Arc Flash Mitigation Using Active High-Speed Switching

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Executive summary

One method of mitigating arc flash hazards associated with medium-voltage switchgear is the installation of active high-speed switch (HSS) systems. These systems are designed to detect and quench a burning internal arc in less than one-third of one electrical cycle. The internal arc is extinguished by the HSS's action of redirecting the fault current path from arcing through open air back to the intended current path of the switchgear bus. The new low-impedance current path provided by the HSS operation collapses the voltage at the point of the fault to near zero so that the arc is no longer sustainable. The system's high speed of operation compared to arc quenching via circuit breaker tripping translates directly to lower arc flash incident energy and minimal equipment damage. Another benefit of such active high speed systems could include switchgear compliance to the IEEE C37.20.7 guide for testing arc-resistant metal-enclosed switchgear without any arc by-product venting requirements. This paper explores application considerations of HSS systems relative to other available means of controlling and reducing the hazards of internal arcing faults in medium-voltage switchgear.

Schneider Electric

Index Terms—Arc flash incident energy (AFIE), arc resistant, arcing fault, bolted fault, high-speed switch (HSS), X/R ratio.

Introduction

The mitigation of arcing fault hazards in medium-voltage switchgear is an urgent concern that is being addressed in many ways by safe work practices, operator training, and innovative products and installations.

The high-speed switch (HSS) system is one of those options. It is conceptually very simple and effective but often viewed skeptically as a radical approach that places too much stress on the power system when it operates. In fact, it does transfer an internal arcing fault to the switchgear bus which does create a bolted fault on the system. When the HSS control system detects illumination with characteristics similar to that of an internal arc, confirmed by a corresponding rate of change of current, an arc flash event is declared, and the normally open HSS very rapidly closes to create a three-phase bolted fault, which thereby extinguishes the higher impedance internal arc, such as that shown in Fig. 1. Some HSS designs may operate based on other characteristics from internal arcing other than light and current, such as temperature, pressure, sound, harmonics, etc.

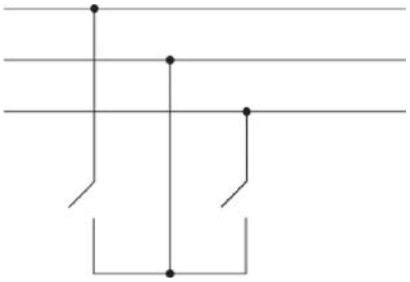


Figure 1
HSS typical schematic

The bolted fault remains on the system until cleared by the source overcurrent device. The stress of a bolted fault is certainly a valid concern, but the HSS should not be dismissed without carefully considering the benefits provided. The intrinsic benefits are as follows:

1) speed of operation:
    a) effective incident energy (arc flash) reduction;
    b) reduction of equipment damage and corresponding downtime due to an internal arcing event;
    c) reduction of motor contribution to an internal arcing event;
2) effective protection even with exposed live parts;
3) independence from overcurrent coordination and arcing fault current variations;
4) no impact on switchgear room (no additional ventilation or ducting requirements).

These benefits translate to improved worker safety, procedural simplicity, power system reliability, improved system availability, and, in some cases, reduced installed cost.

Benefits

Speed of Operation

Commercially available HSS systems detect an arc and close in approximately 4–6 ms (0.24–0.36 cycle at 60 Hz). In contrast, modern vacuum circuit breakers can typically detect and clear an arcing fault in not less than 50 ms (3 cycles at 60 Hz), considering overcurrent or flash detection relay trip contact closure time plus circuit breaker clearing time. In many cases, the operating time is greater than 50 ms, depending on the use of lockout relays, relay and circuit breaker vintage and vendor type, and other variables. Lockout relays add one cycle. In retrofit scenarios, older circuit breakers may be 5 or 8 cycle rated.

HSS is therefore about ten times faster than the fastest circuit breaker-based arc detection and quenching schemes, which leads to the following benefits.

