Collaborative arc flash management solutions in medium voltage switchgear

Introduction

Many articles have been written about arc-flash events, mostly with a single focus. This article brings forth a wider view with a time/distance analysis of different arc abatement technologies in medium-voltage, metal-clad switchgear. The IEEE c37.20.7 [8] actual test results data, obtained from a certified high voltage test facility, offers the reader a true snapshot of pressures developed within standard metal-clad switch- gear enclosure using the latest blend of arc abatement topologies. comparisons are made between the three prevalent technologies, which address an arc flash by time-magnitude approach boundaries. This article also addresses the phenomena associated with electrical arcs within medium-voltage switchgear by developing an introductory understanding of the generation of an arc and the pressure damages that both equipment and personnel may encounter.

Arc-Flash Injuries

Although most arc-flash injuries do not make the daily news, capelli-schellpfeffer, inc. [13] reports that five to ten arc-flash injuries that result in hospitalization occur every day. these include collapsed lungs, third-degree burns, bone fractures, and even death. Medium-voltage switchgear owners have experienced costly damage and power outages. In 1985, ralph lee published "the Other electrical hazard, electrical arc blast burns." his publication described the thermal hazard of an arc flash and specified 1.2 cal/cm² as the curable burn level [1]. temperature levels of an arc flash can reach 20,000 °c, magnitudes in excess of the surface of the sun. these uncontrolled effects of an arc flash are the foundation of serious per- sonal injuries, extended down time, and liability. IEEE 1584 [3] and national Fire Protection association (nFPa) 70e [10] provide safety guidelines, energy calculations, and safety categories for approach boundaries to enter and work on live equipment. The key to safety is removing all electrical power. safety hazards and equipment damage exposure exist when power cannot be removed. In these cases, the operator must adhere to the established safety procedures. in areas of potentially high incident energy, personal protection equipment (PPe) must be worn. however, even the best protective clothing required by the standards in nFPa 70e does not provide protection from explosive debris liberated from the initial pressure wave caused by an electrical arc.

The Arc

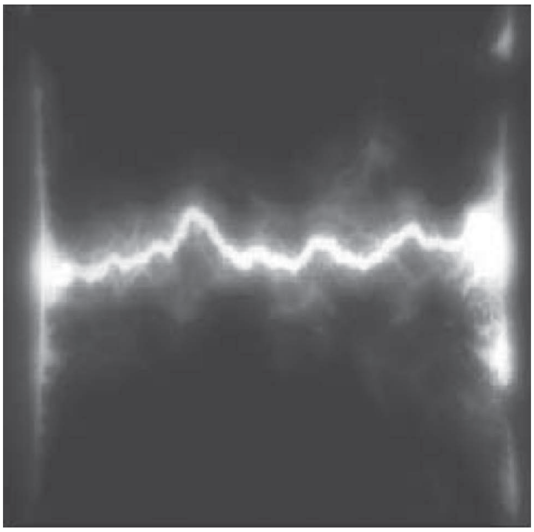

Figure 1 - The arc

It is important to understand some principles of the physical process that make up the formation of an electrical discharge to provide clarity of the events that lead up to and include the safe extinguishing of an arc flash. As a result of heat and or sufficient electrical pressure, electrons break free of their atoms near the surface of the conductor at the location of influence. This, in turn, develops a cloud of electrons through electron collision ionization. An ionic avalanche head builds and at a critical value converts to a streamer discharge. When the gap between the cathode and anode is short, the streamer bridges the gap (Figure 1), causing an arc transition and a complete breakdown [2]. However, if the gap is long, streamers will increase the temperature, continuing the thermal ionization and the development of leader discharges, where streamers further forge toward the anode. In medium-voltage systems, once the anode is reached by the streamer, a complete breakdown takes place, reducing the voltage between the gap and increasing the current between the two electrodes to values near bolted fault current. Regardless of the origin of the arc, the accompanying magnetic field generated by the current directs the arc to travel away from the source until the impedance of the gap is too high to sustain the arc. Damage is most evident at the point where the arc is sustained, presumably misleading forensic fault investigations to locations unassociated with the origin. The arc's plasma state ionizes the immediate surroundings, leaving a trail of ionized gas behind to restrike following each sin 0° of the source. Due to the heat of the arc, a rapidly expanding wave front is developed. It is this wave, producing the pressure, sound, and cloud of free electrons, that indicates additional arc restrikes within vicinity of the original arc.

Incident Energy of an Arc Flash

Because the impedance of the arc is purely resistive, it becomes one of the factors in the determination of the maximum arc fault current En in (1). incident energy, J/cm², is also dependent upon duration of the arc and distance from the arc [3]

$$E = 4.184\ Cf \times En\left(\frac{t}{0.2}\right)\left(\frac{610^x}{D^x}\right)$$

where E is the energy (Joules/cm²), En is the normalized current, Cf = 1 (>1,000 v), D is the distance from the arc (mm), t is the arc duration (s), and x is the distance # factor (table 1) [3, table 4].

