ENHANCING WORKER AND EQUIPMENT PROTECTION THROUGH PASSIVE ARC-FAULT MITIGATION

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Abstract – Existing arc flash standards like IEEE 1584 and 1584.1 present models that can be used to estimate incident energy levels in power distribution equipment but provide limited direction regarding how equipment construction should be considered in the calculations. Users performing arc flash risk assessments are left to apply engineering judgement when considering how barriers or isolation of components should be considered. This can lead to risk assessments that are inconsistent or incorrect.

Current practices regarding arc flash evaluation in barriered and non-barriered equipment are reviewed based on current standards. Gaps and potential concerns are discussed, including the lack of defined criteria to use in calculations, along with lack of criteria for determining when barrier systems are considered effective at preventing, mitigating, controlling or containing arcing faults.

A description of a new system that provides passive protection in low-voltage distribution equipment is presented. By providing improved protection for the incoming conductors and main circuit breaker itself, this line-side protection system reduces or eliminates the uncertainties, which allows for more consistent and accurate application of risk assessments.

The new protection system enables arc flash protection to be provided by a passive, enclosed system that has been tested to verify performance. As such, the calculations and risk assessment are less reliant on assumptions regarding the performance of the equipment. Practical aspects of arc flash analysis and labeling and operation and maintenance of such equipment are also discussed.

Index Terms — arc flash, arc-resistant switchgear, accident prevention, electrical safety

I. INTRODUCTION

Ensuring that workers are adequately protected against arc flash hazards is an important part of any electrical safety program. Arc flash hazards can be managed by employing safe work practices like those described in NFPA 70E [1], engineering controls developed by equipment manufacturers, or use of arc rated personal protective equipment (PPE) that acts as the "last line of defense" for workers exposed to electrical hazards.

NFPA 70E requires that an arc flash risk assessment be performed before conducting work. IEEE 1584 [2] provides a calculation model that can be used to quantify the potential severity of exposure. Unfortunately, evaluating arc flash hazards is not straightforward in real-world equipment. The risk assessment should include evaluating the zones of protection of system protective devices, as well as the impacts of equipment construction. This can be difficult for personnel not familiar with arc flash analysis methods or who lack detailed knowledge of electrical equipment construction.

This paper reviews selected existing industry practices and equipment construction features that create barriers that may provide some degree of arc flash protection, and then discusses potential gaps in these existing practices and potential concerns arising from them. A description of a new type of protection system that can help alleviate many of these concerns is then offered.

II. CURRENT INDUSTRY PRACTICES: BARRIERS

Electrical equipment construction has evolved over time and equipment installed today is generally reliable, safe and effective for distribution of electricity. Many types of equipment are designed with safety features to protect workers that interact with it on a routine basis. Regardless, electrical workers routinely face two main hazards: electric shock and arc flash. There are several barrier systems currently in use in electrical equipment designs to mitigate electrical shocks and arc flash.

A. Barrier Systems for Protection Against Electric Shock

Current industry practices encourage working only on equipment that has been placed in an electrically safe work condition (i.e. de-energized and locked/tagged), which removes the potential for contact with energized parts and thus eliminates the hazard of electric shock. However, in practice, many electrical tasks are performed within portions of equipment that are de-energized while other portions of the equipment (outside the work area) may still contain energized parts. In these cases, regardless of the level of training or qualification of the workers, the hazard of electric shock has not been completely eliminated and still presents a risk. There are several existing equipment design features in use today that are intended to address this concern.

While these designs are not intended to prevent or mitigate an arcing fault, they can be instructive or directly useful in reducing the likelihood of arcing faults, if applied correctly.

1) *Main lug barrier*: For switchboards and panelboards that have an integral main circuit breaker, with the circuit breaker open and control/instrumentation circuits isolated, the majority of the equipment is de-energized. However, the incoming line

conductors and line side of the main circuit breaker will remain energized unless the equipment is isolated at the source external from the panel. CSA 22.2 No 29 [3] has required barriers isolating the line side of main devices in panels for several years. More recently, the UL 67, *Standard for Panelboards* [4], was updated to require panelboards and load centers used in service entrance applications to have barriers over the line side of the main overcurrent protective device. An example of main lug barriers on a low voltage panelboard is shown in Fig. 1.

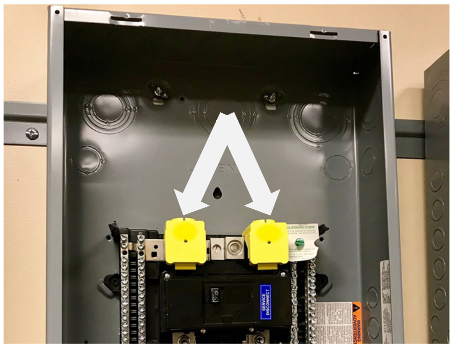


Fig. 1 Photo of Main Lug Barriers

2) *IEC forms of construction*: Electrical switchgear and controlgear that is constructed to IEC 61439-2 incorporates internal barriers between various compartments, which are defined as forms of internal separation [5]. Equipment with form 4 separation (form 4a or 4b) has barriers between each compartment (functional unit) within the equipment. As shown in Fig. 2, for switchgear with form 4 separation if the main circuit breaker is open and work is not being performed in this compartment (VS #1), there would be no accessible energized parts in the rest of the switchgear and no electric shock hazard in VS #2 or VS #3.