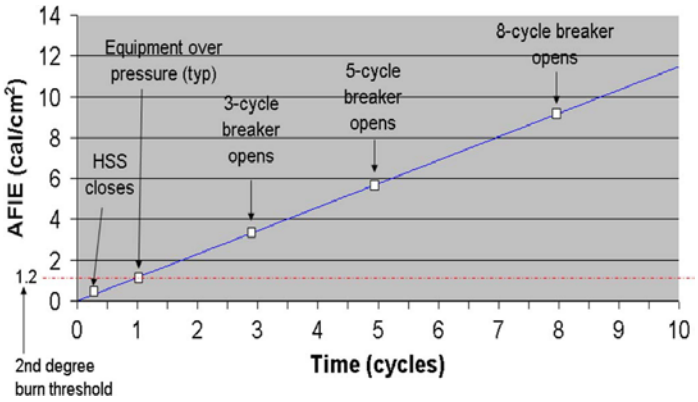
1) **AFIE Reduction**: Arc flash incident energy (AFIE) is directly proportional to the time required to extinguish the arc [1].

   Accumulated AFIE versus time is shown in Fig. 2 for an arbitrary example system: 13.8-kV system with 50-kA available fault current, solidly grounded using standard 36-in (914 mm) working distance and 153-mm bus gap per IEEE 1584 [1].

   For the Fig. 2 example system, AFIE calculations for switchgear with HSS result in less than 1.2 cal/cm2 (the industry referenced second degree burn threshold). At this calculated AFIE, non-melting or untreated natural fiber clothing may be worn along with hearing protection, eye protection, and leather gloves as needed. For the best case circuit breaker tripping times shown in Fig. 2, heavier personal protective equipment (PPE) with flame resistant clothing is required for higher energy exposures. PPE for higher energy exposures is progressively more bulky, hot, and difficult to work in due to loss of visibility and dexterity. Workers are relieved to get out of PPE in hot locations (although there are cooling systems available to lessen the discomfort).

Figure 2

AFIE accumulation versus time example



2) **Equipment Damage Reduction:** Arc blast effects can destroy equipment with the same phenomena that kill and injure people. The IEEE Std. C37.20.7 guide for testing arc-resistant metal-enclosed switchgear [2] does not include internal equipment destruction as a failure criterion. Rework or replacement is expected.

   HSS manufacturer tests and actual field events, however, illustrate that the fast arc quenching limits the damage to the point of the arc occurrence, with minimal additional damage. As a result, troubleshooting, repair, testing, and return to service are simplified and relatively quick. “As a general rule, removing the fault quickly will minimize the damage; however, the overpressure event typically occurs in a time frame of less than 1 electrical cycle” [2].

   For medium-voltage switchgear, HSS systems are the only available devices to date that can compete with the speed of overpressure and equipment destruction, as illustrated in Fig. 2.

Figs. 3–5 demonstrate an actual field operation of an HSS system during an internal arcing event at a large U.S. health care facility and the corresponding minimized equipment damage.

Figure 3
View inside rear cable compartment. Note the aluminum main bus access cover panel incorrect placement and the exposed main bus compartment.

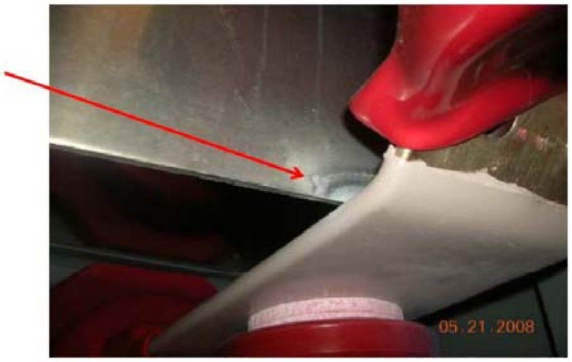


Figure 4
Close view of a phase bus runback. Note the aluminum main bus access cover panel resting on phase bus.

Figure 5
Close view of visible arcing indications to grounded metallic parts (side sheet shown in detail).

The cause of the internal arcing event was the incorrect placement of a main bus access cover inside medium-voltage metalclad switchgear. The switchgear was energized with the metal panel lying on top of two phase buses while simultaneously resting against the side sheet (at ground potential). Damage was minimal. The switchgear was returned to service without further problems on the same day after replacing the affected phase runback bus bars.

3) **Reduction of Motor Contribution to AFIE**: Large induction and synchronous motors can contribute significantly to AFIE in some industrial settings. The medium-voltage feeder breakers supplying motor loads will not trip for motor contribution levels in many cases, so the full motor contribution can persist for several cycles regardless of the main circuit breaker tripping time. In the case of bus differential relay application, the motor contribution will persist until it decays to zero or the associated bus lockout relay and feeder breaker trips, whichever comes first.

