

# NOVEL APPROACH to ARC FLASH MITIGATION for LOW VOLTAGE EQUIPMENT

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**Abstract** - As industry pursues safer workplaces with arc flash mitigation programs, they face major challenges in effectively reducing incident energies on the secondary of medium voltage to low voltage (MV-LV) transformers. When an arc fault occurs on the transformer secondary, primary currents can be below the short circuit range of the primary protection. Typical E-rated fuses can take over 2 seconds to clear while high side device 51 relays will have a waiting period before initiating a breaker trip. Solutions that adjust the LV main breaker's (if applied) protective functions for faster response, do not address arc fault issues on the bus connecting this main breaker to the transformer secondary. This paper presents a method of applying a high speed grounding switch (HSGS) at a location between the MV E-rated fuse load terminal and the transformer's primary connection. Since the transformer's primary voltage is reduced to zero in milliseconds, the low voltage arc flash event collapses quickly to limit incident energies to less than 1.2 cal/cm<sup>2</sup>. Applications can include MV-LV transformers up to 5000kVA.

**Index Terms** – Current limiting fuses, fuse interrupting time, power quality, high speed grounding switches, short circuit capacity (SCC), protective device coordination, low voltage arc flash mitigation.

## I. INTRODUCTION

Industry is facing internal and/or external deadlines to perform arc flash (AF) mitigation within their facilities. Of particular concern is the high incident energies that are present on the bus of low voltage (LV) switchgear close coupled to power transformers. Because of the low primary current during a LV arc fault on the secondary of the transformer, incident energy calculations are frequently well above 40 cal/cm<sup>2</sup>.

Solutions that have been used to date include:

- Replacement of standard E-Rated fuses with fuses having a more inverse time current curve [1].
- Replacement of existing medium voltage (MV) fused load interrupter switches with metal clad switchgear.[2]

- Adjusting protective relay time dials on the LV switchgear main to act faster under an arc flash event. This does not cover the zone between the transformer secondary and the line side of the LV main breaker.

The arc flash mitigation solution discussed in this paper is unique in the industry. The solution consists of a MV High Speed Grounding Switch (HSGS), an arc flash relay on the LV side and MV current limiting fuses. This system can reduce incident energy to below 1.2 cal/cm<sup>2</sup>, the level accepted as that required for the onset of a 2<sup>nd</sup> degree burn.

During an arc flash event on the LV side of the transformer, the HSGS is closed within 4 milliseconds of initiation of an arc placing zero volts on the transformer primary and extinguishing the LV arc flash in milliseconds. The fuses will then open within ½ cycle for the MV fault currents that are well above their current limiting threshold. Simple analysis based on IEEE 1584-2002 [3] equations for low voltage systems (480V and 600V) shows that even with 60kA available, the incident energy can be reduced to less than 1.2 cal/cm<sup>2</sup>.

Results from tests at a high power lab are presented to document arc flash mitigation performance of the system under actual fault conditions. Performance of the MV current limiting fuses demonstrate that concerns about potential power quality issues (system voltage dip) and protection of upstream transformers are effectively addressed by this solution.

Since there is no need to replace the existing MV fused switch or make adjustment to protective relays, there is no impact on existing coordination between overcurrent protective devices. Analyses of typical installations show that this solution is particularly effective in mitigating arc flash hazards at facilities that have MV to LV transformer sizes ranging from 750KVA – 5000KVA.

This solution is appropriate for:

- Heavy and light industrial
- Commercial facilities
- Educational campuses
- Any facility using primary loop fed MV-LV transformers with MV fused switches
- New or existing applications.

## II. DISCUSSION

### A Primary Fuse Protection Issues

Current limiting (CL) fuses have provided many benefits for primary protection of transformers feeding low voltage switchgear. The low peak current and 1/2 cycle clearing time of current limiting fuses for high side faults minimizes stress on the upstream transformer feeding the fault. Current limitation for short circuits allows easy coordination with upstream breakers. Faster relaying times for these upstream breakers typically result in incident energy calculations at the fuse switch of less than 8 cal/cm<sup>2</sup>. CL fuses have been an economical means of obtaining the high interrupting ratings needed in today's power systems. They have provided reliable protection while requiring little maintenance. [4]

Although the CL performance of the MV fuses provides many benefits for large faults on the primary side of the transformer, the relatively low currents of secondary arc faults are well below the CL 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/cm<sup>2</sup>.

