

CONSIDERATIONS FOR THE APPLICATION OF A MV HIGH SPEED GROUNDING SWITCH FOR ARC FLASH MITIGATION OF LV EQUIPMENT

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Abstract - This paper expands on the work of a previous paper that presented the possibility of a significant reduction of incident energy on the secondary of medium voltage to low voltage (MV-LV) transformers with the combination of a high speed grounding switch (HSGS) and traditional MV current limiting (CL) E-Rated fuses. It was shown that when the HSGS is applied at a location between the E-rated fuse load terminals and the transformer's primary connection and controlled by relays on the LV side, incident energy can be reduced to less than 1.0 cal/cm². Whereas the first paper focused on the results from a high power test lab, this paper discusses issues related to its application on typical power systems and lessons learned from installations at several locations. Application considerations include a review of relay requirements, coordination of E-Rated fuses, requirements for resistance grounded systems, modeling in analysis software and field installation considerations.

Index Terms - Current limiting fuses, fuse interrupting time, high speed grounding switches, short circuit capacity (SCC), protective device coordination, arc flash mitigation.

I. INTRODUCTION

Low Voltage (LV) equipment connected to the secondary of transformers protected by MV E-rated fuses often have potential incident energy levels greater than conventional arc rated PPE. Although the current limiting (CL) performance of MV fuses provide many benefits for large faults on the primary side of the transformer, the relatively low currents of secondary arc faults are well below the threshold current of the primary fuse. With clearing times in excess of 2 seconds, equipment connected to the low voltage side of these transformers often has incident energy greater than 40 cal/cm².

The arc flash mitigation solution discussed in this paper is the one first presented in [1]. When controlled by an arc flash relay, the MV High Speed Grounding Switch (HSGS) was shown to have the capability to reduce incident energy to below 1.2 cal/cm², the level accepted as that required for the onset of a 2nd degree burn. With the operating speed of the system, arc flash analyses of typical installations with the IEEE 1584-2002 [2] method shows this approach to be very

effective in mitigating arc flash hazards at facilities that have MV to LV transformer sizes from 750KVA - 5000KVA.

Referring to Fig. 1, the HSGS is placed downstream of the E-Rated fuse. With this approach the HSGS can be closed within 4 milliseconds of initiation of an arc on the LV side. By placing 0V on the transformer primary with the grounding switch, the LV arc is extinguished in milliseconds. As was shown in [1], the current limiting fuses protecting the transformer primary will open within 1/2 cycle after the HSGS closes ensuring power quality concerns of sags and transients are effectively addressed. Since conventional MV current limiting fuses and equipment are utilized for retrofit applications, there should be no impact on existing coordination between overcurrent protective devices or equipment ratings.

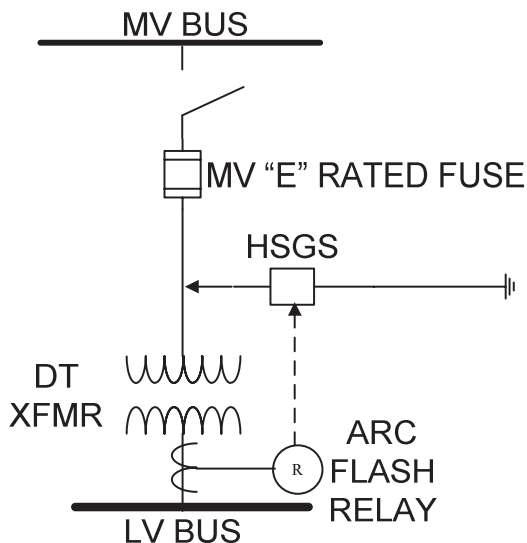


Fig. 1 Typical Industrial/Commercial Facility

In this paper, specific details on the proper application of the HSGS on typical MV power systems are discussed. The various methods of MV system grounding will be considered in the application of a HSGS. Current limiting fuse operation is reviewed to provide the background information necessary to ensure coordination with upstream phase and ground relays and selection of proper equipment ratings. Since the issue is

for the three phase-to-ground fault through the HSGS, only current limiting operation is discussed in detail in section II.

