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MEDIUM VOLTAGE, METAL-CLAD ARC RESISTANT SWITCHGEAR: ENHANCING WORKPLACE SAFETY

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Introduction

As more and more emphasis is placed on personnel safety in the workplace, the need for safer system planning, procedures, tools, and products continually increases. Although the probability of an arcing fault inside metal-clad switchgear is low, the cost in terms of personnel safety and equipment damage is high when an arcing fault occurs. OSHA, NFPA, and IEEE have recognized the hazards associated with arcing faults in electrical systems by specifically addressing measures to minimize the possibility of an arcing fault, and to mitigate its effects on personnel. This paper discusses these issues, emphasizing the role that arc resistant switchgear plays in providing a safer work environment.

Common Causes of Arc Faults In Switchgear

Arc faults within switchgear can be caused by a number of factors, including:

a. Loss of insulating properties resulting from elevated temperatures. This can be caused by applying the equipment above its continuous rating and from improperly torqued or aligned contact joints. Thermographic monitoring may be used to monitor temperature rises so that preventive measures can be taken.
b. The presence of dust, contamination, or moisture on insulating surfaces. These conditions lead to tracking across insulating surfaces, providing a path for conduction between two different potentials. Heaters can be effective in minimizing condensation on internal conductors. The condition of the insulation should be monitored as part of an effective maintenance program, especially in harsher environments.
c. Voids in insulation, which eventually lead to failure of the insulation when stressed at high voltages. Epoxy bus insulation has demonstrated a greatly improved life expectancy based on its homogeneous composition.
d. Human error. The implementation of disciplined work procedures, effective personnel training, and proper tools can minimize the possibility of human error causing an arc fault incident.

Summary of Arc Fault Characteristics

An arc fault within an arc resistant switchgear enclosure is typically characterized by the following four phases:

a. Compression phase: The compression phase starts at t=0 when the arc starts to burn and continues until the pressure can no longer increase.
b. Expansion phase: The expansion phase starts when the maximum pressure has been reached and the pressure relief flaps have opened. This phase lasts approximately 5 to 10 milliseconds.
c. Emission phase: The emission phase occurs when all the necessary pressure relief flaps have opened so that inside air, where the arc burns, is exhausted outside the cell. This continues until the gas in the cubicle reaches the arc temperature. This phase typically lasts 50 to 100 milliseconds in small cubicles, and in larger cubicles it can be considerably longer.
d. Thermal phase: The thermal phase lasts until the arc is extinguished. An arc emits radiation because of its extremely high temperature (10,000 to 20,000 degrees K in the center). The thermal energy emitted during this phase heats, melts, and vaporizes parts of the cubicles and the components mounted in them. The greatest damage typically occurs during this phase, when the thermal stress caused by the radiated heat is responsible for severe burns and ignition of clothing.

Industry Recognition of Arc Flash Hazards

The pertinent documents governing arc flash hazards are:

- OSHA 29 Code of Federal Regulations (CFR) Part 1910, Subpart S
- NFPA 70E-2000, "Standard for Electrical Safety Requirements for Employee Workplaces"
- IEEE 1584-2002, "Guide for Arc Flash Hazard Analysis"
- IEEE C37.20.7-2001, "IEEE Guide for Testing Medium-Voltage Metal-Enclosed Switchgear for Internal Arcing Faults"

OSHA 29 CFR 1910, Subpart S mandates that safe practices be implemented to prevent shock or injuries due to direct or indirect contact with energized conductors. It also addresses the fact that workers who may be exposed to electrical hazards must be qualified and that provisions for the appropriate personnel protective equipment must be made.

NFPA 70E details the steps needed to comply with the OSHA requirements. Specifically, NFPA 70E addresses:

- Worker training
- Appropriate and safe tools
- Safety program with responsibilities clearly identified
- Arc flash hazard calculations
- Personal protective equipment (PPE)
- Equipment warning labels

IEEE Standard 1584-2002 provides a means to calculate the incident energy resulting from an arc flash. Per NFPA 70E, incident energy is "the amount of energy impressed on a surface, a certain distance from the source, generated during an electrical arc event."

It is not considered safe to work around energized equipment generally. However, if and when this is deemed necessary by the owner, the use of the properly rated PPE by properly trained personnel is required.

The incident energy level is used to determine the flash protection boundary (the surrounding area where the incident energy is equal to or greater than 1.2 calories/cm^2). This incident energy level exposes personnel to potential second-degree burns.