### B High Speed Grounding Switch Solution

HSGS have been applied for many years on LV & MV systems to reduce arc flash incident energy levels. They are effective but there is a concern among some liquid filled transformer manufacturers that solving an arc flash problem with a HSGS may actually be creating a problem at the transformer. If the transformer is older and/or has aged insulating paper, the high current induced magnetic vibrations could damage the insulating paper causing a turn-turn transformer fault. Even though the transformer is designed to withstand this long term bolted fault level per ANSI C57.109, the time duration is dependent upon the device 51 protective relay settings and breaker interrupting time frame.

A more effective application with minimal impact on transformers is to apply the HSGS downstream of a CL fuse. Since the fuses will fully interrupt in less than 1/2 cycle, the sourcing transformer will never be exposed to the fault waveform peak. Applying light detection relays at the LV equipment and tripping the HSGS at the MV level solves the LV arc flash in two simple steps. See Fig. 1.

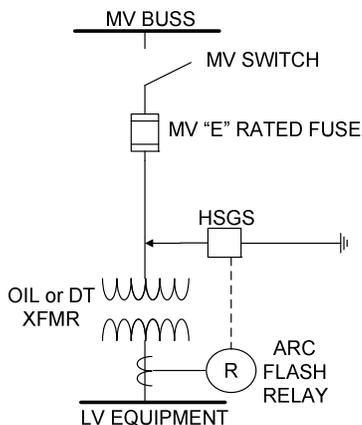


Fig. 1 Typical Industrial/Commercial Facility

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.
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. This step is discussed further in the following sections.

Operationally, the action of the HSGS can be controlled by a maintenance selector switch or in a continuous monitoring relay scheme.

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 three phase fault, zero sequence current will be limited in magnitude and duration on solidly grounded MV systems. MV system grounding method needs to be considered prior to application.

### C Addressing Power Quality Issues with CL Fuses

During operation of the current limiting fuse for a bolted fault at the HSGS, there are two power quality events that need to be considered. After initiation of the bolted fault, there will be near zero volts on the MV power system nearest the HSGS until the fuse element melts. Once the fuse element melts, a transient overvoltage condition can be created on the system.

An investigation was performed to determine the effect that operation of the grounding switch and subsequent fuse operation would have on the power quality of the surrounding system. Both voltage sag and overvoltage are discussed below.

The short circuit element of a fuse, made of strips of copper or silver with regions of reduced cross sectional area called notches, is enclosed in an insulating tube filled with pure quartz sand. See Fig. 2. Designed to carry normal load currents without melting, current limiting operation begins at the initiation of a short circuit. As the short circuit current starts to rise, the temperature of the notches begins to rise very quickly. When the notches melt, a number of small internal arcs are produced in the notch zones. The rapidly increasing resistance of the arcs creates a voltage that forces the fault current to be rapidly reduced to zero.

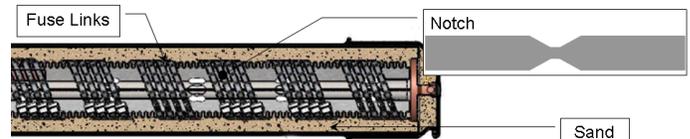


Fig. 2 Illustration of the short circuit element of MV fuse

Fig. 3 shows the waveforms from single phase operation of a fuse interrupting a short circuit 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.

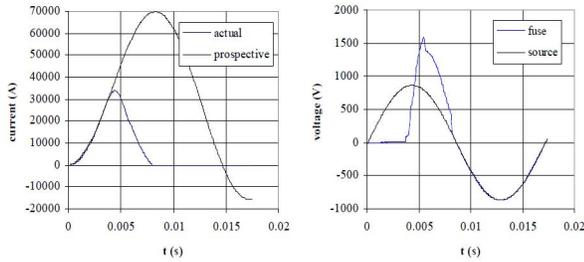


Fig. 3. Current Limiting Operation Waveforms

**Pre-arcing period.** At the initiation of a fault current, the fuse 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 since the voltage drop across the fuse will still be low. Note that the system voltage at the line side of the fuse is near 0 V during the 4ms pre-arcing period shown in the figure. 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.