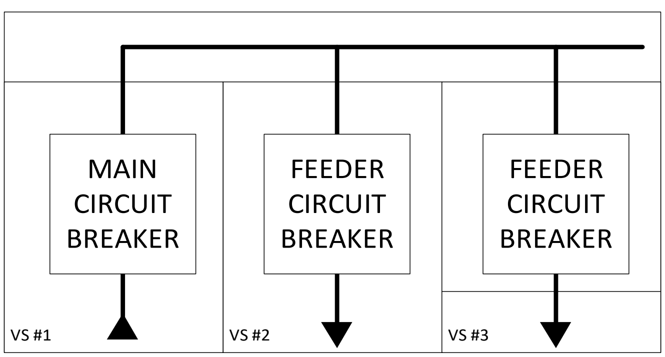
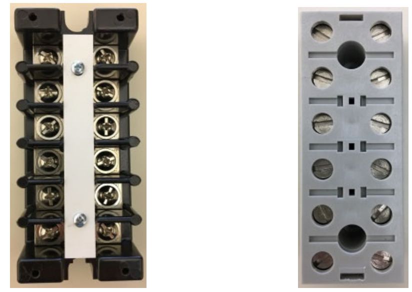


Fig. 2 IEC forms of separation; form 4a in VS #1 and VS #2, form 4b in VS #3

3) *IP2X (fingersafe)*: Electrical equipment and components can also be constructed in accordance with the ingress protection (IP) ratings defined in IEC 60529 [6]. Equipment or components having an IP rating 2X or higher are designed to protect people from incidental contact with the hazardous parts inside. Examples of both conventional and fingersafe terminal blocks are shown in Fig. 3.



(a) (b)

Fig. 3 (a) Photo of conventional terminal block and (b) Photo of fingersafe terminal blocks

B. *Barrier Systems for Protection Against Arc Flash*

Some existing designs of arc-resistant equipment incorporate barriers to mitigate the effects of arc flash. IEEE C37.20.7 [7] includes three suffixes that define the protection offered by the equipment. Arc-resistance of equipment is assessed based on the test criteria defined in the standard, including condition of indicators placed around the external and/or internal surfaces of the equipment and the surfaces themselves after testing.

The basic arc-resistant rating (Suffix A) is based solely on the external surface of the equipment.

Suffix B (e.g. equipment designated Type 2**B**) offers enhanced protection for personnel working in the low voltage control compartment. In addition to the standard testing, indicators are placed inside the low voltage control compartment. Arc-resistance of equipment is assessed based on the condition of all indicators (those around the external surfaces of the equipment and in the low voltage control compartment) and the condition of the external surfaces and the interior surfaces of the low voltage control compartment after the test. This testing validates that the effects of an arcing fault do not propagate into the control compartment. Equipment designed for suffix B may utilize barriers between the main compartments and the low voltage control compartment.

Suffix C (e.g. equipment designated Type 2**C**) offers enhanced protection against equipment damage by isolating all adjacent compartments from each other such that an arcing fault in one section will not impact the adjacent sections. Similar to suffix B, in addition to the standard testing, indicators are placed inside each compartment (e.g. bus compartment, breaker compartment, control compartment, etc.). Arc-resistance of equipment is assessed based on the condition of all indicators (those around the external surfaces of the equipment and those in each compartment) and the condition of the external surfaces and the interior surfaces of each compartment after the test. This testing validates that the effects of an arcing fault do not propagate from one compartment into any other adjacent compartment. Equipment designed for suffix C may use additional or modified barriers between each compartment.

C. *Arc Flash Incident Energy Calculation Standards*

Equipment designs currently available largely accept that a fault can occur and are designed to mitigate the effects of that fault after it occurs. When protocols for testing arc-resistance of equipment were first published, existing designs were tested to determine where improvements were necessary, and the designs were modified to make the equipment more structurally robust to withstand the effects of an arcing fault. More recently, equipment manufacturers have begun to incorporate technology solutions into equipment to actively remove the arcing fault after it begins, such as fiber optic light sensors and high-speed protective relays or devices that change the arcing fault into a more predictable type of fault that can be quickly detected and cleared. However, even with these technology solutions, the equipment is still designed to mitigate the effects of an arcing fault only after it has already occurred within the equipment.

Clause 6.10 of IEEE 1584 states that if an integral main overcurrent protective device is "not adequately isolated," then the upstream overcurrent protective device must be considered as protecting not only the main compartment but also other parts of the equipment [2]. IEEE 1584.1 states that this issue needs to be evaluated for switchboards, MCCs, panelboards and distribution boards and that assessment should be included in the study scope of the work [8].

