods such as pressure sensing, voltage-based logic, or a combination of any of these. The detection and control time may range from a 1/8th of a cycle to over half a cycle depending on device and exact implementation. An arc is usually extinguished under one cycle, potentially faster than a current limiting fuse within its current limiting range. The AQD device may provide a low, close to zero, impedance path between phases or phases to ground, or it may provide a path with impedance low enough to collapse voltage to not allow it to sustain an arc in open air, but not so low as to approximate a bolted fault. AQD may have user adjustable thresholds that impact sensitivity and operating speed. When the device operates the arc may collapse quickly, however the new current path will conduct current till an upstream overcurrent or switching device opens to isolate the circuit. In some cases. the protection may be sufficiently sensitive and fast that damage to equipment at the point of the fault is negligible.

Figure 1 shows where a 480 V arc was initiated while protected by an AQD. In this case an AQD connected on the line side of a substation transformer, between the transformer terminals and the fuses protecting the transformer. The AQD collapses voltage while the MV fuses limit AQD current below the prospective first half cycle peak. [22]

Figure 1 Point of Fault Initiation during AQD Testing

All AR equipment will be dependent on protective devices. For time-limited ratings the exact device is not important, but its clearing time is. For device limited classification the dependency is device specific and must be suitably identified in the equipment labels. Regardless how an AR classification is achieved, proper protective device application, settings and maintenance is critical. Maintenance requirements needed to ascertain the protection should be part of the evaluation for selection of AR equipment. In the case of device limited dependent ratings the dependency on proper maintenance and application may be particularly important.

2) Protective Device Location, Equipment Layout and Task

AR Equipment generally receives one AR classification for the entire equipment. However, different parts of the equipment are protected by different overcurrent devices. Figure 2 shows a typical layout for a low voltage double ended substation. In the drawing several volumes, A through G are identified.

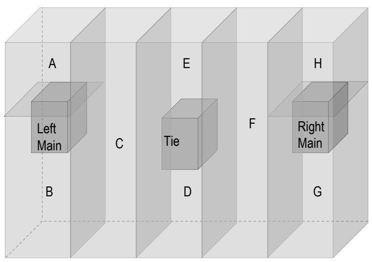

Figure 2 volumes within AR equipment with potentially different risk valuations

Though one AR classification may be applied to all the sections in this equipment different protective devices may be involved in protecting, depending on where an arcing fault may occur. If volumes A and H are assumed to be the incoming power compartments the important protection is not in this equipment and may be located on the other side of a transformer at a higher voltage. Unless that protection was specifically designed to provide sufficiently fast and sensitive protection to operate with the AR classification requirements it is possible, if not probable, that the AR classification does not apply to those compartments.

Furthermore, each volume may present a different risk due to potential arcing fault behavior or probability. The tie (often open) section has two volumes, each protected by a different OCPD. Arcs move away from sources, hence arcing faults on the main horizontal bus or vertical bus in the tie section can move towards the tie and potentially compromise dielectric separation on the other side of the tie. This can lead to two faults within one vertical section which is not a tested fault scenario in the IEEE C37.20.7 protocol. A layout for similar equipment with dual ties and mains in separate dedicated sections ensures that each lineup represents one level of arc flash E_i and that the mains or ties fully provide the requisite protection for the feeder sections. The dual ties can be used to fully isolate the feeder sections when open to deenergize the sections or isolate them from the second source and ensure that an arcing fault cannot cross an open tie. Risk analysis for a task may be valuable to identify if the worker's exposure is not sufficiently mitigated by the AR classification because of which protective device is relied upon. PPE may still be needed as if the equipment did not have an AR classification at all if an AR classification is insufficient.

E. Matching Power Distribution System Characteristics

1) Grounding

A major difference between IEC and IEEE tests for AR ratings is how the neutral of the generator is connected. In the IEEE test protocol, the power source neutral and equipment frame are grounded, in the IEC test protocol the power source neutral is isolated, or impedance grounded such that the neutral current may not exceed 100A. Neither standard permits equipment to be tested using the other standards method.