**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 reaches the instantaneous system voltage the current starts to decrease. Referring to Fig. 4, the negative  $di/dt$  results in a voltage rise across the line reactance that supports the system voltage. This voltage,  $V_x$ , is present until the current is forced to a current zero. Current limiting fuses will melt and clear these short circuits in less than 1/2 cycle. The magnitude of the system overvoltage created by the fuse is dependent upon system parameters and by the rate at which the arc resistance increases. If the resistance rises too fast, a large  $di/dt$  could cause too large of a system overvoltage.

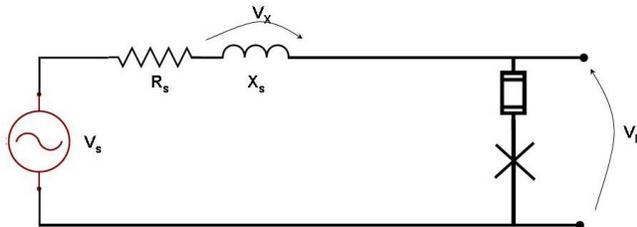


Fig. 4. Circuit showing source of transient arc voltage

### III. TEST OVERVIEW

Tests were performed in a high power test lab to quantify the reduction of LV energy possible with the HSGS with typical LV non arc-resistant switchgear. The equipment tested, shown in the photo of Fig. 5 and the diagram of Fig. 6, was placed into the arc resistant test cell of the test lab.



Fig. 5 Substation test arrangement.

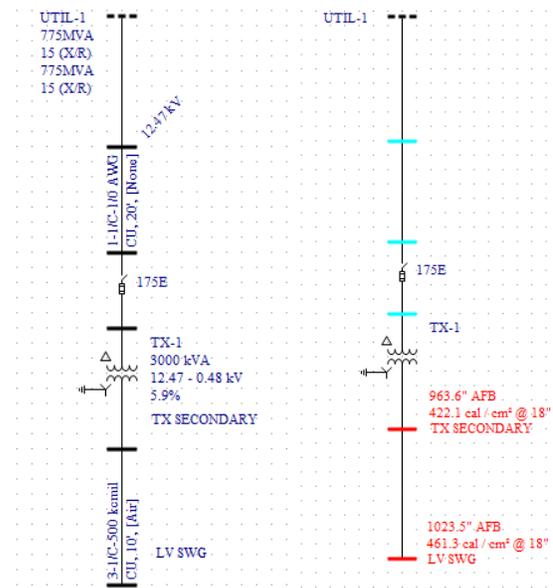


Fig. 6. Calculations Model of Incident Energy and  $I_{arc}$ .

Arc faults were initiated in LV breaker compartments to assess the performance of the protection system with the HSGS. Electrical parameters from the LV system were recorded to measure electrical energy delivered to the arc for tests with the HSGS. For the test without the protection system, the lab removed the LV instrumentation because of the expected destructive energy. A two wattmeter algorithm was used to calculate arc power from the phase currents and the line-to-line voltages. Conventional and high speed video was used to document the release of arc flash hazards. Calorimeters were placed about the opening of the compartments to confirm incident energy calculations. Thermal indicators [untreated cotton fabric] were also placed about the equipment. Electrical parameters from the MV system were also recorded to assess the performance of the protection system and its impact on the power system.

The selected testing order was from the least destructive to the most destructive, but this paper discusses the testing in

reverse order. For tests in the feeder breaker compartment, the instantaneous trip on the main breaker was disabled to ensure reliable test results of the HSGS protection system.

#### IV. TEST RESULTS AND FINDINGS

Test 9 was performed in the feeder circuit breaker compartment (The bottom compartment in Fig. 5). The breaker was removed and a #18 shorting wire was connected between the line side stabs (Fig. 8). Since the instantaneous trip on the secondary main breaker was disabled the primary fuse was the circuit protection for the LV fault. However, anticipating a clearing time of greater than 5 seconds for the primary fuse, the station breaker was set at 500ms.



Fig. 8 Trigger wire on line side stabs in feeder breaker compartment.

The traces in Fig. 9 show the characteristics of the arc event. The event begins when the trigger wire melts and current starts to flow through the arc. The arc current varies throughout the fault but sustains for the full duration of the test when the fault is cleared by the station breaker. During this test the MV fuse never opened.