However, evaluating when a fault could be initiated on the line side of a main protective device often requires the use of "engineering judgement." Consider the case of a 480V panelboard where the incoming cables, the main breaker, the busbars, all branch circuit breakers and all outgoing cables are in the same enclosure with no meaningful segregation. If an arcing fault occurs on the load side of a branch circuit breaker, it is likely that the branch circuit breaker will effectively clear the fault. Similarly, if the fault is on the bus bars, we can probably be confident that the main circuit breaker will effectively clear the fault. However, since there is no segregation, we cannot be certain about where within the equipment a fault may occur or that for work taking place on a branch circuit within the panelboard enclosure that the possibility of a fault on the line side of the main breaker will not occur. Therefore, the arc flash incident energy calculation should be based on the highest energy location.

What if instead of a low voltage panelboard, we consider a low voltage switchboard? These would typically be installed in locations with much higher levels of energy available, especially if installed directly downstream of a utility transformer that is protected by fuses. Should a fault on the load side of the main circuit breaker propagating to the line side, or potential exposure to the higher line-side energy be considered?

This type of fault propagation could even occur on low voltage metal-enclosed switchgear since the load side and line side circuit breaker 'stabs' are adjacent to each other. What about equipment where multiple circuit breakers are 'stacked' on top of each in a single vertical section? If a fault occurs on a circuit breaker in the lower portion of the section, could ionized gases propagate upwards and into other compartments, thereby creating additional faults? Could this type of fault propagation happen even in medium-voltage metal-clad switchgear designs, which unlike equipment designated Type C according to IEEE C37.20.7 is not designed to prevent the passage of these fault products?

D. Engineering Judgment in Practice

Engineering judgment is required across a wide variety of equipment types when considering whether the main breaker can be considered able to clear all faults within the equipment. While those performing arc flash studies can get basic awareness of the problem, there is no definitive industry guidance available.

1) *Manufacturers:* Electrical equipment manufacturers design and build distribution equipment based on codes and industry standards. While designs that are robust and reliable, easy to maintain, and that provide a long service life are goals, most designs did not originally consider the behavior of arcing faults during energized work, either in terms of personnel exposure for equipment that does not have barriers, how that would impact arc flash incident energy calculations, or in terms of being designed to isolate or minimize equipment damage. Even with more modern equipment designs that are arc-resistant, this aspect may not always be considered. Manufacturers are not obligated to consider this when designing equipment to current industry standards.

2) *End-users:* For end-users performing arc flash hazard analysis studies themselves, engineering judgment is required since they typically do not have detailed knowledge of equipment construction. Clearly IEEE 1584 and IEEE 1584.1 highlight the problem, but neither provides clear guidance on these issues that can be used when deciding what inputs and assumptions about equipment design to use in an arc flash study. Therefore, whoever performs the arc flash hazard analysis study is responsible for determining when a fault on the line side of the protective device could occur and when it is not likely to occur. Some end-users who perform their own studies may be part of an organization that has a corporate-wide philosophy for arc flash hazard analysis studies, which may provide the needed additional guidance. However, if additional guidance is not available, they must use their own engineering judgement based on their experience (which may be limited) and the equipment construction (if details are known or available).

End-users that rely on engineering contractors to perform the studies face the same challenge. Although the contractor will make these decisions, the end user may not be aware of the complexity of the problem or may not have the technical staff to provide the appropriate level of contractor oversight. This means (whether they know it or not) they are relying on the contractor to apply this engineering judgment for them.

3) *Engineering contractors:* There are many types of engineering contractors with widely varying levels of experience and expertise regarding electrical study work. As is the case with end-users, some will understand the complex nature of this problem where others may not. It can be expected that firms that have a specialty in performing arc flash hazard analysis studies will at least understand the problem and the complexity, but even then, they may still not have specific guidance that can be applied consistently. One engineering contractor that has a specialty in performing arc flash hazard analysis maintains a detailed technical guide that provides specific guidance in these matters, even including specific models of equipment and/or specific features (i.e. manufacturer options) that provide adequate barriers so that the main breaker can be considered able to clear all faults within the equipment. But even this is based, to an extent, on engineering judgement. In the absence of this type of specific guidance, engineering contractors may rely on default options in analysis software without giving the issue much consideration.

III. GAPS AND CONCERNS

Arc rated PPE is selected based on the incident energy exposure for a given work task at the point in the power system where the work will be performed. Since incident energy levels can vary widely throughout the system, the zones of protection of various protective devices must be taken into consideration. To help illustrate this, a sample system is shown in Fig. 4.