II. BACKGROUND

A. Reducing Incident Energy on LV Equipment with a HSGS

The incident energy reduction scheme discussed in [1] is depicted in Fig. 1. Notice in this scheme the HSGS is applied downstream of the CL fuses protecting the transformer. Since the fuses will fully interrupt in less than $\frac{1}{2}$ cycle after the HSGS closes, the sourcing transformer will never be exposed to the full fault current peak. Applying arc flash light detection relays at the LV equipment and tripping the HSGS at the MV level solves the LV arc flash in two simple steps.

1) Upon sensing of an arcing fault, the relay signals the HSGS to close. When the resultant solid three-phase bolted ground fault collapses the transformer primary voltage to 0V, the LV arc flash extinguishes in milliseconds. The arc flash detection and HSGS closing is accomplished in approximately 4ms. Details for controlling the action of the HSGS are discussed later in the paper.

2) The three-phase bolted ground fault brings the MV system to zero volts. The time duration of this voltage dip is determined by CL fuse interruption time which will be very fast with the entire MV short circuit current (SCC) flowing through the fuse. The larger the SCC magnitude, the shorter the voltage dip duration. The CL fuse becomes a voltage dip duration device and is discussed further in the following sections.

Since this arc flash solution produces a bolted three-phase to ground fault, concern of upstream fast acting ground detection relays tripping is minimized. Since this ground fault is a symmetrical 3 Φ fault, zero sequence current will be limited in magnitude and duration on solidly grounded MV systems. The MV system grounding method needs to be considered prior to application.

B. Primary Fuse Protection

With the HSGS solution providing the LV arc flash protection, the current limiting (CL) fuses are needed to limit both the peak current of the primary fault and the duration of the voltage sag to less than 4ms. For reliable application of the HSGS, it is necessary to consider the SC current limiting performance of the fuse in relationship to other overcurrent protective devices on the MV system.

Fig. 2 shows the waveforms from single phase operation of a fuse interrupting a fault current in an AC circuit. Operation of the fuse can be considered to be two distinct parts: the pre-arcing (melting) period and the arcing period.

1) *Pre-arcing period*; At the initiation of a fault current, the notches in the fuse's element will begin to heat up, and resistance will increase very slightly. Consequently the fault current will be very close to the prospective fault current as shown in the top traces. Note in the bottom trace that the system voltage at the line side of the fuse is near 0 V during the pre-arcing period shown in the figure, since the voltage drop across the fuse will still be low. Since current limiting fuses must melt before the first fault current peak is reached, factors such as the melting I^2t of the fuse, available fault current, fault initiation angle and source X/R ratio can affect the duration of this period. For example, higher fault currents typically result in shorter pre-arcing periods.

2) *Arcing period*. When the fuse element melts, arcing begins in the notches of the element. At this time the fuse resistance and voltage will increase rapidly. When the voltage developed across the arc resistance within the fuse reaches the instantaneous system voltage the current starts to decrease. The maximum instantaneous value of current is referred to as peak let through current (I_p) and is used in determining coordination with upstream Overcurrent Protective Devices (OCPD) instantaneous relay functions and determining requirements for short circuit current ratings. Also used for equipment short circuit ratings is the fuse's maximum clearing I^2t .

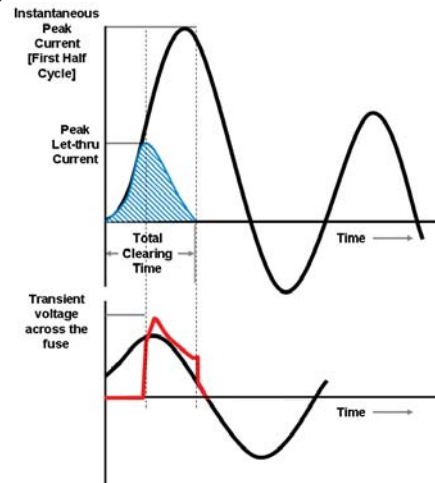


Fig. 2. Current Limiting Operation Waveforms

C. HSGS Arc Flash Protection Performance

Operation of the HSGS protection system can be best illustrated by reviewing some of the results of Test 5 presented in [1]. In this test, the HSGS system was added between the fuses and transformer primary in the circuit shown in Fig. 3. As shown in the figure, the calculated incident energy on the LV bus without HSGS protection was greater than 400 cal/cm².