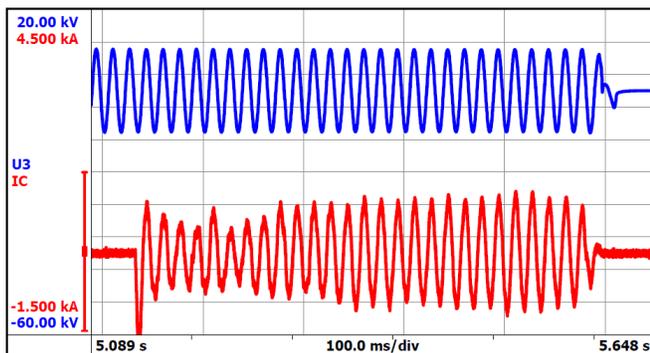


Fig. 9. C phase current (B) and voltage (T) from Test 9.

The rms value of the currents averaged over the duration, shown in the results table 1, are lower than the estimated 1584 arc current of 860A and are consistent with the findings of Wilkins et al [5]. With the primary current, measured at 730A rms for the secondary arc fault, the fuse would have

taken near 13s to clear if the test time had not been limited by the station breaker. During this event, the primary voltage was near 97% of the system voltage. The measured values of  $W_{arc}$ ,  $P_{arc}$  and Incident Energy are recorded in Table 1.

The photos of Fig. 10 were taken from the high speed video of the test 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 [5]. This configuration is considered to be the worst case configuration for incident energy measurements near the opening of the enclosure.



Fig. 10. Photos of test at 1ms and 302ms.

The photo in Fig. 11 shows extensive damage to the feeder 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 bottom photo of Fig. 10.

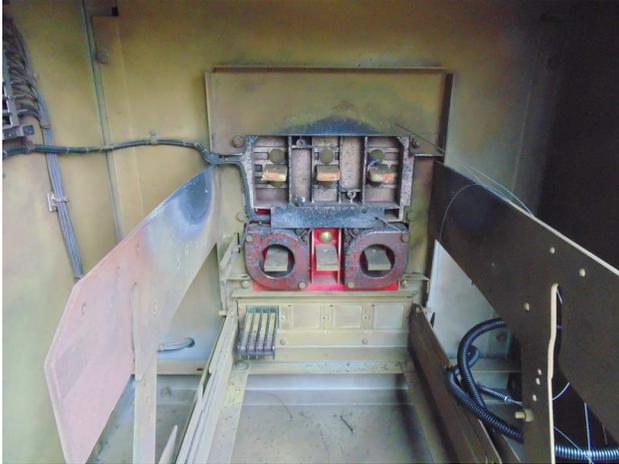


Fig. 11 – Damage to compartment from Test 9

Test 5, was also run in the feeder breaker compartment and used the same test set up used in test 9. This test was run with the HSGS to compare results with the test discussed above. The instantaneous trip on the secondary main breaker

was disabled to ensure that the fuse and HSGS were the primary protection.

The traces in Fig. 12 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. The voltage is near 0V until the trigger wire melts in about 2.2ms. At that time, 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. Approximately 1.5ms later the HSGS closes. This can be seen in primary voltage waveforms at the top of the figure where the trace drops rapidly to near 0V. The primary current, expected to be near 860A<sub>rms</sub> for the secondary arc fault, now begins to rise toward the expected instantaneous value of near 104kA for a bolted fault current on the primary side. However the primary fuse melts 1ms later 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 [7]. The fuses have fully cleared the circuit 2.8 ms after melting.