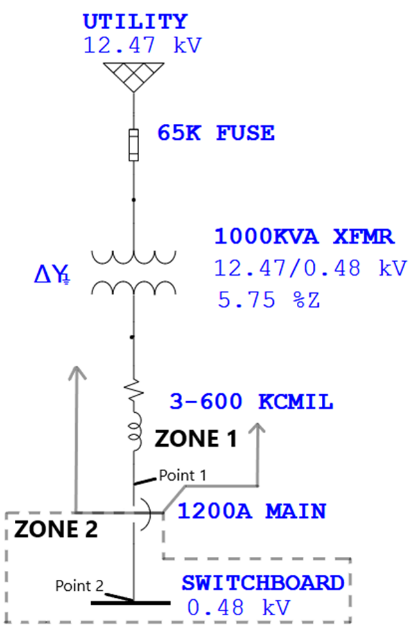


Fig. 4 One-line diagram for sample system

The system shown in Fig. 4 consists of a 480 V switchboard with 1 200 A main breaker, fed from a single 1 000 kVA transformer. The serving utility operates at 12.47 kV and protects the transformer with a 65 A Class K fuse link. Component values are selected to be "typical" – 5 000 A available fault current at 12.47 kV, 5.75% transformer impedance, and 3 sets 600 kcmil copper conductor cable, 7.6 m (25 ft) long, from the transformer to the switchboard. Typical trip settings in the middle of the available range were selected for the 1 200 A main. Two zones of protection are defined – Zone 1, from the primary fuse to the 1 200 A main breaker (including the line side of the breaker), and Zone 2, for locations downstream of the switchboard main breaker. Two potential fault locations are also shown - Point 1 on the line side of the switchboard main circuit breaker and Point 2 at the switchboard main bus. Point 1 and Point 2 fall within Zone 1 and Zone 2, respectively.

The incident energy levels for this system at a typical working distance of 457 mm (18 in.) are calculated based on a VCBB configuration using IEEE 1584, and the results are shown in Table I. The table also shows the calculated bolted fault current (I_{BF}) and arcing fault current (I_A), as well as the arc duration based on the protective device clearing time. The Zone 2 energy is relatively low because the main breaker trips instantaneously, but Zone 1 energy is relatively high because of the longer fault clearing time.

To illustrate how these calculations are applied to PPE selection, consider the elevation drawing in Fig. 5, which shows the physical layout of the switchboard shown in Fig. 4. Protection Zone 1 extends from the incoming terminals of the switchboard to (and including) the line-side terminals of the main circuit breaker in the left-hand section, while the remainder of the switchboard is in Zone 2, protected by the main circuit breaker.

TABLE I
INCIDENT ENERGY CALCULATION SUMMARY

Fault Location	I_{BF} (kA)	I_A (kA)	Arc Duration (sec.)	Incident Energy (cal/cm^2)
Point 1 (Zone 1)	17.5	13.5	0.55	15.6
Point 2 (Zone 2)	17.5	13.5	0.05	1.6

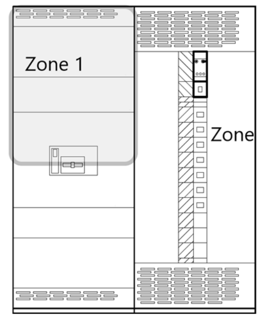


Fig. 5 Switchboard Elevation Drawing

PPE selection for work tasks in Zone 1 (e.g. voltage measurements at the source-side terminals of the main circuit breaker) would be based on the Zone 1 incident energy. A worker taking voltage measurements at the load-side terminals of the main circuit breaker would still be exposed to Zone 1 energy, so the PPE selection would not change despite the location technically being inside Zone 2. What about a worker taking voltage measurements in the right-hand section of the switchboard? Is this worker still exposed to Zone 1 energy? Section B.2.4.1 of IEEE C37.20.7 notes that "fault gases" produced by an arcing fault could potentially cause flashover within the equipment, effectively transferring the fault to another compartment in the equipment. [7] Could an arcing fault in the right-hand section of the switchboard in Fig. 5 produce ionized gases that could cause a fault to propagate by restriking in Zone 1? In such cases, selecting arc-rated PPE to provide protection for the lower Zone 2 incident energy might not be enough.

A. Effects of Barriers

In situations such as the one described above, when can a worker be confident that they are effectively isolated or guarded from the higher Zone 1 incident energy? NFPA 70E Annex O [1] recommends the use of safety-related design requirements that may help "eliminate hazards" or "reduce risk" through reducing the likelihood and/or severity of exposure. Section O.2.4 lists several methods that "…have proven to be effective at reducing risk associated with an arc flash or shock hazard…", including several items that involve some manner of barrier or guard:

1) *Installation of fingersafe equipment*: while "finger-safe" equipment may help reduce the likelihood of occurrence of an arc flash event, it is not necessarily tool or test-probe-safe, and

so contact with energized parts and the resulting hazards may still occur. It may have no effect at all once an arcing fault is established. As noted in [9], finger-safe design is not considered to be adequate protection against arc flash events.

2) *Installation of insulating barriers:* There are a variety of insulating barriers available, with varying effectiveness in terms of arc flash protection. The "main lug barriers" mentioned in Section II meet NEC 408.3(A)(2) [10] requirements, but as one manufacturer notes, "…addition of service barriers…reduces the likelihood of electric shock but does not reduce the severity of an arc flash incident." [11] Arc suppression blankets are a type of barrier that can be temporarily installed when work is taking place. One manufacturer states that they are intended to be used "…as a barrier for protection from the explosive and incendiary effects of arcs and flashes….". However, they also note that the blankets "…do not eliminate or reduce requirements for proper PPE for arc flash protection." [12] Systems of barriers between phases and/or between phase and ground have been shown to help limit the duration of arcing faults in low-voltage motor control centers and switchgear [13], [14], but the systems described do not necessarily prevent or limit arcing faults at all potential locations within the equipment. IEC/TR 61641 [15] provides guidance on criteria that must be met for a section of equipment to be considered an "arc ignition protected zone", sometimes referred to as an "arc free zone" – i.e., an area where it is unlikely for an arcing fault to occur under normal circumstances. However, since IEC 61641 is a "Guide" and not an IEC standard, conformance is ultimately based on agreement between the manufacturer and user on the interpretation of test results. No such guidance is currently provided in the US product standards or testing guides.