The incident energy also is used to determine the appropriate PPE required for the application. The incident energy level is dependent on various factors, including system operating configurations, voltage, length of the arc, arcing current, protective device settings, time to clear, and distance from arc fault to workers. In a given work environment, the calculation needs to be performed at various locations where any of these variables will change. Note that the highest level of arcing current does not always result in the highest incident energy level. A lower level of current that results in a longer arcing duration may cause higher incident energy levels at the workers' location. Care must be exercised to prescribe the appropriate PPE for the application. Overly conservative requirements can restrict worker movement, vision, hearing, and comfort level unnecessarily. This in itself can be the cause of an unsafe situation.

An incident energy level above 40 cal/cm^2 is considered unsafe, even with the prescribed PPE. Regardless of the incident energy level, additional practical steps can be taken to improve the safety level of the work environment. These include the use of arc resistant switchgear, provisions for closed door or remote circuit breaker racking and operation, and special protective schemes to minimize arc fault durations and magnitudes.

Overview - Evolution of Arc Resistant Switchgear Standards

Interest in arc resistant switchgear designs and ratings was evident thirty years ago in Europe, where medium voltage switchgear typically included uninsulated bus, which increased the likelihood of an arc fault occurrence. As a result, a draft Annex AA to IEC 298 (currently IEC60298), "A.C. Metal-Enclosed

Switchgear and Controlgear for Rated Voltages Above 1 kV and Up to and Including 52 kV", was created in 1976 and was eventually approved by the IEC in 1981.

As a result of the interest in improving safety in the workplace in North America, Annex AA was used as a guideline in the preparation of the EEMAC G14-1-1987, "Procedure for Testing the Resistance of Metal-Clad Switchgear Under Conditions of Arcing Due to an Internal Fault". Refinements were made in EEMAC G14-1 based on "lessons learned" in the preceding years of applying Annex AA. EEMAC G14-1-1987 defines three accessibility types:

Type A: "switchgear with arc resistant construction at the front only"
Type B: "switchgear with arc resistant construction at the front, back and sides"
Type C: "switchgear with arc resistant construction at the front, back and sides, and between compartments within the same cell or adjacent cells" (exception: adjacent main bus compartments)

IEEE C37.20.7-2001, "IEEE Guide for Testing Medium-Voltage Metal-Enclosed Switchgear for Internal Arcing Faults", is based on these two predecessor documents, but also includes improvements as deemed appropriate. This document is currently being reviewed by the working group and will be refined further in the next revision. Part of this revision process will include an attempt to harmonize the requirements with the current IEC practices. IEEE C37.20.7 also defines three accessibility types:

Type 1: "switchgear with arc resistant designs or features at the freely accessible front of the equipment only".
Type 2: "switchgear with arc resistant designs or features at the freely accessible exterior (front, back, and sides) of the equipment only"

Annex A to IEEE C37.20.7-2001 addresses a third accessibility type that addresses arc resistance designs or features between adjacent compartments within the same cell or adjacent cells (with the exception of the main bus compartments). These are identified by the use of suffix "C" as follows:

Type 1C: "switchgear with arc resistant designs or features at the freely accessible front of the equipment only", along with arc resistance designs or features between adjacent compartments within the same cell or adjacent cells (with the exception of the main bus compartments)
Type 2C: "switchgear with arc resistant designs or features at the freely accessible exterior (front, back, and sides) of the equipment only", along with arc resistance designs or features between adjacent compartments within the same cell or adjacent cells (with the exception of the main bus compartments)

The testing associated with each of these documents is based on all covers and doors being properly secured, and all vents and vent flaps set to their correct operating positions. Therefore, the ratings assigned based on testing to these standards apply only under these conditions.

Testing is performed at the prescribed voltage and current levels with the specified flammable cotton indicators strategically positioned to detect the escape of hazardous gases. Assessment criteria include:

1. Door, covers, etc. do not open. Bowing or other distortion is permitted except on those which are to be used to mount relays, meters, etc.
2. That no parts are ejected into the vertical plane defined by the accessibility type
3. There are no openings caused by direct contact with an arc
4. That no indicators ignite as a result of escaping gases or particles
5. That all grounding connections remain effective

Characteristics of Arc Resistant Switchgear Designs

Arc resistant switchgear is characterized by some special design features necessary to achieve the required ratings. Typically, these include:

a. Robust construction to contain the internal arc pressure and direct it to the exhaust chambers designed for the purpose of safely venting the gases
b. Movable vent flaps that open due to the arc fault pressure, increasing the volume containing the arc products
c. Special ventilation designs with flaps that are open under normal operating conditions, but slam shut when an arc fault occurs
d. Closed door circuit breaker racking and operation

ABB's SafeGear utilizes a patented series of vent flaps in conjunction with an arc chamber to safely vent the arc gases away from personnel. This design makes it possible to stack the circuit breakers two-high within one cell.