> HSS addresses this issue in large measure due to the fast arc quenching time. Again, the margin of improvement is approximately a factor of 10, based on the speed of quenching the arc via HSS versus circuit breaker.

Effective Protection with Exposed Live Parts

The IEEE Guide C37.20.7 guide for testing arc-resistant metal-enclosed switchgear [2] states that "The use of equipment qualified to this guide is intended to provide an additional degree of protection to the personnel performing normal operating duties in close proximity to the equipment while the equipment is operating under normal conditions." The standard excludes alteration of the equipment from normal operating condition and from activities above or below the equipment, such as catwalks, installations on open grating, cable vaults, and so forth. Any opening in the equipment invalidates the arc resistant category and can expose personnel to the full effects of the arcing event. Arc-resistant switchgear is arc resistant only when all covers are secured in place.

HSS systems, however, operate effectively regardless of exposed live parts or the personnel performing work above or below the equipment. Working around exposed live parts should normally be prohibited, but situations can and do arise where the risks associated with equipment shutdown exceed the risks of working with the equipment opened.

Independence from Overcurrent Coordination

HSS systems rely on light sensors, current transformers, and possibly sensors for other parameters to detect an arc and initiate HSS closing. The bolted fault current resulting from HSS actuation has to be cleared by the source overcurrent device within the withstand ratings of the switchgear and HSS system, but the protection of the worker is effective even if the relays in the system are improperly coordinated or if the arcing fault magnitude is not as anticipated.

The selective coordination of overcurrent devices is often in direct conflict with the need to trip the source circuit breaker(s) as fast as possible for arc flash hazard mitigation purposes. For example, if the instantaneous trip level is above the lowest arcing fault current magnitude, the relay may not trip instantaneously, resulting in high AFIE. On the other hand, if the instantaneous trip level is set low enough to trip quickly for all possible values of arcing current, selective coordination with downstream devices is frequently compromised. Therefore, all values of arcing fault current magnitude must be considered from highest to lowest. This requires careful judgment and frequent tradeoffs between selective coordination and AFIE mitigation. There are many reasons that arcing fault current levels can change, including utility system upgrades or system switching, plant switching between main, tie, and in-plant generator circuit breakers, varying quantities of running motors, and so forth. Additionally, many times, the utility system changes without the customer being made aware.

Various means of addressing these issues have been implemented with success.

Bus differential relays are fast (approximately 80 ms from overcurrent detection to arcing fault elimination) yet inherently selective but cannot detect arcing faults outside the protected zone current transformers, which, in most metalclad switchgear, do not encompass the cable compartments. For example, the bus differential relays installed at the health care facility cited in this paper did not detect the arcing fault condition because the bus differential current transformers are inside the breaker cell while the fault occurred in the cable compartment. Another example is that, while a worker may have an additional degree of protection when racking a breaker from the front of the equipment, he may not be protected if the cable compartment is opened.

Zone selective interlocking schemes (approximately 80 ms from overcurrent detection to arcing fault elimination), also called fast trip schemes, achieve selective coordination via restraint signals from the feeder circuit breakers going back to the main. If the main detects a fault but receives a restraint signal from the feeder, the main breaker relay times out normally per its time–current curve, allowing the feeder to selectively clear the downstream fault. If the main detects a fault without a restraint signal, the main trips instantaneously since the fault logically must be on the switchgear bus. The main circuit breaker relay must, however, detect the fault at arcing current level, and it must still coordinate with the feeder. Feeder breakers cannot be permitted to trip on motor contribution; otherwise, they will restrain the source breaker(s) and defeat the scheme entirely. Multisource lineups such as main–tie–main add still more complexity.

Alternative maintenance setting switches (approximately 80 ms from overcurrent detection to arcing fault elimination) are used to lower relay pickup levels and sacrifice coordination only when personnel are present or maintenance is being performed. Again, the main circuit breaker relay must detect the fault at arcing current level, and careful procedural rules must be implemented to ensure that personnel do not forget to turn on the maintenance trip settings when beginning the work or forget to turn it off when done. Occupancy sensors have been used to turn on inputs to electronic relays that automatically lower the relay instantaneous settings and then restore them when personnel leave. While the reduced settings are in effect, there is a possibility of nuisance nonselective tripping.