3) *Installation of covers & compartmentalization:* as discussed in Section II, internal barriers and compartmentalization that help meet "forms of separation" requirements can help reduce exposure to energized parts and thus have safety benefits. How "compartmentalized" does equipment have to be before it is acceptable to reduce the level of required arc flash PPE? Is it enough for the barriers to merely reduce the likelihood of contact with energized parts? Should barriers prevent propagation of faults by helping contain or restrict the flow of ionized gases? Do they have to contain the effects of an arcing fault inside the compartment? At present, all these questions are left to the judgement of the person performing the arc flash study or arc flash risk assessment, as existing industry standards (aside from requirements for arc-resistant switchgear) do not directly address these issues or define testing to demonstrate performance.

4) *Installation of arc-resistant Switchgear:* as discussed in Section II, Type 2C arc-resistant switchgear per IEEE C37.20.7 is tested to demonstrate that the effects of an internal arcing fault are limited to a single section in a piece of equipment. Similarly, IEC/TR 61641 defines Arcing Classes B and C as limiting the effects of the arcing fault to certain portions of the equipment.

B. Barriers & The Risk Assessment

NFPA 70E 130.5 requires an arc flash risk assessment to be performed to identify potential arc flash hazards, estimate the likelihood and severity of injury, and to determine protective measures to be used to help reduce the risk. A simple example of an arc flash risk assessment involves work tasks that can be considered "Normal Operation," which can be done without arc-rated PPE as long as "normal operating conditions" exist (i.e. equipment doors and covers are closed and secured; the equipment has been properly installed and maintained; the equipment is used in accordance with its listing, labeling, and the manufacturers' instructions; and there is no evidence of impending failure). See NFPA 70E 130.2(A)(4) and Table 130.5(C) [1].

The result of this assessment is based on the reduction in likelihood of an arc flash event, not on the ability of properly-installed equipment to contain an internal arcing fault, as "normal operation" can apply to panelboards, switchboards, etc. that are not rated as arc-resistant per IEEE C37.20.7. This reduction in likelihood is qualitative and not quantitative – i.e. there is no definitive metric that must be met before the equipment can be considered to be in a normal operating condition. Instead, the judgement of the personnel performing the risk assessment is required, as it is not always clear whether normal operating conditions exist. When workers are not familiar with the history of the equipment (e.g., contractors or service personnel), this evaluation becomes even more difficult.

For situations not specifically addressed in NFPA 70E, such as the internal barriers and compartmentalization discussed in Section II and III.A, further judgement is required even though such features may reduce the likelihood of occurrence of an arc flash event. How much must the likelihood be reduced before PPE can be reduced or eliminated altogether? How does a worker know whether barriers are sufficient to reduce exposure or to prevent restrike or propagation? When performing an arc flash analysis, IEEE 1584.1 recommends that a "qualified person with skills and knowledge of electrical equipment construction" make the determination of which protective device to consider for incident energy calculations based on "equipment configuration and construction" [8] but provides no specific recommendations on how to make this type of determination.

Faults in electrical equipment of any kind, including arcing faults, are relatively rare. Arc flash events have potentially life-changing effects, though – they can be thought of as a classic "low frequency, high impact" event. In such situations, is risk assessment based on judgement or experience appropriate? Such judgements will vary from worker to worker, potentially making it difficult to implement consistent safe work practices.

IV. LINE-SIDE ARC ISOLATION

Any worker exposed to arc flash and shock hazards is at risk of injury. When the arc flash incident energy levels at or near the area where work is being performed are high, as in the example shown in Section III, the risk is elevated. Even if the switchboard were put into an electrically safe work condition, the act of testing to verify the equipment is de-energized could expose a worker to electrical hazards. However, if it is possible to isolate and/or mitigate the arc flash hazard in Zone 1, this would significantly reduce the level of risk the worker faces throughout the equipment.

This section describes a system that allows for such isolation that may remove the ambiguity present in many existing solutions. Not all parts of these ideas have been completely validated and additional work is required to do so. In the interim, we must rely on existing standards and practices to help assess equipment performance.

A. *System Description & Characteristics*

An ideal design for Zone 1 in equipment such as the switchboard from our example would be for this area of the equipment to be inherently rated to contain or quickly clear any arcing fault that might originate within it. If Zone 1 were contained within a conventional arc-resistant enclosure, this could provide good protection for a worker in Zone 2. However, the equipment itself would still be at risk for damage caused by an arcing fault inside Zone 1, as arc-resistant construction does not necessarily imply the presence of features to prevent an arc from occurring or for limiting its duration.