Approach Boundaries by Incident Energy

The IEEE 1584 model for incident energy calculations provides a means to compute the flash protection boundary at medium voltages. Using overcurrent relay coordination, it is apparent that approaching exposed energized parts or performing breaker racking operations on medium-voltage switchgear puts operators beyond the flash protection boundary.

TABLE 1.
Factors for equipment and voltage classes

Systems Voltage (kv)	Equipment type	Typical gap between conductors (mm)	Distance x factor
0.208-1	Open air	10-40	2.000
	Switchgear	32	1.473
	MCC and panels	25	1.641
	Cable	13	2.000
>1-5	Open air	102	2.000
	Switchgear	13-120	0.973
	Cable	13	2.000
>5-15	Open air	13-153	2.000
	Switchgear	153	0.973
	Cable	13	2.000

Note that the distance x factor is used in 5.3 as an exponent.

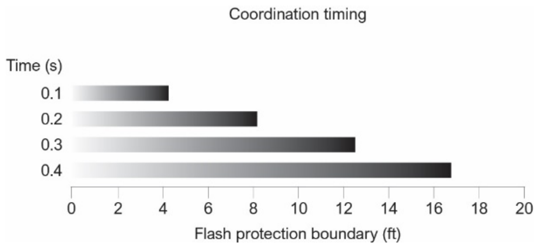

Figure 2 - The coordination of time overcurrent

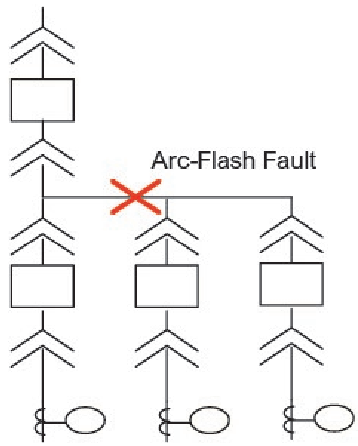

Figure 3 - Typical one-line with feeder arc flash.

Example 1

Using 50/51 relay coordination at 0.4 s with the assigned parameters, the capacity rating of the transformer is 25 MVA, V is 13,800, Z is 8%, and t is from 0.4 to 0.1 s. In this example (Figure 2), the flash protection boundary exceeds 10 ft as the coordination time of the protective relay exceeds 0.2 s, representing a constraint logistically unattainable in some installations with limited space.

When confronted with these circumstances, alternative techniques become necessary. One approach would be to manage the arc before it generates excessive incident energy, thus reducing the distance of the flash protection boundary. Another approach would be to lower the available fault current by changing the transformer impedance or capacity rating. This may adversely affect large motor starting ability at the site. Technologies that reduce the time of the arc exposure can be incorporated to minimize the incident energy and thus reduce the flash protection boundary distance.

Distribution Switchgear

In 1970s, circuit breakers evolved from oil-type plain break interrupters to vacuum breakers. Medium-voltage, metal-clad switchgear developed as a means of arc control and arc fault prevention. However, through lack of maintenance, improper procedures, human error, and racking mechanism problems, they continue to pose a threat of an arc fault. The majority of arc faults take place when human interface disrupts the quiescent state of the insulation barriers and connections. Opening the access door to a breaker compartment introduces a copious mixture of humidity, contaminants, and pressure change, which enables localized dust and debris to further degrade the insulation system. The fundamental metal-clad enclosure design has proven to minimize thermal arc fault incidents when the doors are closed but lacks the ability to impede the mechanical mayhem developed by overpressure generated by the arc. With an arc fault on the main bus, circuit breaker trip curves invite additional damage in feeders due to the intentional delay of the coordinated fault protection scheme (Figure 3).

During an uncontrolled arc, the typical medium-voltage protection schemes using 50/51 overcurrent relays do not respond to the arcing overcurrent in sufficient time to prevent serious damage. If the arc goes unchecked, heat at the location of the arc rises in temperature to plasmatic proportions. The metals associated with the anode and cathode of the arc can melt, causing a bolted fault elsewhere. In some instances, the inner enclosure wall becomes the anode, acting as a sacrificial anode spurting molten steel and generating additional conductive ionized gases. The thermal differential produces a severe pressure wave, which creates an explosion of hot gases, molten metals, and a devastating sound blast in excess of 140 dB. Even the best PPE equipment does not provide protection from the pressure wave or from the shrapnel typically associated with the blast. It only protects from the heat wave itself. Dynamite is an example of this energy. Each megawatt of arc power is analogous to one stick of dynamite, but with a slower pressure wave front [5]. The arc fault incident energy may be eluded with the correct PPE, but the fault will cause unrecoverable damage to the equipment, inhibiting the ability to repair and recover from the outage within a reasonable time frame. Prolonged arcing on the inner walls of the metal enclosure can burn through the wall, creating secondary compartment failures, which may cascade in an avalanche manner throughout the balance of the switchgear lineup.