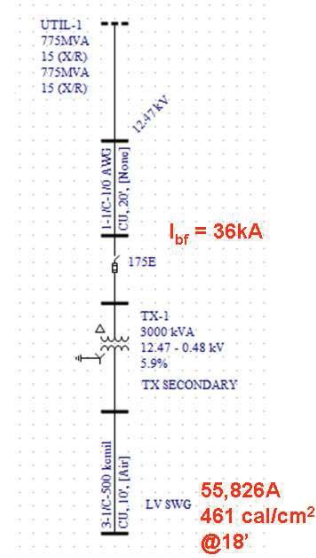


Fig. 3. Model of Incident Energy and I_{arc} calculations.

Tests were performed in a high power test lab to quantify the reduction of LV arc energy by the HSGS with the equipment shown in the photo of Fig. 4.



Fig. 4 Substation test arrangement.

Test 5 was performed in the feeder circuit breaker compartment (the bottom compartment in Fig. 4). The breaker was removed and a #18 trigger was connected

between the line side stabs. The instantaneous trip on the secondary main breaker was disabled to ensure that the HSGS and the E-Rated fuses were the primary protection. The traces in Fig. 5 show the performance of the protection system.

Refer first to the low voltage traces at the bottom of the figure. The event begins when the station making switch is closed and current starts to flow through the trigger wire. This is marked as 'A' on the trace. The voltage is near 0V until the trigger wire melts in about 2.2ms. At that time (B on the trace), current starts to flow through the arc and an irregular shaped arc voltage appears. The arc current continues to rise towards an instantaneous value expected to be greater than 30kA until the HSGS closes approximately 1.5ms later. This can be seen in the primary voltage waveforms at the top of the figure where the voltage trace drops rapidly to near 0V (C on the trace). The primary current, expected to be near 860A_{rms} for the secondary arc fault, now begins to rise toward the expected instantaneous value of near 90kA for a bolted fault current on the primary side. However the primary fuse melts 1.1ms later (D on the trace) when the instantaneous current reaches 23.4kA in phase A. The voltage across the fuse now begins to rise. Due to the di/dt at melting the voltage developed across the source inductance is added to the source voltage. The resulting peak value of 25.0kV is well below the limits of IEEE C37.46 [3]. The A phase fuse has fully cleared the circuit 1.3ms after melting (E on the trace). The remaining fuses cleared the other phases 1.5ms after the A-phase fuse cleared. The three phase power waveform is shown in figure 6 and was integrated to obtain arc energy.