Arc flash detection relays (52–57 ms from arc detection to arcing fault elimination) that combine light sensors, current sensing, and high speed relay outputs are immune to overcurrent coordination and arcing fault current magnitude but rely on the relatively slow circuit breaker tripping to quench the arc. HSS systems (4–6 ms from arc detection to arcing fault elimination) are likewise immune to the downstream coordination and arcing fault current magnitude considerations but have the advantage of speed. The short-circuit withstand rating of the HSS itself is all that needs to be considered in setting the source circuit breaker relays with regard to arc flash protection. For circuit breaker-based arc quenching (other than arc flash detection relays), relay settings are critical and must consider all possible arcing fault current magnitudes.

Power system short circuit, coordination, and arc flash studies must be kept up-to-date and relay changes implemented as necessary. This statement is always true, but for HSS installations, it is less critical because the arc flash hazard protection is unaffected. A related benefit is that selective coordination for critical systems is made much simpler.

No Impact on Switchgear Room

Arc-resistant switchgear that relies on circuit breaker tripping must have a safe path to vent the arc by-products. Ceiling and wall clearances, overhead equipment, doors, windows, building capability to absorb pressure wave, fireproofing, weather, and vermin ingress are among the considerations. Additionally, the arc-resistant switchgear may be larger and heavier than the standard switchgear. These factors can grow the size, cost, and complexity of the switchgear room. Some HSS systems have been tested and comply with IEEE C37.20.7 [2] (all accessibility types: 2, 2B, and 2BC), and they negate the need to purchase passive arc containment (heavily reinforced cubicles).

HSS system installations may require an additional section to accommodate the HSS; otherwise, the installation is identical to that of the standard non-arc-resistant switchgear, as no arc byproducts need to be accommodated.

Other Considerations

Creation of Bolted Fault Stresses

Medium-voltage arcing faults are high magnitude, as determined by the following IEEE 1584 [1] calculations and as shown in Fig. 6:

$$\log I_a = 0.00402 + 0.983 \log I_{bf} \qquad (1)$$

$$I_a = 10^{\log Ia} \qquad (2)$$

where

I_{bf} bolted fault current (in kiloamperes);
I_a arcing current (in kiloamperes).

Fig. 6 stops at 63 kA, which is the highest currently available interrupting rating for medium-voltage metal-clad switchgear.

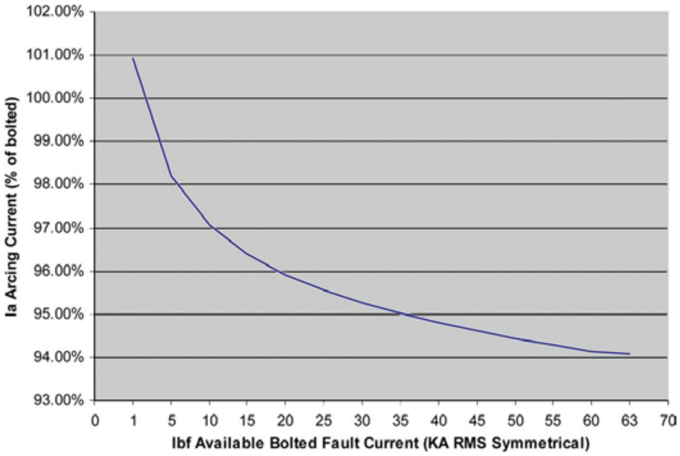


Figure 6
Arcing fault current as percent of bolted fault current.

Arcing fault magnitudes are calculated at greater than 94% of the bolted fault magnitude.

However, these RMS symmetrical magnitude comparisons do not yield an accurate picture of the HSS applying a bolted fault in an approximately 1/4 cycle after the arcing fault occurrence. The arcing fault circuit X/R in most medium-voltage systems will be in the range of 2.5–4 when calculated, assuming that the arc is purely resistive [8], [9], as calculated per Appendix A. The bolted fault circuit X/R will typically be a much higher value than this for most medium-voltage systems. Therefore, the dc offset component of fault current will suddenly increase when HSS actuates. The peak current will be nearly as high as it would be for initial closure directly into a bolted fault, even though the RMS symmetrical ac component will be only a few percent higher. Note, however, that the worst case peak currents following HSS actuation cannot exceed bolted fault levels, although they are quite close. Calculations for the fault current waveforms are shown in Appendix B.