Compendium of Solutions

Venting

Attempts have been made to insure the safety of the operating personnel by strengthening the enclosures to withstand the blast and venting the hot gases, molten materials, and shrapnel away from the operator. The pressure blast and thermal effects are redirected within the switchgear enclosure. Design enhancements include special hinges, a more robust structural skeleton, an automatic directional venting system, and improved wall integrity. This approach only proves effective when the integrity is maintained by the operator, as the doors are closed and there is a safe place to intentionally expel the gas [6]. Because the vented system intentionally allows the pressure wave and thermal wave to develop to extreme peak levels, internal unrecoverable cabinet damage is unavoidable. Arc-resistant switchgear relief vents open typically near 600 lbf/in2. In tight locations where other equipment exists and personnel are required to enter, venting is a limited option. When switchgear buildings are located in or adjacent to hazardous (classified) locations, venting the arc plasma to the exterior of the building is not allowed. Also, in industrial areas where corrosive atmospheres or volatile fumes exist, venting hot gases is clearly not an option.

Arc Detection

Proven technological advancements in arc management and operator safety have been ramping up. An example of such advancement is an optical arc-detection sensing system designed to recognize unwanted damaging arcs exhibiting magnitudes of typically >8,000 lx [7]. Fault current magnitudes and grounding schemes dictate actual values of lux generated. The evolution in optical arc-detection system reliability since the technology's first introduction in the 1980s has been significant. One such advancement is the inclusion of self-supervised algorithms, which continuously check and advise the status of the detection system. Modern arc-detection systems comply with American National Standards Institute (ANSI) C37.90—protective relay standard—in their electromagnetic interference compatibility requirements, a very necessary yet difficult design criteria to pass. Third-party tests are conducted to insure

compliance to standards such as radiated emissions from 30 MHz to 1 GHz (Figure 4), surge and electrical fast transient immunity to 4 kV, reliability and functional repeatability. In more advanced protection schemes, the initial rise in current detected in the current transformer is logically ANDed with a value of lumens detected by the optical sensors. The sensors are set to operate on higher lumens other than those caused by natural arc occurrences when opening or closing a circuit. Incorporating optical technology with circuit breakers operating within the typical three to five cycles (50–83 ms) minimizes the incident energy. Optical detection can reduce incident energy up to 1/8 of unabated arcs. Optical detection devices sense the arc and within 1–2 ms send a shunt trip signal directly to the appropriate circuit breaker. Adding optical detection technology in Example 1, and incorporating a three-cycle breaker, using t (total) = 50 ms
(breaker) + 2 ms (detection and activation) the flash protection boundaries shown in Figure 5 are established. Although this may appear to be sound solution, the arc and pressure wave continue to increase in magnitude while waiting for the circuit breaker to trip. Arc detection alone purports improved abatement of thermal effects but supports no degree of pressure minimization.

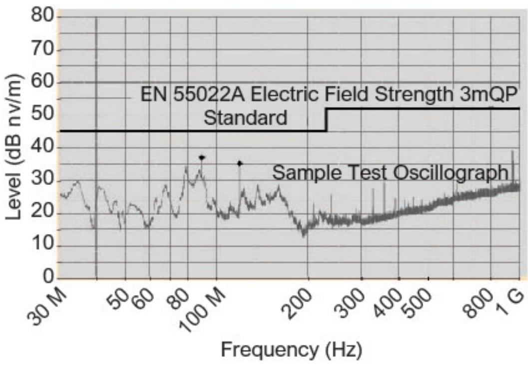

Figure 4 - Radiated emissions (a sample oscillograph of protective relay test)