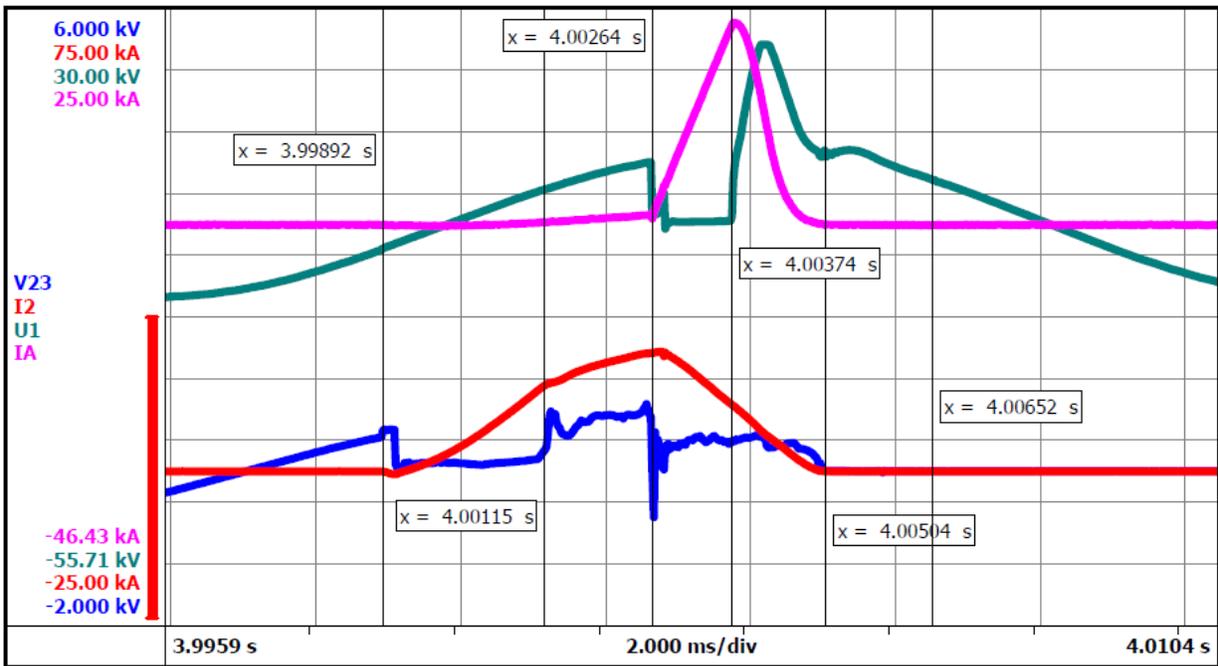


Fig. 12. Test 5 waveforms showing operation of system. The low voltage traces are on the bottom.

Fig. 13 shows the waveforms of the power calculated from the current and voltage data. P<sub>tot</sub> is the calculation of MVA with primary (MV) quantities. P<sub>x</sub> is the power calculated from measured LV quantities (assumed to be watts delivered to arc). The low voltage power trace in blue shows that for near 2 ms after the HSGS closed, arc energy was transferred into the arc at a reduced power level. It is the authors' belief that the additional power transfer is from energy stored in the circuit. The large rise in primary power (red trace) after HSGS

closure is mostly the arc energy within the primary fuses. The calculated  $W_{arc}$  of 27.6kW resulted in a maximum incident energy measurement of 0.4 cal/cm<sup>2</sup>. The measured values of  $W_{arc}$ ,  $P_{arc}$  and Incident Energy are recorded in Table 1.

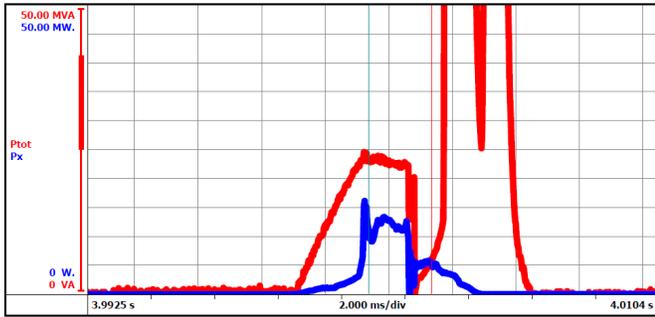


Fig. 13. Power measurements from Test 5

Frames from the high speed video were reviewed. The photo in Fig. 14 shows the farthest reach of the (glowing) hot gases generated from the arc. As evidenced from the photo of Fig. 15, minimal damage was sustained by the equipment.



Fig. 14. Photo at 4.2ms from high speed video of Test 5



Fig. 15 Photo of damage to feeder compartment after arc fault with HSGS protection.

In Test 7, performance of the HSGS was evaluated for a simulated arc fault due to a racking failure. The same electrical circuit was used as in test 5. The LV main circuit breaker was racked out and a trigger wire was connected between the line side breaker stabs. Using a remote racking device, the test was initiated remotely by racking the breaker onto the bus (see Fig. 16). The arc fault occurred several seconds into the test when the breaker stabs made contact with the energized line side stabs. Because of the racking device position no calorimeters were placed in front of the circuit breaker compartment.