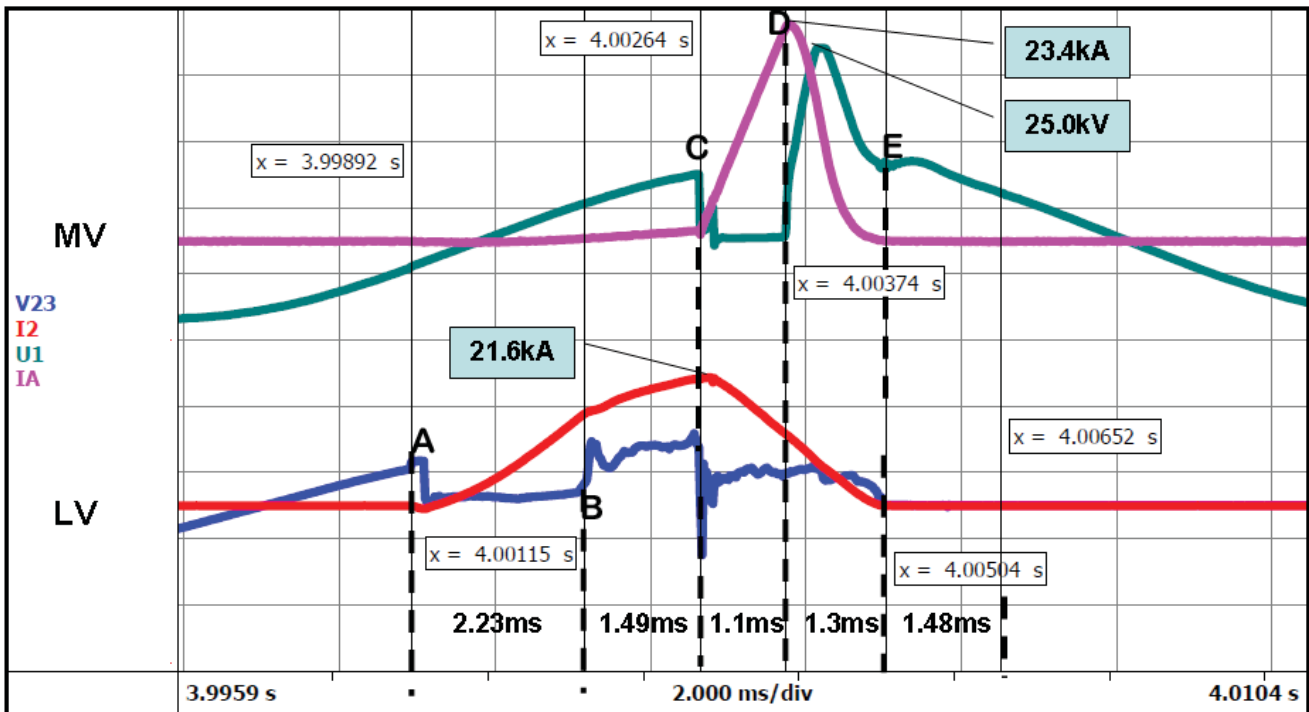


Fig. 5. Test 5 waveforms showing operation of system. The low voltage traces are on the bottom.

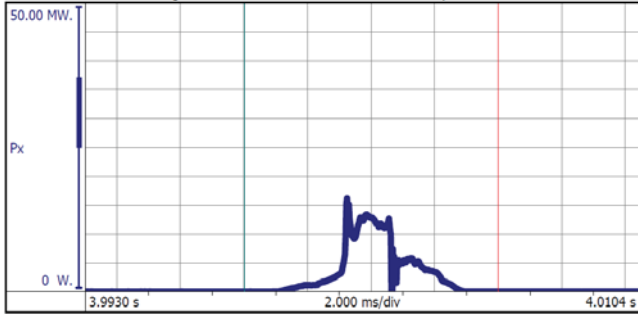


Fig. 6. Power measurements from Test 5

Test 9 was performed in a similar fashion as Test 5 but without the HSGS to compare results. This test was limited to near 0.5 seconds. Frames from the high speed videos were reviewed.



Fig. 7. Photos of test 9 at 302ms from high speed video.

The photo of Fig. 7 was taken from the high speed video of the test 9 and shows that faults initiated in this manner would generate outward plasma flows in a manner similar to the test box using the horizontal electrode configuration in the research performed for [4]. This configuration is considered to be the worst case configuration for incident energy measurements near the opening of the enclosure [4] [5].

The photo in Fig. 8 shows extensive damage to the breaker compartment under test. It appears that copper oxides have coated all the components within the compartment. Copper oxides were also present throughout the LV bus structure due to the expansion of the plasma ball during the duration of the test. See expulsion of gases from the side of the equipment in the photo of Fig. 7.

The photo in Fig. 9 shows the farthest reach of the (glowing) hot gases generated from the arc in Test 5 with the HSGS. As evidenced from the photo of Fig. 10, minimal damage was sustained by the equipment.