Therefore, momentary and interrupting duty on the source overcurrent device, switchgear bus, and other system equipment should be considered to be equal to bolted fault levels, regardless of whether HSS system is installed or not.

This is not a new concern for system design or equipment ratings, although it might be considered by some as unwise to apply the HSS and intentionally subject the system to the possibility of a bolted fault. This is a judgment call that has to be weighed against the significant advantages of HSS system installation.

Transformers and large medium-voltage induction and synchronous motors are expensive and long-lead time equipment that are of particular concern with regard to application of HSS. These concerns are discussed hereinafter.

1) **Transformers**: Transformer design standards require withstand of bolted through-faults. The through-fault protection curves stop at 2-s duration. Refer to Fig. 7 for an example [4]. In this example, a transformer with 4% impedance must withstand 25 times (1/0.04) the normal base current for 2 s. Any properly coordinated system, with arc-resistant equipment or not and with an HSS system or not, meets the appropriate curve requirements and protects the transformer for all symmetrical fault currents shown on the curves.

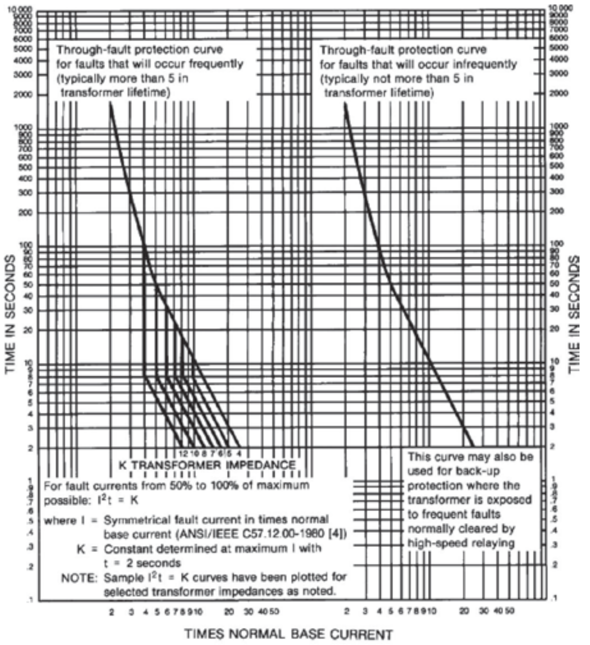


Figure 11-21—Through-fault protection curves for liquid-immersed Category III transformers (1668–10 000 kVA single-phase, 5001–30 000 kVA three-phase)

Figure 7

Transformer through-fault protection curve example (from IEEE Std.242-2001 (Buff Book) [4]).

Even for high X/R ratios found in medium-voltage systems, the asymmetrical dc offset current will have decayed to zero well before the transformer damage curve is approached. For example, a system X/R ratio of 25 results in an L/R (inductance/resistance) time constant of 0.066 s for a 60-Hz system

$$L/R = (X/R)/(2\pi f) = 25/(2 * 3.1416 * 60) = .066. \quad (3)$$

Five time constants (0.33 s) later, the dc offset magnitude is less than 1% of the maximum dc offset. Therefore, the additional dc offset transient caused by HSS operation is not usually an important factor with regard to transformer through fault curves.

DC offset transient current is, however, critical to electromagnetic force on current-carrying parts. This force is proportional to the peak current squared, which does include the asymmetrical dc offset and is a function of the system impedance and X/R ratio. Symptoms of accumulated mechanical stress on transformers include insulation compression, insulation wear, and friction-induced displacement. Again, the transformer design and test standards address this concern by defining the first cycle asymmetrical peak that the transformer must withstand [5], [6]

$$K = I_{SC\ (\text{peak asym})}/ISC\ (\text{sym RMS}) \quad (4)$$
$$K = \sqrt{2}\ (1 + e^{-\pi/(X/R)}). \quad (5)$$

These half-cycle asymmetrical peaks are based on the worst case zero closing angle on the voltage wave and equate to the withstand ratings required for the metal-clad switchgear where HSS is installed. Proper system design and specification takes the asymmetrical factor into account, and again, this should be true regardless of HSS installation or not.

2) **Medium-Voltage Motors:** For the first few cycles after a fault at the motor terminals, induction and synchronous motors initially supply the ac component current to a fault based on motor subtransient reactance X”d, followed by ac and dc decay to zero after several cycles. The dc component depends on the fault point X/R ratio and the point-on-wave of fault initiation. For HSS application, the important considerations are the thermal effects and electromagnetic forces on motor current-carrying parts, which are proportional to the total peak current squared.