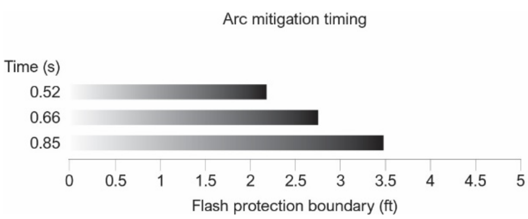

Figure 5 - Arc mitigation timing

Controlled Shunt Arc Management

The next generation of arc management technology introduces a comprehensive perspective in safety and equipment preservation. Topologies that include controlled arc management in concert with arc detection are now being incorporated into medium-voltage, metal-clad switchgear systems. Using a plurality of approaches to detect and manage an arc event by rapidly transforming the impedance parallel to the arc offers myriad of advantages. Parallel shunting can be accomplished in 6 ms. By inserting lower impedance in shunt with the arc as an alternative path, the arc fault is no longer in an electrical environment capable of sustaining an arc. The damaging thermal development is negated and pressure associated with the arc is reduced to safer levels tolerated in most IEEE C37.20.2, Standard for Metal-Clad Switchgear [9]. The optical detection system initiates the arc shunting device. A trip signal is directed to the appropriate circuit breaker bypassing the overcurrent protection relays. Arc management by way of a shunt impedance transformation takes place in 6 ms. The impedance of the arcing bus is taken to 0 X using a rapid-acting mechanical switch incorporating the principles of a tubular induction coilgun. Coilguns repel nonferrous projectiles out of a coil through the action of eddy currents induced in the projectile. This high-speed mechanism creates a three-phase crowbar actuating at speeds near 128 m/s. When using managed shunt impedance within a 40-kA system design, the integrity of personal safety remains intact with or without the enclosure doors open because the incident energy remains within NFPA 70E Hazard Risk Category 1, and the pressure wave does not have time to approach destructive peak values. The elimination of the arc prevents excessive incident energy levels from developing, limits the pressure wave, and prevents shrapnel discharge insuring limited damage. This translates to quick, inexpensive repairs as well as providing the maximum assurance of operator safety.

Example 2

In this 25-MVA Z = 8% example, extinguishing the arc after 6 ms, significant incident energy levels are realized beyond 30 in. Bolted fault current:

$$I_{bf} = \frac{MVA/Z}{V \times \sqrt{3}} = I_{bf} = \frac{25/0.08}{13.8 \times \sqrt{3}}$$

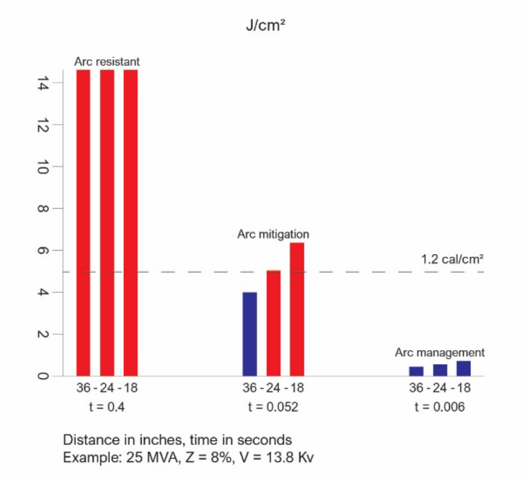

Figure 6 - Typical topologies timing is compared

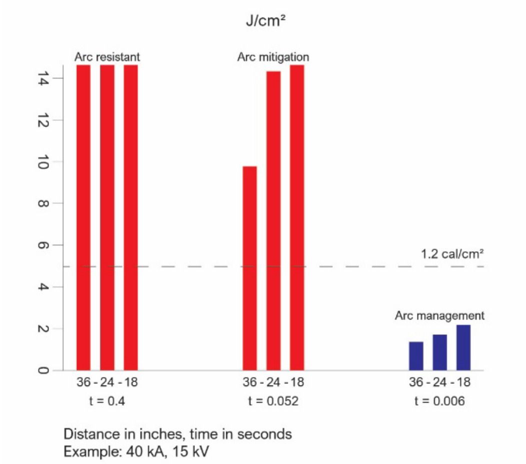

Figure 7 - Arc abatement topologies are compared at 40 kA.

$I_{bf} = 13.1\ kA$

Arcing fault current [3]:

$I_{arc} = 10^{0.00402+0.983\ Log\ I_{bf}}$

$I_{arc} = 12.63\ kA$

Normalize: IEEE 1584 Section 5, Table 4:

$K_1 = -0.555$ Box
$K_2 = -0.113$ Grounded
$G = 153$ Switchgear gap.

Normalized arc current [3]:

$Log(E_n) = K1 + K2 + 1.081 \times Log\ I_{Arc} + 0.0011G$
$En = 4.9\ kA$

Plot incident energy (E) from the normalized energy (En) for the flash protection boundary:

- 0.4 s 50/51 overcurrent coordination arc resistant
- 0.052-s arc detection
- 0.006-s arc management
- Cf = 1, >1 kV
- X = 0.973, distance factor, Table 1
- t = 0.4, 0.52, 0.006, vented, mitigated, managed
- D = 457, 610, 914 mm
- Displayed in inches: 36, 24, 18

$$E = 4.184\ Cf \times En\left(\frac{t}{0.2}\right)\left(\frac{610^x}{D^x}\right)$$

In Figure 6, the density of heat is compared using three technologies, a 25-MVA source at 8% impedance and assuming the switchgear enclosure doors are open. The times were selected based upon a three-cycle breaker and 400-ms coordination for overcurrent relays. In this example, approaching the switchgear would be limited without removing power or the use of multilayer flash suit other than with the arc management approach. In contrast, consider the high-voltage laboratory test requiring a full 40 kA of fault current. Figure 7 is presented to provide a snapshot of the density of heat of 15-kv switchgear in C70.20.7 test circumstances. It is obvious that innovative arc-abatement technology does make a difference.