Fig. 16. Remote racking device used for line side fault of main circuit breaker.

The traces in Fig. 17 show the performance of the system. Performance of the system was very similar to test 5. The secondary currents were limited to the values shown in the summary table. Voltage is near 0V for 2.6 ms. The instantaneous primary current, after HSGS operation, is limited to 23.2kA when the primary fuses melt. The peak value of 23.3kV is well below the limits of IEEE C37.46. Unfortunately, instrumentation for the  $V_{an}$  channel was lost during the test. This prevented the calculation of the arc energy on the secondary system. However, the measured energy on the primary was more than 40% lower than test 5.

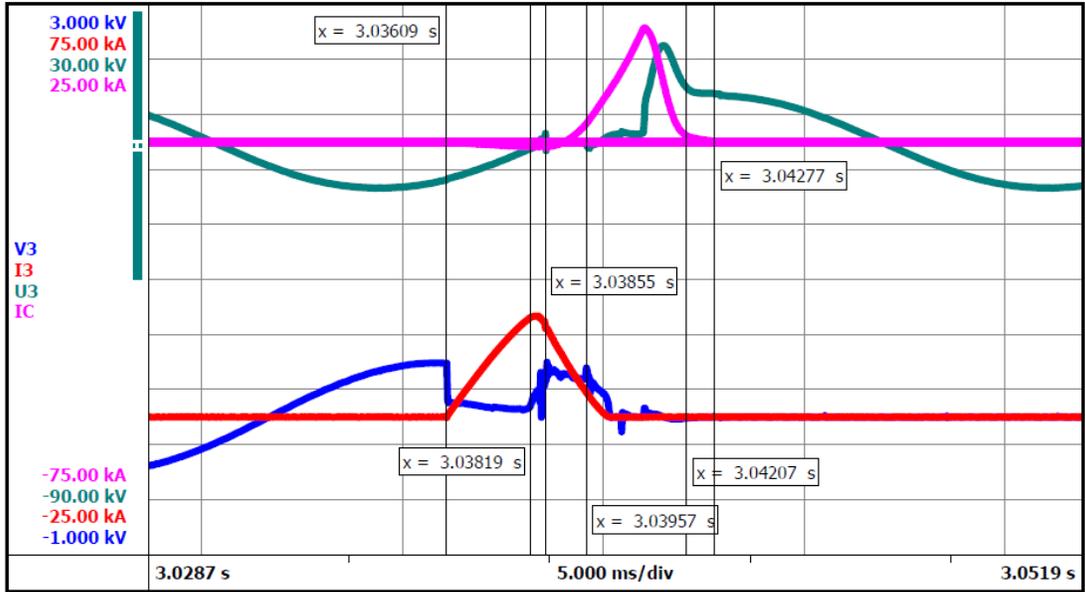


Fig. 17. Test 7 waveforms showing operation of system. The low voltage traces are on the bottom

Frames from the high speed video were reviewed. The photo in Fig. 18 shows the farthest reach of the hot gases generated from the arc. As evidenced from the photo of Fig. 19, minimal damage was sustained by the equipment.



Fig. 18. Line side fault with HSGS protection



Fig. 19. Damage to Main Compartment after Test 7

## V. SUMMARY OF TEST FINDINGS

Table 1 contains a summary of the key measurements of the tests discussed. The maximum incident energy of  $0.5 \text{ cal/cm}^2$  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 values of  $W_{\text{arc}}$  were less than 100 kW (100kJ) for faults with the HSGS. Consistent with [8], 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 2.6 ms in both tests.