Equation (5) can be used to compare the short-circuit duty imposed by an arcing fault being allowed to remain on the switchgear bus, compared to a bolted fault initiated by HSS. For a 2500-hp motor with X/R = 20 at 4160 V, the full load current is 347 A, assuming that 1 HP = 1 kVA. For the Xd” value of 0.1 per unit, the worst case initial symmetrical bolted fault contribution is 3470 A. The arcing fault contribution calculated by (1), and indicated in Fig. 6, is 3429 A. The arcing fault X/R calculated per Appendix A is 6.13. Neglecting the motor supply conductors, the bolted fault X/R for the motor contribution is 20. Comparing the results for K in (5) using these two values of X/R shows that the bolted fault peak current due to HSS operation is 116% of the peak current due to an arcing fault alone, resulting in 135% electromagnetic force on the motor windings when the HSS closes versus the forces generated by an arcing fault that is cleared normally. The same 2500-hpmotor except with a Xd” of 0.167 results in 106% peak current ratio and 113% electromagnetic force. The same 2500-hp motor except with a Xd” of 0.2 results in only 100.5% peak current ratio and 101% electromagnetic force.

The point here is that large motors can, in many cases, be applied in HSS-equipped systems without the greatly increased risk of damage due to peak short-circuit current contribution but should be evaluated using realistic machine impedances as well as manufacturer input. There are many other application design considerations for systems with large motors, but none that the authors would consider to be affected by the use of HSS.

In summary, the bolted fault is not a new concern for system design or equipment ratings. In many cases, the significant advantages of HSS will override this concern.

Arcing Ground Faults

Arcing ground faults on solidly grounded medium-voltage systems are expected to escalate to three-phase faults [1]. HSS operation is the same for a three-phase fault.

HSS system manufacturers are aware that impedance grounded systems are often applied at medium voltage, that the resulting low ground fault current magnitudes reduce the probability of an arc developing, and that the fault should be cleared or annunciated by system ground fault relays, depending on system design. Minimum current HSS actuation levels are built into the electronics detection logic to prevent unnecessary HSS closing operations.

Ungrounded medium-voltage systems should not be used regardless of whether HSS system is present. HSS should function as intended with any type of system grounding other than ungrounded.

Power System Stability

For sophisticated power systems with multiple utility sources, in-plant standby generation, cogeneration, and so forth, network stability simulation analyzes the effect of network disturbances on the system. Disturbance types include utility isolation, fast transfer, motor starting, fault study, loss of generation, relay operation, etc.

The thought that an internal arcing fault would not cause loss of stability where a bolted fault (due to HSS actuation) would is questionable. Stability analysis would have to be done to prove such a scenario for an arcing fault at 94% or more of the bolted fault current, and then, the user would be relying on the good fortune of not ever having a bolted fault occur. Stability studies are most often based on the worst case three-phase bolted fault [7]. HSS system application should have no bearing on the stability issue.

Conclusion

The HSS system may be likened to an automobile airbag. Hopefully, it will never have reason to operate for the entire life of the equipment, but if needed at any time, it must operate instantly. Nuisance operation is unforgivable. The device cannot be tested in normal operation. It has to be trusted.

HSS designs have not been in existence for very many years. As time passes, more success stories that confirm the robustness that manufacturers claim for the switch, light sensors, and electronics are expected.

HSS systems should be seriously considered for installation in medium-voltage switchgear. Other means of enhanced equipment protection from arc flash hazards are available. Switchgear size, importance, cost, complexity, growth needs, and architectural considerations should be considered along with plant safe work practices, procedures, and other available arc flash mitigating features.

HSS systems may be a viable solution to arc flash hazard mitigation in particular situations such as the following:

1) where equipment is expected to be opened while energized;
2) where other means of AFIE reduction do not reach the target PPE category;
3) where selective coordination is most critical;
4) where extended switchgear downtime cannot be tolerated;
5) where the switchgear location cannot accommodate venting mechanisms for arc by-products.

A risk versus benefit analysis is recommended when installing HSS on the secondary of older or less robust power transformers that, due to operating history or test results, are considered near end of life.