A solution that builds on the passive barrier system described in [14] for draw-out circuit breakers which stretches and cools the arc has demonstrated significant benefits. A "line-side arc isolation" (LAI) module, which combines principles of both arc-free and arc-resistant construction, achieves a passive self-clearing capability with clearing times similar to those of fast-acting circuit breakers. The LAI module uses a system of barriers to not only reduce the probability that an arcing fault could occur, but also to reduce the arc intensity and duration by the stretching and cooling it. These barriers, coupled with an exhaust system to evacuate energy from the enclosed module, force the arc to "die of a cold" and self-extinguish.

An example of an LAI module in an equipment enclosure is shown in Figs. 6, 7, and 8.

Fig. 6 shows the isolation module with the outer cover in place.

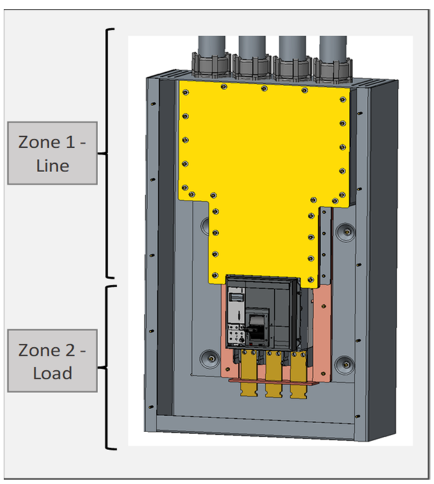


Fig. 6. Line-side arc isolation module.

Externally, this module resembles an explosion-proof enclosure. This is no coincidence – explosion-proof enclosures are designed such that any gas leakage, in this case between the outer cover and cable compartment, is forced to pass through long openings with small cross-sectional area such that the escaping gases are cooled below the ignition temperature of the gases outside. In the case of the LAI module, these "overlap seals" ensure that any gases that do escape the enclosure are cooled to reduce the heat energy to a low level, typically below 1 cal/cm^2 at a typical working distance of 457mm (18 in.) at which point arc flash hazards are minimized. Note that this also minimizes the probability of arc propagation due to migration of ionized gases, as arcing plasma temperatures greater than 2000^{o}C are typically required for it to be conductive [16]. While the plasma temperatures were not directly recorded during the testing of the LAI module, the measured incident energy values external to the modules are inconsistent with the presence of a significant quantity of such heated plasmas.

Fig. 7 shows the LAI module with the outer cover removed to expose the inner terminal cover and cable compartment.

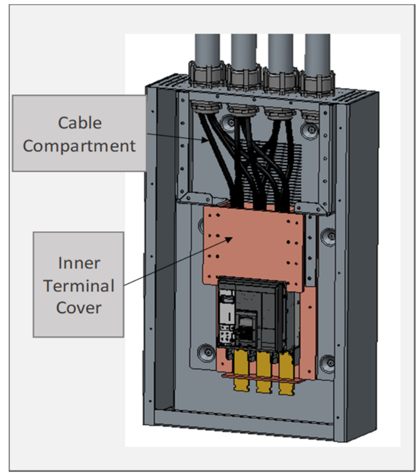


Fig. 7. LAI module with outer cover removed.

The inner terminal cover extends from the line-side terminals of the circuit breaker upward, and it forms the outer portion of the terminal shield system designed to create an insulation barrier that also interacts with an arcing fault to help cool it.

Finally, Fig. 8 shows the module with the inner terminal cover removed to expose the channels where the power conductors connect to the line-side circuit breaker terminals. These channels are formed by the rest of the terminal shield system, along with front and rear covers. Also shown is a typical location for an exhaust system.

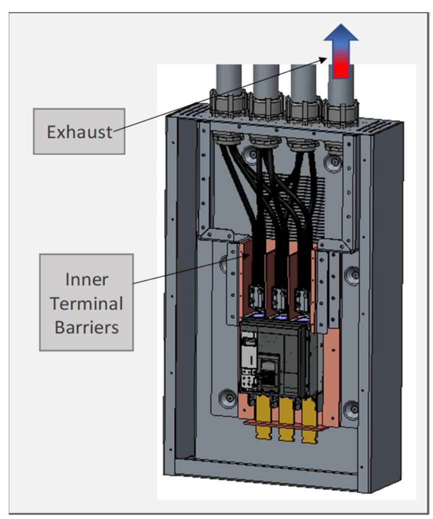


Fig. 8. LAI module with inner cover removed.

As with circuit breakers, an exhaust path is required to ensure that the energy created during an arcing event is sufficiently evacuated from the power connector area so as to facilitate rapid clearing of the arc. A mesh or other barrier could be installed to protect against intrusion from rodents or other foreign objects. As is the case with conventional arc-resistant equipment, the exhaust needs to be conducted away from the line-side module to an area that does not pose exposure risk to personnel. For this equipment, it is done by an exhaust conduit extending to the top of the LAI enclosure. The plasma that exits via this conduit, unlike the leakage plasma discussed above, will be typically be of a temperature above 2000ºC; hence the need for the prudent location of the exhaust. Testing of prototype designs has indicated that the quantity of plasma will be slightly more than that produced by a circuit breaker interrupting a short circuit but will be insignificant when compared to a typical internal arcing test conducted to qualify arc-resistant equipment.