It is important to consider how the power system, where the AR equipment is used, is grounded. The IEEE working group considered available test data and determined that a solidly grounded system is "worst case" (Figure 3). For additional discussion of this see "IEEE C37.20.7 Guide for Testing Switchgear rated up to 52kV for Internal Arcing Faults – Important Changes to the New Editions by M. Wactor [23], section V. A.

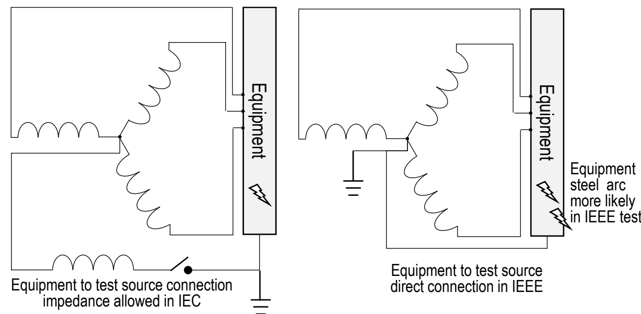

Figure 3 IEC and IEEE power connections for AR testing

Using IEC AR gear that has been tested on a source without its neutral connected to the equipment steel may not be appropriate if the system is solidly grounded, an arc to the enclosure steel, even for a single-phase fault could breach the exterior steel and present a considerable hazard to nearby personnel without sufficient PPE. However, if the IEC equipment is rated for earthed arcing faults (I_{Ae}) then this condition has been explicitly tested, which is outside of the testing within IEEE C37.20.7.

2) System Topology

Larger power systems may operate under different topologies. Arc flash studies should evaluate all the various topologies to provide E_i values under varying system conditions in the Arc Flash report. Configurations that may result in high energy values may be rare and a risk evaluation may determine that maintenance or diagnostic tasks that expose personnel to energized conductors during the times that the high energy topology is active are not to be carried out. Similarly, it may be determined that during these times the AR classification is also not viable. Hence operations or tasks that rely on that rating should also not be carried out when the topology is such that too much energy is available at the equipment. Topology variations that should be considered in an arc flash study and an AR equipment classification include:

- Closed and open ties within equipment that may link multiple sources not normally linked.
- Automatic-throw-over schemes and transfer switches that can repower a faulted bus after a first OCPD operates.
- Emergency or standby sources in parallel, or islanded
- Motor contribution form motor banks. Such contribution may not flow through the principal OCPD and not cleared quickly.
- Changes in the utility grid or circuits that vary available fault current. Either too low or two high a current could impact protection negatively.

F. One risk Control Among Others, Which is Best?

The hierarchy of risk control provides a mechanism with which to rank and stack risk controls. The hierarchy is described as prioritizing controls in terms of effectiveness. However, it could also be considered as prioritizing them in terms of propensity of failure due to human error and complexity. Elimination and substitution are usually single decisions early in the system or application design process, easily verified and not easily changeable. Engineered systems will require proper maintenance, repair, upkeep, and engineered systems must be applied correctly as they are not equally useful in all situations. They require regular maintence over time, as well as occaisional unscheduled repair. However, their protective functions are usually automatic and mostly independent of behavior by the protected. Elimination, substitution, and engineered systems are higher-order controls. Training, administrative procedures and PPE are lower-order controls because they depend on the behavior of those exposed to the risk, i. e. the protected. The effectiveness of training depends on understanding by trainee as well as trainer as well as timing of the training. The content of the training must match the need and those trained must absorb and remember the training when it is needed. Administrative procedures must be followed to have an effect correct for the need. Taking shortcuts and misunderstanding procedures can weaken their effect. PPE is considered the last line of protection as it may not be absolute protection and is also dependent on correct human behavior. PPE must be worn, even if uncomfortable, it must be maintained and must be appropriate for the risk and application.