Fig. 9. Photos of test 5 at 4.2ms from high speed video

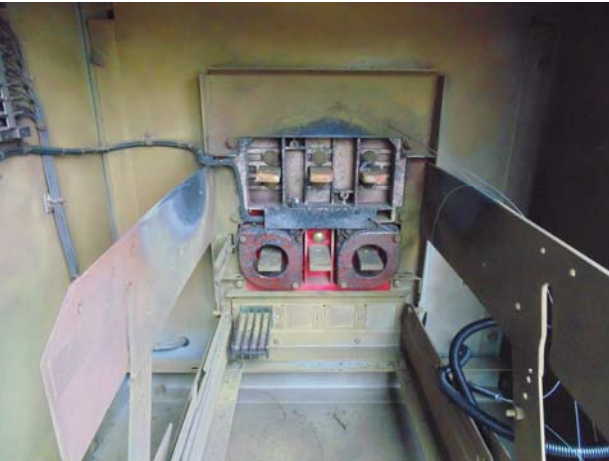


Fig. 8 – Damage to compartment from Test 9



Fig. 10 Photo of damage to feeder compartment after arc fault with HSGS protection.

Table I contains some of the key measurements of the tests discussed in [1]. The maximum incident energy of 0.5 cal/cm² measured by the nine calorimeters is consistent with a calculation with the IEEE 1584 model using a clearing time of 6ms for the LV arc fault. The measured arc energy in Test 5 of 27.6kW is comparable to the current limiting ability of a UL Class J fuse [6]. Consistent with [7], equipment exposed to arc faults of this limited magnitude of arc energy could be repaired and returned to service. The fuses limited the undervoltage condition to less than 2.4 ms in test 5.

TABLE I
SUMMARY OF LAB TESTS

Quantity	Test 9	Test 5
LV		
I _{bolted}	55.1kA	55.1kA
I _{arc} (predicted)	22.2kA	22.2kA
I _{arc} (avg.)	19.0kA*	8.7kA
I _{peak} (kA)		21.6 kA
Arc Duration	458ms	3.89ms
Incident Energy (cal/cm ²) (Predicted)	27.2	0.4
Incident Energy (cal/cm ²) (Measured)	49.8	0.5
W _{arc}		27.6 kW
P _{arc}		16.1 MW
MV		
I _{peak} (at fuse melt)		23.4 kA
Longest Undervoltage		2.4ms
Longest Overvoltage		1.5ms
Peak Voltage		25.0kV

*- LV Instrument CTs were removed for Test 9

III. APPLICATION CONSIDERATIONS

A. MV System and Switchgear

1) *Background Information:* Because of the unequal opening times of the current limiting fuses there is the possibility of a zero sequence current created during fuse opening. This ground current and the current limited phase currents need to be considered for coordination with upstream relays, conductor sizing and equipment requirements.

Test 5 was run on a solidly grounded system. In Fig. 11, the three phase currents and the sum of these currents are shown on the same trace. Until the first fuse melts, there is little ground current. With the first two fuses melting near the same time, the arc impedance within those two fuses gives rise to unbalanced currents and a zero sequence current is created. When the first two fuses clear 1.3ms later, the entire C phase current appears as a zero sequence current on the traces. The C-phase fuse limits this current to a peak value (I_p) of -21.2kA and an event duration of 3.9ms. The calculated I²t of the zero sequence current is 487.6 kA²t.

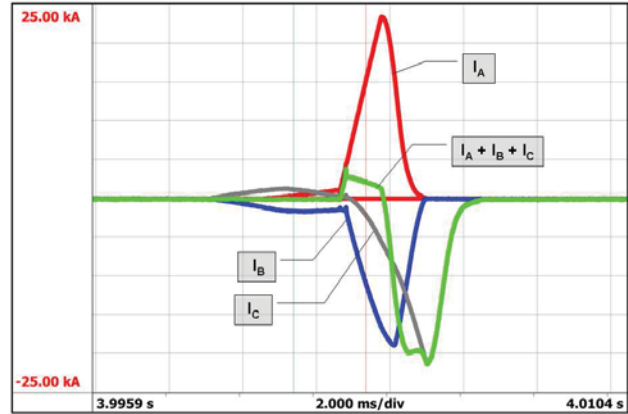


Fig. 11 – Three phase currents and I₀ from Test 5.