The overall system needs to be mechanically robust since the internal pressures generated during an arcing event are on the same order of magnitude as those in low voltage circuit breakers of similar performance. UL 50 [17] provides guidelines regarding the mechanical robustness of enclosures, including resistance to external mechanical loading. While more development in this area is needed, it seems reasonable that similar guidelines could be employed for this system to reduce concerns about intended intrusions, deflections or penetration during maintenance.

B. System Benefits and Performance

As discussed previously, the presence of high incident energy levels in Zone 1 of the example switchboard presents a concern that must be addressed. Even if an employee is protected by some sort of a barrier while working in Zone 2, what happens if actions in Zone 2 produce an arcing fault in Zone 1? This could potentially occur as a result of jarring something loose, or from dropping a tool into energized bus. It is also possible for an arc to initiate in Zone 1 on its own, possibly due to the “weekend effect” where equipment turned off on Friday evening and re-energized Monday morning could flash over due to accumulated condensation [18]. The risk of such events is not easily quantified, but it is clear that the arc flash risk is not zero for any equipment that has not been completely de-energized.

The risks increase for work tasks performed on or around energized equipment, such as voltage testing or the insertion/removal (racking) of circuit breakers. Any arc created in Zone 2 carries with it the risk of transfer and restrike in Zone 1 due to the dispersion of arcing plasma, which has been observed through barriers having openings as small as 1mm [18].

The key advantages of the LAI module are its ability to reduce the likelihood of internal arcing faults occurring and its ability to reliably reduce the duration and intensity of any arcing faults that do occur. Testing results have shown that the LAI module achieves similar performance to the system described in [14] in terms of reductions in clearing time and peak current along with system damage by forcing arcing faults inside the module to self-extinguish.

More specifically, this system has been developed and validated using the testing methodology of IEEE C37.20.7 for system voltages up to 600V and for available fault circuit currents to 100kA. Typical performance values are a fault clearing time of less than 15 milliseconds and peak currents reduced by more than 60%. These current clearing characteristics are similar to the performance of a 600A current limiting circuit breaker.

Fig. 9 shows an oscillogram from a sample internal arc test on a LAI module that was tested at 485 volts and 111 kA prospective current according to IEEE C37.20.7.

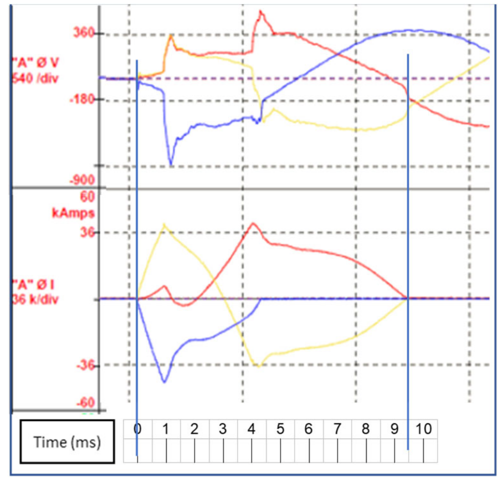


Fig. 9. Oscillogram from testing of LAI module.

The upper curves of Fig. 9 are the voltage traces, while the current traces are shown at the bottom. The maximum voltage magnitude seen in is 900V, generated approximately 1 millisecond after arcing commences. This voltage limits the peak current to 46.6 kA, which is significantly reduced from the 242kA protective peak current (111kA x 2.18, based on 19% test circuit power factor) for this circuit. The total fault duration is 9.5 milliseconds, which is important for two reasons. First, faster clearing reduces the total energy delivered to the arcing fault, thereby lowering the potential for burn risk and equipment damage. Second, by clearing the arc within the module, the performance of the system is independent of the clearing time of the upstream overcurrent protective device. Even a line-side arcing fault should be cleared before any upstream protective device operates, meaning that selectivity between the upstream device and the local main breaker is not affected.

The level of incident energy created by any line-side faults within the module is minimized by the fact that both the magnitude and duration of any internal arcing faults that do occur are limited. Based on the parameters of the test shown in Fig. 9 (i.e., 111kA available bolted fault current and 9.5ms clearing time), the prospective incident energy is calculated as 1.62 cal/cm^2 at a 457mm (18 inch) working distance. Note that this is the energy value within the LAI compartment. The exhaust system helps redirect energy away from a worker’s location, and as discussed previously, any “leakage” is significantly cooled. As a result, incident energy measurements at worst-case locations around the LAI module were found to be significantly less than 1.2 cal/cm^2.

The isolation provided by the LAI module also means that the main circuit breaker in Zone 1 may be used as the lockout/tagout (LOTO) point for the equipment, rather than requiring lockout at a disconnect farther upstream, for any work within Zone 2. The enclosure protects against the shock hazard from energized components in Zone 1 similar to a conventional deadfront enclosure, while the arcing fault isolation and passive clearing ability provide effective protection against the arc flash hazard. This could be particularly beneficial in situations where the LAI module is applied as a part of service-entrance equipment, where LOTO would normally have to be done at an upstream utility disconnect. Further, the ability to keep the LOTO point close to Zone 2 enhances visual verification and continuous understanding of LOTO status.