Large medium-voltage motors should be evaluated for use on HSS-equipped systems using actual machine and supply conductor impedances as well as manufacturer input. In many cases, the additional stresses placed on the motor due to HSS closing will be minimal.

HSS systems can provide substantial rewards without exposing the power system to undue risks beyond the unavoidable.

Appendix A

Arcing Fault X/R Ratio Calculations

Medium-voltage arcing fault current is calculated based on bolted fault current per IEEE 1584 [1]

$$\log Ia(KA) = 0.00402 + 0.983 \log Ibf$$

$$Ia(A) = (10\text{^}\log Ia) * 1000.$$

The X/R ratio for the arcing fault current is based on a purely resistive arc as mentioned in [8] and [9]. Refer to Fig. 8 for the equivalent circuit.

The arcing fault X/R ratio is calculated as follows:

Z1 bolted fault=Z1 sys=VLN/Ibf (ohms),

where VLN=Vsys/sqrt3

$Xsys = Z1\ sys * \sin(\tan^{-1} X/R)$

$Rsys = Z1\ sys * \cos(\tan^{-1} X/R)$

Z1 arc fault=VLN/Ia (ohms), where VLN=Vsys/sqrt3

Z1 arc fault=Z1 sys in series with Rarc

$Z1\ arc\ fault = sqrt\ ((Rsys+Rarc)^2+Xsys^2)$

$(Z1\ arc\ fault)^2=(Rsys+Rarc)^2+Xsys^2$

$(Z1\ arc\ fault)^2=Rsys^2+2 * RarcRsys+Rarc^2+Xsys^2$

$Rsys^2+2 * Rarc * Rsys+Rarc^2+Xsys^2$

$- (Z1\ arc\ fault)2=0$

$Rarc^2+2 * Rarc * Rsys$

$+ (Rsys^2+Xsys^2 - (Z1\ arc\ fault)^2) =0$

Solve for x = Rarc using quadratic equation : ax^2+bx

$+c=0$

$a=1,\ b=2 * Rsys,\ c=Rsys^2+Xsys^2-(Z1\ arc\ fault)^2$

$Rarc = (-b +/- sqrt(b^2 - 4 * a * c))$

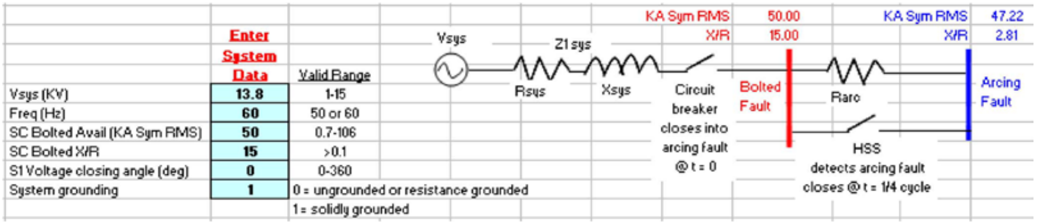
$/2a$ (quadratic solution)

Arcing fault X/R = Xsys/(Rsys+Rarc).

For the Fig. 8 example circuit, an arcing fault occurs on a 13.8-KV system with 50-kA RMS symmetrical amps available at X/R = 15. The resulting expected arcing fault current is 47.22 kA at X/R = 2.81.

Figure 8

Arcing fault equivalent circuit with HSS



	Enter System Data	Valid Range
Vsys (KV)	13.8	1-15
Freq (Hz)	60	50 or 60
SC Bolted Avail (KA Sym RMS)	50	0.7-106
SC Bolted X/R	15	>0.1
S1 Voltage closing angle (deg)	0	0-360
System grounding	1	0 = ungrounded or resistance grounded 1= solidly grounded

KA Sym RMS 50.00

X/R 15.00

KA Sym RMS 47.22

X/R 2.81

Appendix B

Fault Current Calculations and example

Figs. 9 and 10 show the waveform plots for the circuit parameters of Fig. 8. Sustained arcing fault current and sustained bolted fault current waveforms were calculated per [10, eq. (3.2.10)]

$$\mathrm{I}(t) = \mathrm{V_m}/\mathrm{Z}[\sin(wt+\theta-\ \varphi)\ -(\sin(\theta-\ \varphi)\ \in^{-\alpha t}]$$

where

$\mathrm{V_m}$ maximum line-ground voltage = $\sqrt{2}\mathrm{V_{sys}}/\sqrt{2}$;

Z Z1 positive sequence impedance magnitude (in ohms);

ω angular frequency(radians/second) = 2πf;

f frequency (in hertz);

t time (in seconds);

θ fault closing angle on the voltage waveform (in radians);

φ fault power factor angle = arctan (X/R) (in radians);

α R/L.