2) *Equipment Grounding Considerations:* The grounding conductor must be able to withstand the current waveform shown in Fig. 11. To ensure adequate sizing of the ground conductor it is best to select the conductor to withstand the I_p of the fuse for the available ground current without damage. To find the maximum I_p of the fuse utilize the fuse let through chart [8]. Since the HSGS bonding conductor has to carry fault current for approximately 5ms, a #2AWG is more than adequate.

3) *Bracing Considerations:* Consult with the manufacturer of the HSGS to ensure adequate spacing and sizing of conductors connecting the switch to the load side of the fuses to ensure that they carry the current waveform without damage to the insulation. For MV systems having SCC up to 50kA, the jumper cable from the load side of the fuses to the HSGS can be as small as #2AWG for adequate thermal withstand capability. The CL fuse will limit peak current in ½ cycle or less. Confirm if bracing of the #2AWG cable is adequate based on distance.

4) *Ratings:* The rating of the HSGS needs to be greater than the available fault current and voltage at the point of application. The rating of the HSGS used in Test 5 was 50kA and 17.5kV. The current limiting action of the fuse may allow application on systems with larger available fault currents.

5) *Coordination Consideration:* It is important to review upstream relay settings and algorithms to ensure that upstream relays do not trip for these short duration phase and ground currents. Different measurement algorithms of instantaneous trip functions respond differently to the current limited waveforms shown above [9] [10]. For example, with a peak detector algorithm, the I_p of the fuse must be lower than the instantaneous trip setting in rms current times 1.414 [9]. Since the I_p of the fuse is dependent on the available fault current, the use of let-through charts or tables is required. As shown in [10] a lower setting can be utilized for relays using a Fourier analysis algorithm.

6) *Considerations for Resistive Grounded Systems.* If the MV system is not solidly grounded, but low resistance neutral grounded, the application shown in Fig. 12 needs to change. This also applies for high resistance grounded or delta MV systems.

Consider the case where the HSGS closes all three phases to ground simultaneously on a resistive grounded system. At this point, the LV arc flash is essentially over. With HSGS closing as in Test 5, phase A & B fuses melt in 1ms (MV

system voltage recovery starts) with full CLF interruption by 1.5 – 2 ms (SCC dependent). When phase A & B CL fuses clear, the entire phase C current becomes a zero sequence current. The only path for this fault current is through the phase C fuse, to HSGS phase C pole, to the transformer's neutral, BUT is now limited by the source neutral return path's resistance. Consequently, there is a large reduction in phase C fault current once phases A & B CL fuses open.