Other benefits include:

- Fault clearing based on a passive system – reducing the need for maintenance, as well as reducing the likelihood of failure or misoperation.
- The system addresses all arcing faults, no matter what the mechanism of fault initiation.
- The module is expected to be resistant to arc propagation or restrike, both from Zone 1 to Zone 2 and from Zone 2 to Zone 1.

C. Zone to Zone Transfer Testing Improvements

As discussed in both Section II and Section III, evaluation of the ability of equipment enclosures to deal with internal arcing faults is currently left up to some degree of “engineering judgement.” Of concern is the possibility of arc propagation from one zone to another. While IEEE C37.20.7 mentions this phenomenon, it is primarily focused on ensuring the integrity of the external envelope and may not adequately address this concern. Suffix C ratings are intended to show isolation between adjacent compartments within a switchgear assembly, but at present, Suffix C only applies to equipment that does not have any open common compartments, such as medium-voltage metal-clad switchgear.

Further work is required to modify or develop a testing protocol to evaluate this phenomenon in all types of equipment, but some principles could include:

- Developing test guidance regarding arcing locations and enclosure geometries that may promote arc propagation or restrike.
- Developing a system or method to determine that dielectric strength of the area immediately proximate to the line-side zone has been suitably compromised during the test.

The nature of the LAI module described in this section should prove capable of resisting zone-to-zone arc transfers, and any that are transferred to the module should be cleared quickly. Further development of testing protocols will help to improve confidence the performance of it or similar systems.

D. Application, Operation, and Maintenance Considerations

The enclosure and barrier system described would tend to increase internal equipment temperatures, which have to be taken into account when determining the continuous current rating of the equipment.

The LAI module is intended to be a “protected space” that is closed during installation and then only reopened when the system has been de-energized. Maintenance of the conductors and connections may be more difficult, as the cover precludes diagnostics such as thermographic scanning. However, equipping the LAI module with embedded thermal sensors would be one way to allow for diagnostic information to be obtained without requiring that the module be opened. Use of a permanently-mounted “absence of voltage” detector meeting the requirements of NFPA 70E 120.5 could also help mitigate the risk to workers when they do need to open the line-side compartment.

The LAI module should not impose any limitations on equipment interrupting ratings, so that it can be applied in any system appropriate for the main breaker. The fact that it is self-extinguishing with a predictable clearing time means that application is independent of the trip characteristics of the upstream protective device. System selectivity can be maintained with either an upstream low voltage breaker or medium voltage fuse.

E. Arc Flash Analysis and Labeling

The LAI module, once validated by testing, would help to simplify arc flash analysis for the equipment in which it is installed by virtue of the degree of isolation it provides. For example, consider the module shown in Fig. 6 applied in the main section of the switchboard shown in Fig. 5. In this case, Zone 1 would be enclosed inside the LAI module, while Zone 2 is downstream of the main circuit breaker. For work tasks performed in Zone 2, there is no exposure to Zone 1 energy and propagation of an arcing fault to the line side terminals is unlikely. As such, PPE for Zone 2 can be selected based on the protective characteristics of the main circuit breaker.

During normal operation of the equipment, there is no exposure to arc flash hazards of Zone 1. There is only exposure when the outer cover of the LAI module is removed, which should only be done with the equipment de-energized. Therefore, arc flash labeling for the switchboard could be based only on Zone 2 energy. If certain application details are known (e.g. breaker type and settings, available fault current), the isolation of Zone 1 makes it possible to simplify the specification and design of equipment to meet a defined incident energy design criterion for Zone 2. The inner protective module can be labeled to show the Zone 1 incident energy, but personnel would not be exposed to this energy level in normal situations.

V. CONCLUSIONS

Equipment construction and the zone of protection associated with system protective devices both play a role in arc flash analysis. However, these effects are sometimes overlooked when arc flash analyses are performed. Even when they are taken into account, there is no present consensus in the industry on how different types of equipment should be evaluated. This paper describes a new type of line-side arc isolation module that can potentially be applied in many types of low-voltage distribution equipment, providing positive isolation between protective zones and reducing the chance that employees may be inadequately protected based on inaccurate or incomplete risk assessments.

The system contains and quickly extinguishes arcing faults on the line side of the main circuit breaker in the equipment, the location where incident energy levels are typically the highest. For tasks performed downstream of the main circuit breaker, workers can be confident in the selection of PPE based on the trip characteristics of the main circuit breaker and arc flash labeling can be simplified as well. The main circuit breaker can also be used as a lockout/tagout point for all work within the equipment downstream of the main breaker. Use of features such as embedded thermal sensors and "absence of voltage" detectors can help in day-to-day operation and maintenance.

Similar fast clearing times may be achievable with active arc flash mitigation systems, but to ensure full protection from Zone 1 energy, the system would be required to trip a remote circuit breaker in upstream equipment. An arc-resistant enclosure around Zone 1 could protect an employee working in Zone 2, but faults in Zone 1 could cause extensive equipment damage. The line-side arc isolation module has the potential to combine the benefits of active systems to reduce arcing duration and intensity with the mechanical robustness of arc resistant enclosures and adds the ability to reduce the likelihood of an arc from occurring as well. As a passive system, it also has the advantages of simpler design, construction, and operation, resulting in fewer potential failure modes.

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VII. VITA

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