Application Perspective

The three arc-control strategies have various impacts on the typical petrochemical application of medium-voltage, metal-clad switchgear. The venting arc control methodology, while preventing catastrophic damage to the surrounding equipment and facilities, presents significant challenges to the user of the equipment. These challenges include additional size and weight as compared with conventional metal-clad switchgear. Additional challenges are the plasma venting location (inside or outside of switchgear housing), the additional pressure associated with venting plenums, venting outdoors in or adjacent to hazardous/classified locations, the ineffectiveness during maintenance operations when doors need to be opened, the routing and installation of field and interconnecting cables, and other site-specific issues. The arc-detection strategy can offer various advantages, including possible retrofit applications to existing switchgear installations and less equipment damage due to faster detection and clearing time when compared with traditional overcurrent relay-based protection schemes. This methodology is not disabled during maintenance operations where doors or panels may be opened. This method also has a number of disadvantages including the requirement for a three-cycle upstream circuit breaker that can be activated by the arc-detection system quickly. The reduced damage would still be significant enough to require internal switchgear cleanup and repair before the equipment could be placed back into service. Another significant disadvantage would be the facility downtime and possible damage to the facility process and production systems that would result from a spurious trip or malfunction of the arc- detection system, resulting in a facility-wide power outage.

The arc management method using a shunt device offers further advantages over the arc-detection strategy as it generally builds on that technology. It can offer further reduction in available arc energy, which increases safety for the electrical operations and maintenance staff at the site. This method does not require a three-cycle upstream circuit breaker to isolate the switchgear and further reduces the damage to the equipment should an arc fault occur. One disadvantage of this method is the requirement for a shunt or bypass bus bar system or an additional section in the lineup to facilitate the shunt device suppression of an arc that may occur anywhere in the equipment. This method would also be subjected to similar spurious trips, as described above. Overall this methodology offers more advantages as compared with the other two arc mitigation strategies.

Timelines in Medium-Voltage Systems

In a medium-voltage system, the maximum arcing current within the fault reaches a calculated value ~96% of full fault current in solidly grounded system. However, if the arc were allowed to continue, the temperatures would transcend near 20,000 °C, causing vaporization of the electrode to a highly conductive explosive mixture. All materials, including copper, aluminum, steel, and conductive supports in the vicinity, would be converted to plasma, rendering toxic fumes, high carbon residue, and molten debris. The immediate elimination of the arc is the safest way to prevent catastrophic damage and ensure the safety of the personnel in the vicinity. The physics of an electrical arc provides the arc quenching alternative. When a parallel impedance lower than the impedance of the arc is present, the higher current path shunts the arc, which in turn extinguishes the arc. An alternate impedance only 5% lower than the arcing current impedance is sufficient to extinguish the arc. Optical detection technologies sense the arc in the early stages of the streamers photon liberation and are logically ANDed with an abnormal rise in current to initiate the arc quenching process. An electrical path parallel to the arc is engaged in less than half a cycle. This extinguishes the arc preventing temperatures and pressure waves from reaching their peak damaging and harmful values.

Arcing Currents in MV Systems

Examining the arcing current's magnitude and time domain provides a satisfactory snapshot of the timeline of the energies.

Example 3

For applications with a system voltage of 1,000 V and higher, IEEE Standard 1584-2002, Section 5.0, Model for Incident Energy, provides the means to compare the bolted fault current to the arcing current.
Using the parameters from Example 1,

$$Capacity\ rating\ transformer\ =\ 25\ MVA$$
$$Z = 8\%$$
$$I(bf) = 13\ kA$$
$$I_{arc} = 10^{0.00402\ 0.983 Log\ Ibf}$$
$$I(arc) = 12.63\ kA$$

The ratio between the full fault current and the arcing current is

$$I\ (arc)\ /I\ (bf\ )\ = 97\%.$$

Because arcing current reaches near bolted fault current, a lower impedance shunt path of only a few percent will extinguish the arc.

Fault Current Rate of Rise

The current in any arc fault rises exponentially in a relationship to the X/R ratio of the source. Typically, the time for the fault current to raise to its full magnitude I(arc) takes ~8 ms. Incorporating an arc impedance transformation at 6 ms removes the arc affording significant advantages to both the pressure wave and incident energy that create thermal damages. The maximum transfer of energy is when R(arc) is equal to the reactance of the source X(l). For the purpose of displaying the fault current rate of rise, the following is presented. The inductance can be found by

$$L = \frac{\sqrt{3} \times V^2}{\omega \times MVA/7}$$

Using the aforementioned parameters as an example,

$$V = 13{,}800$$
$$Z = 8\%$$
$$I(arc) = 12.63\ kA$$
$$MVA = 25$$
$$L = 2.79\ mHy$$

Theoretical R = watts (arc)/ I (arc)^2

$$R = \frac{\cong 0.7 \times 25M/0.08}{12.7K^2}$$

$$= 1.36\ \Omega$$

Rate of rise

$$I_{rise} = 1 - I(arc) \times e^{-tR/L}$$

It is evident that the arcing current rate of rise reaches a significant magnitude within the first few milliseconds, engendering potential safety hazards and damaging results if not addressed with comparable time abatement devices (Figure 8).