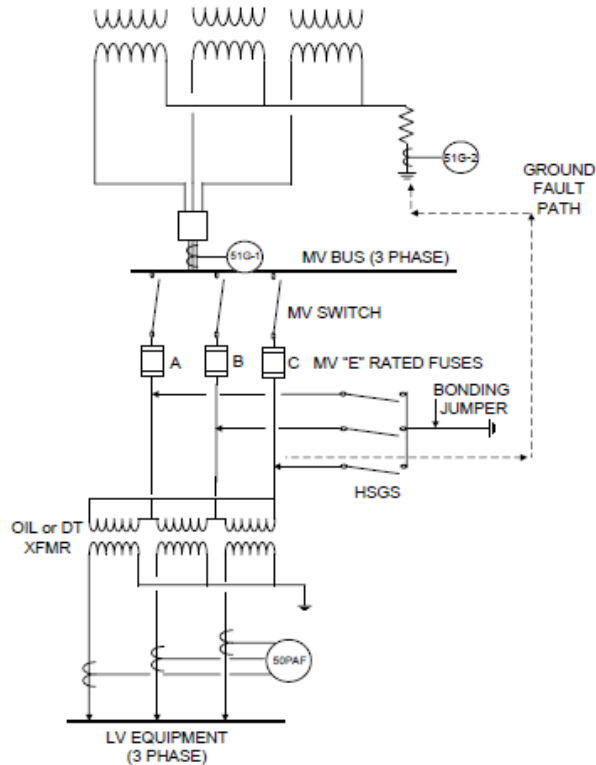


Fig. 12 – Three phase HSGS on resistive grounding system.

Typically in industrial plants, the limited ground fault current will be in a range of 200-600A; power plants up to 1200A. The phase C transformer primary could remain energized for an extended time. With the most common delta-wye connection for MV-LV transformers, all three transformer phases have the same evenly applied potential. Since there is no potential difference between the delta windings, there is no current flow, and therefore there is no induction to generate secondary potential. With no supporting LV secondary potential, the LV AF collapses in milliseconds.

However, a sustained bolted line-to-ground phase C fault on a low resistance grounded system will be detected and eventually tripped by the upstream 51G-1 or 51G-2 protection relay 1-2 seconds later. This action trips the entire MV BUS resulting in poor plant reliability.

Even with the higher ground fault values of 1200A, the 51G-1 or 51G-2 will likely be faster than the phase C CL fuse under these conditions. For delta systems there is no ground current but plant ground fault alarms would likely be activated.

To prevent this reliability issue, the MV switch should be installed (or retrofitted) with a shunt trip activated by the same signal that trips the HSGS. For closing similar to Test 5,

Phase A and B CLF would still interrupt in about the same time-frame, about 1ms. However, phase C may not melt. The upstream 51G-1 or 51G-2 will see ground current within its pick up range. Therefore the switch's shunt trip needs to operate before the 51-G1 trips the MV BUS.

Subsequent to HSGS operation, all three HSGS switches and all three fuses should be replaced, since the phase C fuse may have been subjected to near melting I^2t .

B. LV System.

1) *Relay Considerations:* To obtain the maximum performance of the HSGS, tripping with a 50PAF function (Phase overcurrent relays with Arc Flash light sensors) should be applied. As demonstrated in fig 5 and 6, with a operating time for the relay and HSGS less than 4ms, it is possible to limit the magnitude of the peak arc power and hence pressure buildup within equipment. Reliable operation of the 50PAF is critical to the enhanced safety of the system.

C. Modeling HSGS in Power System Analysis Software.

Since this is a unique approach to arc flash protection, some special considerations must be used to accurately represent the incident energy reduction performance discussed above. You should consult with your analysis software vendor to ensure proper representation in their calculations.

To adequately represent the performance of an HSGS and a 50PAF function you must set the clearing time of the bus of interest. An example of this is shown below for a 3000kVA transformer using the HSGS system. In this example the operating time of the 50PAF relay is 3ms, while the operation time of the HSGS is 2.5ms. The clearing time for arc flash events on Bus 3 is set to 6ms. The incident energy calculation of 0.6 cal/cm² is a little higher than the actual test results for this application.

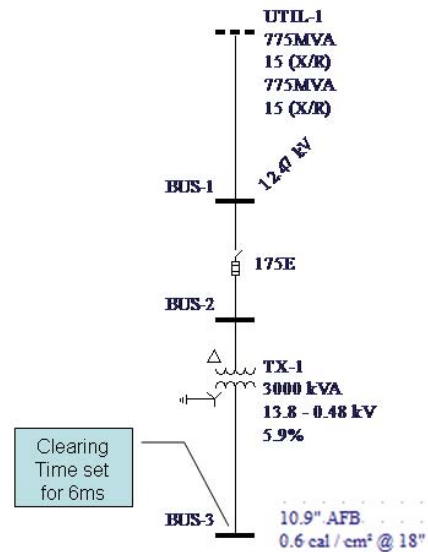


Fig. 13 – Incident Energy Calculation Example

D. Field Installation Considerations.

The following guidelines and insights gained from field retrofits should help to minimize installation time, ensure reliable operation and minimize problems during installations.