The effectiveness of a risk control and where it is categorized on the hierarchy of risk controls may not be the only criteria. Cost, complexity, and practicality may also influence which risk controls are used. A paper by L. Floyd and M. Valdes discuss implementation of “Prevention through Design philosophy in in electrical systems design” [24]. The main point of that paper is that implementation of PtD design philosophy may iteratively design in risk controls till the residual risk that remains is acceptable within the context of lower order controls that can be expected to be reasonably implemented by the workforce that will operate and maintain the system, and the resource constraints that may impact decision making. The paper “Assessing Solutions to Electrical Hazards” [#] also describes an FMEA (Failure Modes and Effects Analysis) based process that may be used to rack and stack investments in safety to select those that are most impactful on a specific system.

AR classified equipment is neither mutually exclusive with other controls nor does it necessarily eliminate the need for other controls. Some, but not all, tasks may benefit from the AR characteristics of the equipment and in many cases, it may provide some benefits but not all that are needed in facility. When designing protection that minimizes the fault energy that equipment may be subjected to, that same protection may minimize the E_i a worker may be exposed to in the system where the AR classification does not provide protection. It is important to realize that AR classification provides a benefit at the equipment that carries the rating, but not at the circuits or loads that the equipment may feed outside of the equipment enclosure, however the protection within the equipment is important for those circuits and loads. Figure 4 shows the value of fast protection in terms of E_i mitigation for some voltages and situations, using the model for horizontal electrodes which directly target the worker, in a close box, which concentrate the arc energy and normally represents the worst-case incident energy values for electrode exposure. In the example 50 ms (3 60 Hz cycles) can keep incident energy below 8 calories up to 45 kA available at 480 V and 150 ms protection (9 cycles at 60 Hz) can keep E_i below 25 cal in 4.16 kV and 12.47 kV systems.

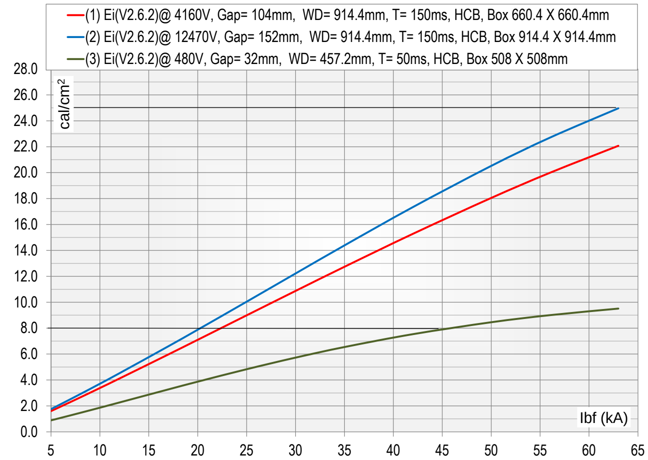

Figure 4 Arc Flash incident energy (Ei) at various typical calculation parameters

Modern protective equipment can provide fast and sensitive protection. In LV applications, often reducing E_i enough to allow for category 2 PPE (NFPA 70E-2023, *TABLE 130.5(G) Selection of Arc-Rated Clothing and Other PPE When the Incident Energy Analysis Method Is Used*). In medium voltage applications it may be more difficult to get PPE to that low a level, however category 3 PPE is reasonably achievable with a well-designed protection system. See Figure 4 for reference.

An arc flash analysis may determine that the E_i at the incoming compartments is too high for an acceptable level of PPE to be relied upon hence AR classified gear may become a more attractive option. However, high energy is often caused by slow and, or insensitive protection. Is that protection even fast enough to operate within the requirements of available AR ratings at a line side compartment? If not, the problem may be the protective scheme, not the lack of AR equipment. This is not an uncommon issue when a remote OCPD, fuse or circuit breaker, operating at a higher voltage is that protection. Transformer line side protection is often relatively insensitive to secondary voltage arcing fault currents and may result in a protection time that exceeds the AR classification requirements for the equipment. A CB implementing a protective scheme specifically designed to offer good AF energy mitigation at the secondary terminals of a transformer can address the problem, but it usually requires special attention by system designers to achieve. See the following references for discussions on transformer secondary protection [25, 26, 27].