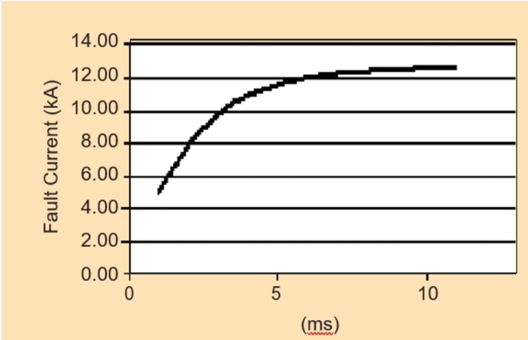

Figure 8 - Current rise time: there is a dangerous increase in magnitude within the first few milliseconds.

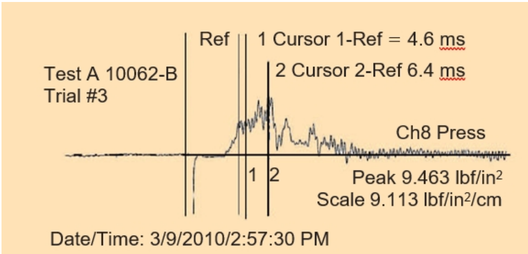

Figure 9 - The pressure wave during tests.

Pressure Wave

The complexity and variables that make up the pressure wave limit reasonable mathematic examples. However, under laboratory controlled arc-fault testing, the actual pressures are obtained by sensors and accelerometers. Expansion rates of 700 mi/h have been observed. Controlled tests of arc-flash events in an unmanaged system show that the peak pressure magnitude is reached at 9–10 ms after the arc is initiated.

The test laboratory ran a number of 40-kA fault tests on some medium-voltage, metal-clad switchgear of specific design in the first quarter of 2010. The metal-clad enclosures were standard IEEE C37.20.2 design yet incorporated arc management shunt impedance technology and optical detection. All sections of the enclosure were subjected to the C37.20.7 test standards. The pressure was recorded in each compartment under test, and histograms were developed (Figure 9). The arc management performed as designed in each test with an average of 5.1 ms to take the bus to zero volts. Pressures were recorded from 3.7 to 9 lbf/in2 at the point the voltage recorded zero; however, they continued to rise to a peak average of 13.8 lbf/in2 near 7 ms.

Arc-flash testing in accordance with ANSI C37 20.7 requires an arc-flash trigger comprised of a small-gauge wire shorting the bus. With power applied, the trigger wire burns open, initiating a 40-kA arc flash. The bus in Figure 10 is a simulation of a circuit breaker in the upper bus compartment.

Following the test event, the cloth barriers are inspected for damage due to burning from possible arc-flash energy exiting the gear, and the section is also inspected for damage caused by the pressure wave. By quenching the arc in the first half cycle, the only apparent sign of the event is a carbon trace (Figure 11). The pressure was halted at 5.5 ms, averting pressures that would otherwise create structural damage and pose additional safety hazards.

The condition of the PT drawer (Figure 12) following the arc-flash event (Figure 13) clearly demonstrates limited damage indicative of technology, which addresses the arc in the first half cycle. In contrast, Figure 14 displays the damage of an arc-flash event where the arcing was not limited by any arc mitigation strategy.

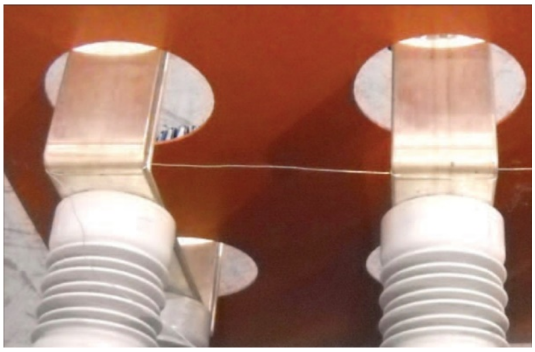

Figure 10 - The breaker arc-flash trigger is set up before the test. (photo courtesy of Shallbetter, Inc.)

Figure 11 - The breaker test damage results show only carbon residue. (photo courtesy of Shallbetter, Inc.)