HSS current waveforms were calculated as follows.

For $0 < t \leq 0.004167$ second (1/4 cycle)

$$\mathrm{I}(t) = \mathrm{V_m}/\mathrm{Z}[\sin(wt+\theta-\ \varphi)\ -(\sin(\theta-\ \varphi)\ \in^{-\alpha t}]$$

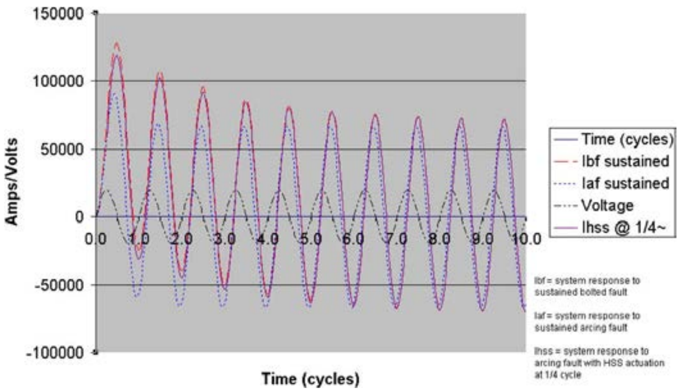
where system parameters are based on arcing fault circuit.

For $t > 0.004167$ second (1/4 cycle)

$$\mathrm{I}(t) = \mathrm{V_m}/\mathrm{Z}\left[\sin\begin{array}{c}\left(\omega(t-\ .004167)+\ \theta+\frac{\pi}{2}-\ \varphi\right)\\ -\ \sin(\theta+\pi/2-\ \varphi)\in^{-\alpha(t-0.004167)}\end{array}\right]$$
$$+\ \mathrm{I}(0.004167)\in^{-\alpha(t-0.004167)}$$

where system parameters are based on bolted fault circuit.

Figure 9
Waveforms resulting from the circuit of Fig. 8.



Ibf = system response to sustained bolted fault

Iaf = system response to sustained arcing fault

Ihss = system response to arcing fault with HSS actuation at 1/4 cycle

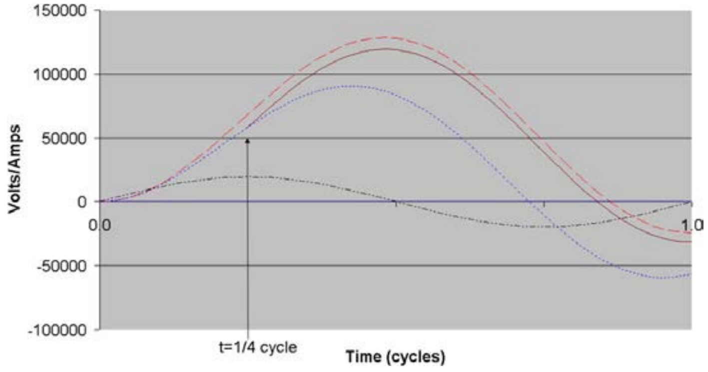


Figure 10
Close-in view of first cycle of Fig. 9.

Note that the HSS current waveform is between the sustained arcing fault waveform and the bolted fault waveform.

The maximum peak current for the HSS closing is 119.3 kA, compared to 128.3 kA for the bolted fault. The HSS closing transient is 93% of the bolted fault.

The zero closing angle results in the worst case current magnitudes for directly closing into a bolted fault, but the maximum magnitude for the HSS closing transient for this situation occurs at a 342◦ closing angle, instead of the zero angle shown. For the 342◦ closing angle, the HSS closing operation results in the peak magnitude of 121.6 kA or 94.8% of the bolted fault peak magnitude. Therefore, for the circuit parameters of Fig. 8, the maximum peak fault current due to the closing of HSS will be 94.8% compared to closing directly into a bolted fault.

The interrupting duty for circuit breakers at three cycles and beyond is essentially equivalent when comparing HSS closing to closing directly into a bolted fault.

The application of HSS cannot cause the peak momentary or interrupting duty to increase to higher than the bolted fault levels.

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