TABLE 1  
SUMMARY OF LAB TESTS

Quantity	Test 9	Test 5	Test 7	Comments
<b>LV</b>				
$I_{bolted}$	55.1kA	55.1kA	55.1kA	
$I_{arc}$ (predicted)	22.2kA	22.2kA	22.2kA	Per 1584 SWG and solid ground
$I_{arc}$ (avg.)	19.0kA*	8.7kA	6.4kA	* - Primary current X turns ratio
$I_{peak}$ (kA)		21.6 kA	18.6 kA	Test 9 had no secondary CTs
Arc Duration	458ms	3.89ms	3.87ms	Test 9 duration from analysis of MV current
Incident Energy (cal/cm <sup>2</sup> )	27.2	0.4	0.4	Predicted at 24"
Incident Energy (cal/cm <sup>2</sup> )	49.8	0.5		Measured at 24"
$W_{arc}$		27.6 kW <sub>s</sub>		No calorimeters on racking test (7) No LV instrumentation on test 9 Van input lost on test 7
$P_{arc}$		16.1 MW		HSGS tests need further analysis
<b>MV</b>				
$I_{bolted}$	36kA	36kA	36kA	On MV system
$I_{arc}$ (predicted)	0.86kA	0.86kA	0.86kA	For secondary arc fault
$I_{avg}$	0.73kA			During arc event $I_{arc}$ less than 4ms in duration
$t_{HSGS}$ (relay & HSGS)		3.7ms	2.5ms	From event initiation to HSGS closed
$t_{fuse}$ (prearcing)		1.1ms	1.0ms	From HSGS closed (0V) until first fuse melts
$t_{fuse}$ (arcing)		2.8ms	3.2ms	From first melt until last fuse clears.
$I_{peak}$ (at fuse melt)		23.4 kA	23.2 kA	Potential 104kA peak from source
Longest Undervoltage		2.4ms	2.6ms	Based on time of last fuse to melt.
Longest Overvoltage		1.5ms	1.4ms	On MV system
Peak Voltage		25.0kV	23.3kV	Highest $\Phi$ -N
$W_{total}$ (MJ)	6500 kW <sub>s</sub>	61kW <sub>s</sub>	34kW <sub>s</sub>	Total W measured by test lab

## VI. POWER QUALITY DISCUSSION

When a fault occurs on a downstream feeder, the entire bus feels the voltage depression and all downstream connected loads are impacted. The voltage depth and duration during a MV system disturbance is related to three parameters:

- Fault magnitude vs. upstream impedance determines the depth.
- Relay operating time.
- Protective device interrupting time determines the duration.

Concerns for improved power quality have led to several investigations into the severity of voltage sags due to fault conditions. [9][10][11][12] Depending on the depth and duration, voltage sags can cause drop outs of various industrial equipment such as adjustable speed drives, motor starters, control relays, PLC and computers.

Several papers have compared the duration of the pre-arcing time of current limiting fuses to a voltage tolerance envelop known as the ITIC curve (Information Technology Industry Council) to determine if the duration of the resulting voltage sag is within the accepted limits [10][11][12]. Since bolted faults were evaluated in these investigations the voltage sag was considered to be 0 volts. The current-limiting fuse pre-arcing times of less than 5 ms were well within the ITIC limits.

A national power quality testing laboratory performed several studies on low voltage motor starters [13]. During testing, the applied voltage was reduced in rapid percentage steps for a measured number of Hertz and LV starter dropout characteristics were recorded. Table 2 shows the laboratory's test findings.

TABLE 2  
LV STARTER HOLD-IN/DROP-OUT

%Applied Voltage	VD Duration (Hertz)		
	Size 0	Size 1	Size 3
50	1.5	1.5	2.0
40	2.0	-	3.0
37	-	2.0	-
33	-	2.5	4.0
30	2.5	-	-
25	-	-	4.5
20	3.0	-	5.5
15	-	3.0	-
10	-	3.5	7.0

Comparing table 1 vs. table 2, the longest undervoltage is 2.6ms (0.156 cycles; table 1), all LV starters during a faulted bus will not drop out, i.e., all would stay energized. The CL fuse interrupting time is so short.

When the fuse melts, the arc voltage across the fuse is imposed on components connected to the feeder. However, the maximum allowable arc voltage across an E-Rated current limiting is identified in ANSI/IEEE C37.46 [7] and shown in Table 3. By selecting the fuse voltage rating as the next rating higher than the system voltage, arc voltages should be well below the Basic Insulation Level (BIL) of the system components.

TABLE 3  
MAXIMUM ARC VOLTAGES

Voltage Rating	Maximum Arc Voltage (kV)	
	< 12A	>12A
2.8	12	9
5.8	23	18
8.3	38	26
15.5	70	49

Data collected from tests performed with the shorting system are shown in Table 1. These results show that the voltage sags and overvoltages created during operation of the system provide a reasonable margin of security for the connected loads.

## VII. 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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## IX VITAE

**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, MO 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** works with Mersen, in Roswell, GA. In his 22 years with the company he's 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 is serving 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. Currently employed by Superior Power Products in Florida.