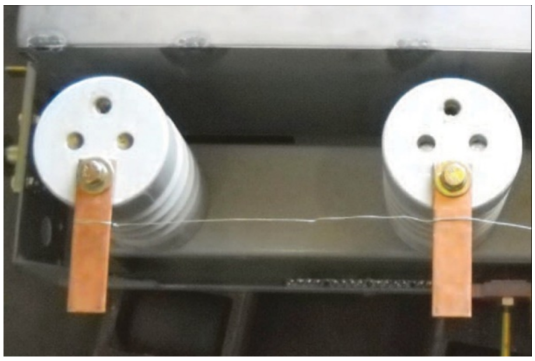

Figure 12 - The pT drawer arc-flash trigger is set up before the test. (photo courtesy of Shallbetter, Inc.)

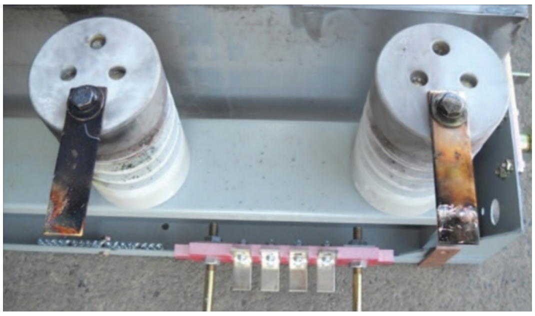

Figure 13 - There is limited damage to the pT drawer after an arc flash. (photo courtesy of Shallbetter, Inc.)

Figure 14 - The damage caused when there is no intervention can be catastrophic.

The results of the laboratory tests 1–6 (Figure 15) agree with the results of unabated arc-flash tests in that pressures peak near 10 ms but do demonstrate a much lower internal pressure. This result is typical when the arc is mitigated early in the cycle. As demonstrated, the internal pressures inside the switchgear due to internal arcing events do not reach such extreme levels as found in vented systems.

Other studies have concluded that internal equipment pressure can reach 90 lbf/in² within 10-ms time frames [11]. By examining arc resistant equipment, it is easy to conclude that unaddressed pressures are extremely hazardous when contained and are even more hazardous with the doors open. Limiting the pressure wave serves to diminish the characteristics that cause bodily harm.

IEEE 1584 Section 5 [3] and the SI conversion of joules to grams of TNT [12] provide a snapshot of the equivalent sticks of dynamite in an arc-flash event compared with timelines of different arc abatement technologies. The energy is devastating. Figure 16 illustrates the equivalent grams of TNT to corresponding sticks of dynamite for the following example.

Example 4

$$V(arc) = V \times (1 - Iarc/Ibf)$$

$$TNT = 1.73 \times Iarc \times Varc \times \frac{tarc}{4{,}184}$$

$$Sticks\ of\ dynamite = \frac{TNT}{230}$$

where V is 13,800, Ibf is 40 kA, Iarc is 32 kA, Tarc is 0.006–0.4 s, ton of TNT (energy equivalent)/KJ is 4,184, and TNT per stick is ~230g.

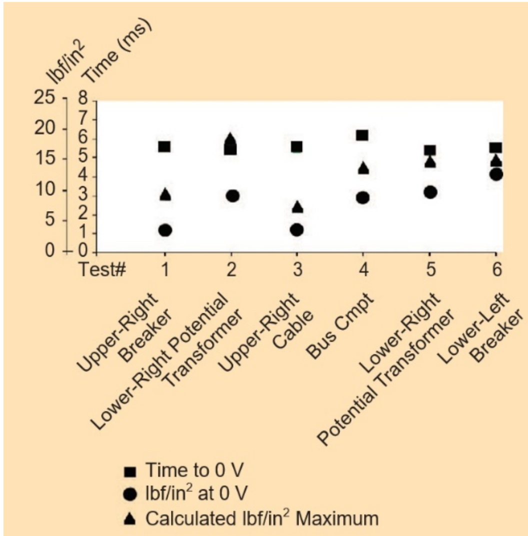

Figure 15 - ll laboratory test results are plotted.

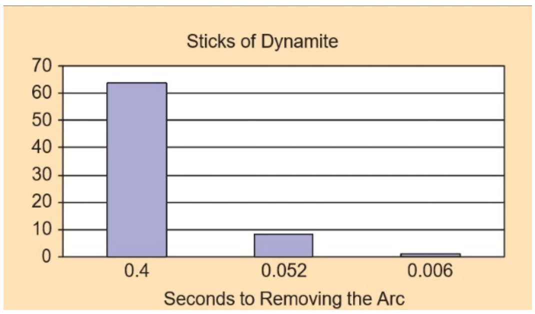

Figure 16 - Dynamite is compared with arc.

It may appear that high resistance grounding can provide some pressure relief by reducing the overall energy on line to ground faults but it is ineffective for line-to-line faults. The solution is to limit the time that the pressure has to develop. To do so, the arc must be extinguished before the peak development of the pressure wave. Allowing the wave to build to peak magnitudes generates serious explosive energy, which is sufficient to destroy switchgear enclosures, cascade to adjacent compartments, and cause death even with the proper PPE.