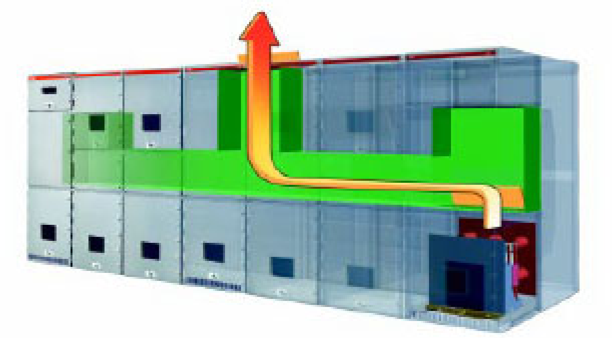


Figure 1. Internal horizontal and vertical arc chamber vents arc gases safely away from personnel.

Front doors, rear and side panels are designed, secured, and tested to ensure that they withstand the potentially high pressures until the relief flaps open and pressure subsides, without being blown from the cubicle or allowing dangerous hot gases to be released to the front, rear, or sides of the switchgear. Doors are reinforced with channel steel, and secured with special hinges and hardware. Interlocking flanges and gasket material are used to seal in flames and keep hot gases from igniting flammable materials near the switchgear.

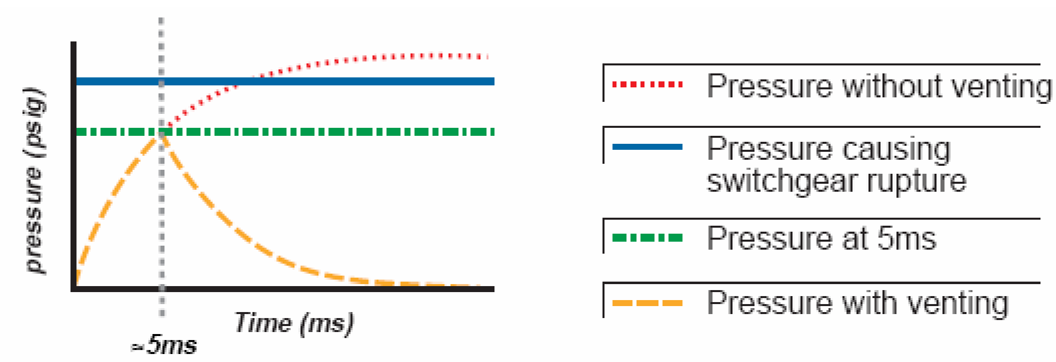


Figure 2. Typical pressure vs. time relationship for switchgear internal arc fault.

The use of a double wall construction between cells has been demonstrated to be very effective in withstanding the heat and pressure created by the arc fault. The heat dissipation and resistance to burn-through is enhanced considerably by the use of double 14 gauge side sheets separated by an air gap of approximately 3/16 inch.

The integrity of the low voltage control and protective device circuitry is critical. Low voltage compartments, which contain the protective relays, meters, devices, and wiring, should be separate reinforced modules. This protects not only the devices themselves, but the control bus and wiring which may otherwise be destroyed as a result of the arc fault. This is extremely important as the protective scheme is being relied on to limit the duration of the arc fault.

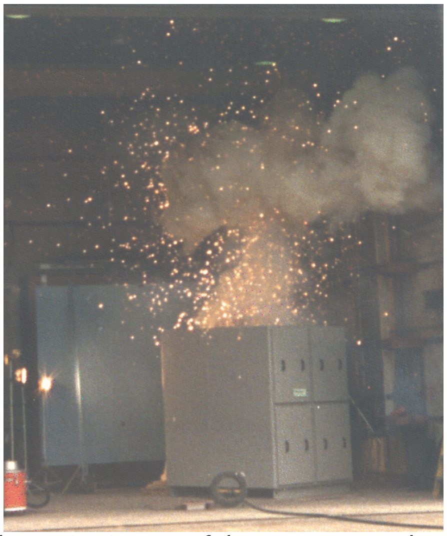


Figure 3. Successful arc test on 15 kV metal-clad switchgear.