1) *Mounting technique for ease of replacement:* Referring to figure 14, note that the lower base mounting bolts and upper phase connections are readily accessible for ease of disassembly and re-installation. Pre-configured mounting assemblies from the manufacturer can minimize the time to retrofit the HSGS into the MV switch cabinet.



Fig. 14 An example of a 3 pole HSGS retrofit

2) *Grounding:* As grounding of the HSGS is a primary factor for proper operation of the system, a solid ground connection must be made from the base of the HSGS assembly to system ground. This connection should be tested with a Digital Low Resistance Ohmmeter (DLRO) to ensure maximum contact resistance of 50 microOhms.

3) *Phase conductors:* Mounting of the primary switching elements and connections to the MV equipment should adhere to ANSI/IEEE C37.20.2, Standard For Metal-Clad Switchgear [11] for spacing, sizing, connections.

4) *Testing.* Standard NETA acceptance tests [12] should be used for MV equipment.

5) *Mounting arc flash sensors for reliable operation.* As discussed above, tripping with phase overcurrent relays with arc flash light sensors (50PAF) function allows for the maximum performance of the HSGS. Proper installation and operation of the 50PAF is critical to the enhanced safety of the system. The mounting and routing of arc flash sensors should take into account several important factors:

1. Ensure that all the compartments and areas to be monitored per protection scheme are covered.
2. Ensure that the sensors are exposed to the primary contacts and other main locations for detection of light from an arc fault.

3. Avoid contact of sensors with energized parts.
4. Mount sensors to prevent damage to the fiber optics. Avoid sharp edges and improper bend radius that, may cause detrimental losses to the light signal to the relay.
5. Proper mounting and routing to ensure that no obstructions are introduced to normal equipment operation / maintenance / testing.
6. Proper mounting of fiber optics within equipment to mitigate nuisance tripping from the light emitted from normal fault clearing operation of air magnetic circuit breakers.

IV. CONCLUSIONS

The integration of two historically proven technologies offers the system designer LV arc flash solutions not attainable applying each product individually. Combining MV current limiting fuses and high speed grounding devices provides the user with very effective low voltage arc flash mitigation.

All calculated values in this paper are relative. Thorough engineering analyses needs to be performed depending upon the specific application and system configuration.

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VI. AUTHORS' INFORMATION

Ray Catlett received his BSEE degree from University of Missouri-Rolla and a Masters Engineering Management from Washington University where his focus was technology assessment and innovation. He has been employed with ABB since 2000 in many roles, presently a Senior Technical Consultant. He has more than 30 years of design, analysis and consulting experience in power systems and has co-authored previous PCIC papers. Inducted into the Academy of Electrical and Computer Engineering, Missouri University of Science and Technology. He is a senior member of IEEE and a registered professional engineer in the states of Missouri and Texas.

Mike Lang received his BSEE degree from Georgia Institute of Technology and a MBA from Georgia State University. He is employed with Mersen, in Roswell, GA. In his 24 years, with the company he has held various field engineering positions and currently serves as principal field engineer. A member of the IEEE 1584 working group, he has participated with the IEEE/NFPA Arc Flash Collaborative Research and Testing Project by serving on the Research Testing and Planning Committee and the Technical Advisory Committee. He currently serves as co-chair of the Steering Committee of the IEEE/NFPA Arc Flash Collaborative Research and Testing Project.

Steve Scala received his BSEE and MBA from University of New Haven where his focus was Power Systems. He was recently employed with ABB as Protection and Controls Business Development Manager. In this role, Steve was tasked to promote the development of new technologies and market capacities. Steve has over 15 years of field engineering, design, installation and testing experience. He is currently employed by Superior Power Products in Florida.