Similarly in a vertical section with a tie device as shown in Fig. 2, compartments E and D, there is a possibility that an arcing fault can transmit from one side of the tie to the other setting up a fault scenario not tested as part of the AR classification. An IEEE 2C classification which indicates the gear has been tested to ensure that an arcing event cannot propagate across compartments may control this risk. 2C supplemental classifications are not common in the industry.

G. How Close is Close Enough?

IEC 62271-200 for MV equipment, provides for various internal arc classified equipment designations: Type of accessibility: A (restricted to authorized personnel only), B (unrestricted accessibility, including that of the general public). Varying sides of the enclosure are rated with front being the minimum requirement but sides and rear being optional. As well as the level of fault current, time and whether the fault is single phase or three phase. The access dimension does not exist in the equivalent LV requirements. For LV IEC In IEEE access type is not an identified parameter.

The testing requirements for IEC MV equipment then are different based on access type. With restricted using a heavier cloth, 150g/m^2 located further away from the structure, 300 mm. unrestricted uses 40 g/m^2 at 100 mm. IEC LV requirements are 150g/m^2 at 300mm. The IEEE guide seems to split this difference using 150g/m^2 at 100 mm.

In all cases the distance between the light cotton burn-indicators and the equipment steel is significantly less than the 15" to 18" that is usually the minimum working distance used in arc flash calculations. Hands, could, however be located closer than the distance used for AF calculations or the 100 mm AR test indicator distance. This may make the case that even if it is acceptable to operate equipment controls without a significant level of PPE, good hand protection may be advisable.

IV. SUMMARY

AR gear should be understood as one of several possible risk control, with its merits and weaknesses. The IEC standard for MV Equipment includes language clarifying this point. Some illustrative text is included below:

> *"9.103.1 If the assembly is installed, operated and maintained in accordance with the manufacturer's instructions reference, there should be little probability that an internal arc occurs, but it may not be completely disregarded. Failure within the enclosure of an assembly due either to a defect or an exceptional service condition or maloperation may initiate an internal arc, which constitutes a hazard, if* persons are present.
> *When selecting an assembly, the possibility of the occurrence of internal arc faults should be properly addressed, with the aim of providing an acceptable protection level for operators and, where applicable, for the general public.*
> *This protection is achieved by reducing the risk to a tolerable level. According to ISO/IEC Guide 51:2014 [13], risk is the combination of the probability of occurrence of a harm and the severity of the harm."*

And;

> *"9.103.3 The first protective measure if the risk of an internal arc fault is not negligible is to specify IAC classified assemblies. Other measures may be adopted to provide protection to persons in case of an internal arc. These measures are aimed to limit the external consequences of such an event."*

The standard includes tables and other text identifying potential causes of Arc Flash incidents and alternative risk mitigation methods than could be considered. Though the document states that IAC Equipment may be a first consideration, it should not be the only consideration for Arc Flash risk control.

Within the IEEE Guide Annex B provides detailed information on how to install and apply AR equipment though it does not discuss it as risk control relative to others. Nevertheless it is such and the decision to select it versus alternative investments should be so considered.

V. CONCLUSIONS

AR equipment is a recognized and accepted way to control arc flash risk to personnel. Whether relying on passive or active protection to achieve the AR classification both have advantages and disadvantages. AR equipment provides excellent risk control under some usage situations but may not provide sufficient risk control under others. Like many risk controls, it is neither perfect nor suitable in all situations and for all tasks.

However, if the benefit of AR equipment for a specific application is evaluated using a risk assessment perspective methodology cognizant of where the equipment is to be installed, how it is to be operated and maintained it may be possible to evaluate it adequately. The investment planned to be allocated to the AR capability may be better invested in risk controls that are more effective for the application, or such other investments may serve to compliment the AR equipment. The key is to understand the exposure to risk to be controlled and where the AR capability is of value to control potential risk,

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VII. VITAE

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