Consideration must also be given to provide sufficient clearance above the switchgear to allow the gases to be dispersed properly and not to be reflected back into the area that could be occupied by personnel. Where appropriate clearances are not possible due to the design of the building, an exhaust plenum can be provided to safely vent the gases outside the building to an area that is not accessible to personnel. The plenum design must be tested to verify that the potential back pressure does not cause a failure of the arc resistant integrity of the equipment.

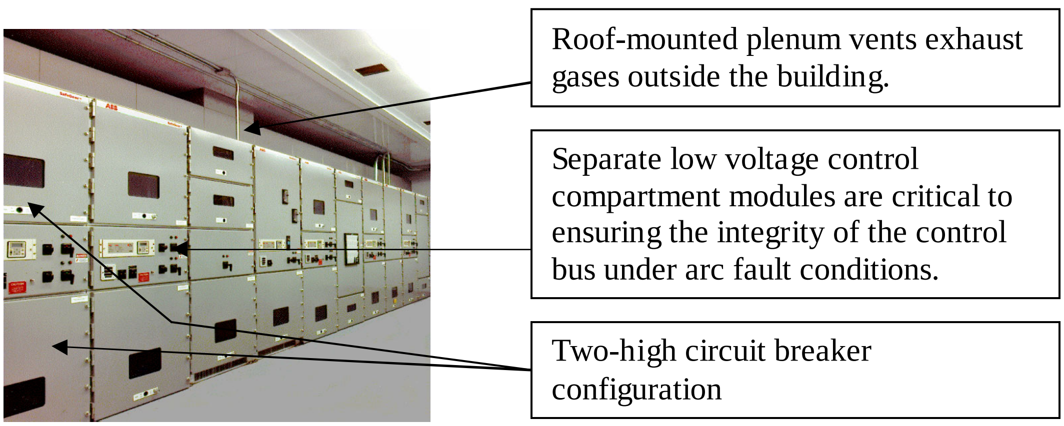


Figure 4. Exhaust plenum mounted on roof of two-high switchgear in PDC building.

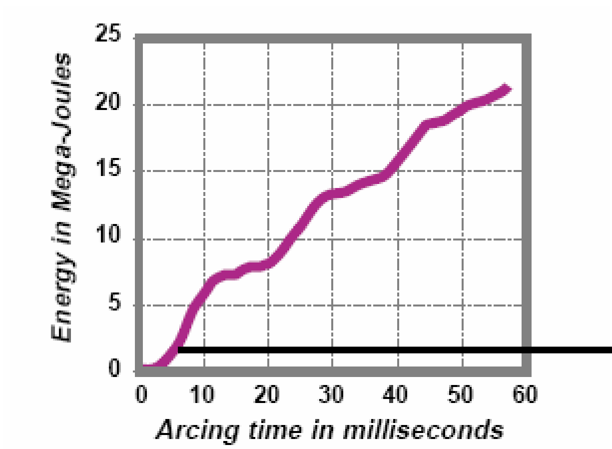
System Protection Approaches

The system protection scheme should be designed to limit the total energy that results from internal arc faults, and specifically, to limit the current magnitude and duration to values that are within the arc resistant ratings of the switchgear. Various approaches can be used to achieve this, including:

1. Arc detection system: Very fast identification of an arcing fault can be achieved by sensing a combination of light, sound, pressure, and current rate of rise. Using these parameters, an arcing fault can be identified in 2 to 4 milliseconds, at which time a trip signal is sent to the

circuit breakers supplying power to the fault. In this situation, the equipment is subjected to the peak pressure because of the tripping time of the circuit breaker, but the duration of the fault, and therefore, the overall energy level, is reduced. Peak pressure occurs within approximately 20 milliseconds. Total clearing time with this approach will be approximately 70 to 100 milliseconds.