Pressure, I Rate of Rise, Incident Energy

Where flash protection boundaries must be minimized, the need of technologies to operate and limit the time frame of the arc-flash event is emphasized. Energy rise time is typically the same in medium-voltage asymmetrical arc faults. Obtaining a safer working environment and minimizing the equipment damage can be accomplished by reducing the time of arc exposure. During energized diagnostic procedures or other necessary exposed energized operations, a maximum arcing time of less than a half a cycle is recommended. When the arc plasma is allowed to continue for longer durations, the temperature continues to rise exponentially to fire flash points of the copper and steel. Arc energy, current rate of rise, and pressure follow the same rate of increase. Each was presented in this article to allow the reader to evaluate the coordination of an arc event in a time scale comparing the use of overcurrent detection used in metal-clad arc resistance enclosures, optical detection to bypass the coordination curves of the overcurrent protection, and arc removal through shunt impedance.

Conclusions

The preceding graphs of the current rate of rise, pressure development, and incident energy illustrate the dangerous levels of combined energies obtained within a half cycle at 60 Hz following the initiation of an arc event. To eliminate injury and equipment damage and provide for quick repair, it is clear that the duration of arc fault must be addressed before the energies reach their associated dangerous magnitudes. The actuation time of circuit breakers, three to five cycles (50–83 ms), plus their associated coordination settings to clear faults offer limited protection. Bypassing the coordinated trip settings with an arc-detection scheme limits some of the damage and reduces the incident energy. That of course assumes that no cascading faults in the adjacent compartments take place and the circuit breaker is maintained in good working order. Managing the arc fault by deploying a symmetrical impedance parallel to the arc before the damaging energy's development is essential to maintaining equipment integrity and assuring absolute safety. Controlled symmetrical impedance shunting all the conductors, and thus in turn shunting the arc generated on any phase conductor including ground faults, is advantageous to the protection of the electrical equipment and personnel. Medium-voltage arc faults are asymmetrical and approach 96% bolted fault conditions in solidly grounded systems. The application of controlled symmetrical shunt impedance to remove the arc elevates the arc fault current to bolted fault magnitudes, an increase of only 5%. Advantageously, in symmetrical controlled low impedance across the bus, the system, both source and load, is placed in an electrical environment conducive to the least potential damage.

Without a third-party IEEE C37.20.7 certified type-rated enclosure or using only optical recognition, de-energizing the entire system may be the only safe way to approach the gear for maintenance or repair. PPE will not be effective for a pressure blast with the doors of the switchgear opened.

Incorporating a symmetrical shunt impedance approach technology, which minimizes the pressure wave and greatly limits the incident energy, appears to be a sound solution for arc-flash management in medium-voltage switchgear. It overcomes the potential damaging drawbacks of vented switchgear and provides a level of safety unmatched by any other technology. The safety implications alone provide reasonable assurance that working flash boundaries are attainable and maintenance is permissible when working on some live systems. All of the technologies presented in this article offer some degree of operator safety. When space is limited, maintenance must be performed with power present, or approach boundaries are not attainable with PPE, the immediate elimination of the arc through controlled shunting is recommended.

References

[1] R. Lee, "The other electrical hazard: Electrical arc blast burns," IEEE Trans. Ind. Applicat., vol. IA-18, no. 3, pp. 246–251, May/June 1982.

[2] Dr. D. Sweeting, "Arcing faults in electrical equipment," in Proc. IEEE Petroleum Chemical Industry Conf., 2009, pp. 1–11.
[3] Guide for Performing Arc-Flash Hazard Calculations, IEEE Standard 1584, 2002.

[4] S. E. Lane, "Switchgear Developments."

[5] J. Lane, "Arc-Flash Hazard Analysis."

[6] E. W. Kalkstein, R. L. Doughty, A. E. Paullin, J. Jackson, and J. Ryner, "The safety benefits of arc resistant metalclad switchgear," in Proc. IEEE Petroleum Chemical Industry Conf. Rec., 1994, pp. 309–317.

[7] Instruction Manual, AQ 110 Arc Protection Unit, Rev 1.2, Arcteq Relays Ltd., Vaasa, Finland, 2010.

[8] Guide for Testing Metal-Enclosed Switchgear Rated up to 38 kV for Internal Arcing Faults, IEEE Standrad C30.20.7, 2001.

[9] Standard for Metal-Clad Switchgear, IEEE Standard C37.20.2,1999.

[10] Standard for Electrical Safety in the Workplace, NFPA Standard 70E, 2004.

[11] Safety by Design, Powell Application of Arc-Resistant Technology, AR:-045-20K, Oct. 2003.
[12] A. Thompson and B. N. Taylor, Guide for the Use of the International System of Units, 2008 ed., Special Publication 811, NIST, Gaithersburg, MD.

[13] C. St. Pierre, "Putting arc faults calculations into perspective," Electr. Const. Maintenance, June 1, 2004.

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