2. High-speed fault making devices: Using sensors similar to those described above for the arc detection system, upon sensing an arcing fault, a very high speed fault making device can be activated to apply a three-phase fault on the power system. The energy is diverted from the arcing fault to the three-phase bus circuit, which is designed to withstand this energy. This effectively removes the source of energy to the destructive arcing fault. Simultaneously, a trip signal is sent to the circuit breakers supplying power to the faulted area. As in the arc detection system above, the total clearing time will be approximately 70 to 100 milliseconds. However, the energy is now contained in the bus bars. The arcing fault energy was diverted within 4 to 5 milliseconds. Therefore, the danger and destruction caused by the arcing fault is limited significantly. The three-phase fault is applied before the switchgear is subjected to the peak pressure of the arcing fault. The resulting display and equipment damage is negligible.



Graph shows typical energy associated with a 40 kA fault. Destructive energy is removed from arcing fault in 5 milliseconds by a high-speed fault-making device, limiting it to approximately 2-3 mega-joules.

Figure 5. High-speed fault-making device limits destructive energy significantly

3. Differential relaying scheme: By monitoring and summing the currents flowing in and out of the defined protective zone, the differential scheme can be set up to be very sensitive and to operate very quickly. When the sum of the currents in and out of the protective zone do not equal zero, the high speed differential relay picks up and trips the appropriate circuit breakers that are supplying power to the zone. With high speed differential relaying, the total interruption time will be less than 100 milliseconds. Although this scheme is typically fast, sensitive, and limits energy by reducing the fault duration, it only protects the defined differential zone.

4. Grounding schemes and ground fault protection:

   i. Solidly grounded system: Ground fault protection can be used to sense and interrupt ground fault currents. With no intentional impedance in the ground return circuit, ground currents can be high. Settings dictated by coordination with upstream and downstream devices can cause tripping to be delayed. Additional protection, e.g., differential zone protection, is advisable.

   ii. Low resistance grounded system: The low resistance grounding system reduces the probability of a single phase-to-ground arcing fault. If one occurs, it may evolve into a multi-phase arcing fault. Ground fault relaying should be set to quickly identify this condition and remove all power sources supplying the fault.

iii. High resistance grounded system: With the ground current limited by the high resistance, system operation can continue after the first phase-to-ground fault occurs. However, the ground fault should be located and removed quickly to avoid overvoltage stresses, which increase the probability of a second phase to ground fault.

iv. Ungrounded system: Since the ground current is limited by the phase-to-ground capacitive reactance, system operation can continue after the first phase-to-ground fault occurs. Similar to the high resistance grounded system, the ground fault should be located and removed quickly to avoid overvoltage stresses, which increase the probability of a second phase-to-ground fault.

5. Partial discharge monitoring: A method of predicting potential failures is to monitor switchgear insulation for partial discharge levels while in service. The data obtained can be used to identify trends over time, which enables the user to correct the problem before catastrophic failure occurs.

Summary

Metal-clad switchgear, with fully Insulated primary conductors, major parts of primary circuits isolated in grounded metal, and primary circuits isolated from secondary circuits by grounded metal, is designed to minimize the potential for internal arc faults. However, if and when they occur, arc faults can be catastrophic in terms of danger to personnel and destruction of equipment. Proper application, maintenance, and operation by qualified personnel can further reduce the probability of internal arc faults.

With ever increasing interest in workplace safety, the need to address the hazards of arcing faults and arc flash is recognized throughout the electrical industry. OSHA, NFPA, and IEEE have each published documents that cover the requirements and guidelines associated with these potential issues. OSHA 29 CFR 1910, Subpart S mandates the requirements, NFPA 70E defines the steps necessary to meet the OSHA requirements, and IEEE 1584 provides a means to calculate the incident energies, which enable the user to prescribe the appropriate personnel protective equipment. In selecting the proper personnel protective equipment, note that the highest arc fault currents do not always result in the highest incident energy. A lower arc fault current for a longer duration may result in a higher incident energy level than a high arc fault current for a short duration.

Arc resistant switchgear can provide an additional level of safety over conventional switchgear, by directing the arc gases, in the event of an internal arc fault, away from the area where workers may be present (in front of, beside, or behind the switchgear). The industry standards governing the arc testing of arc resistant switchgear have evolved from IEC in the 1970's, to EEMAC in the late 1980's, to IEEE in 2001.

Protective devices and schemes can also be used to reduce incident energy levels by quickly identifying arc faults and minimizing the associated destructive energy. This can be done by reducing the arc fault current magnitude and / or time duration. If the protective scheme is dependent on control power, it is important to ensure that the low voltage control bus is designed in such a way that it will not be destroyed in the event of an internal arc fault.

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