USING A MEDIUM VOLTAGE CONTROLLABLE FUSE TO MITIGATE ARC FLASH ENERGIES ON LOW VOLTAGE SWITCHGEAR

By Mike Lang
Principal Field Engineer

I. INTRODUCTION

Arc flash incident energy calculations are frequently well above 40 cal/cm^2 for low voltage (LV) equipment connected directly to the secondary side of power transformers due to existing electrical system designs and transformer fuse protection options. Many companies use this value as the upper limit for energized work. Consequently these companies must now insist on outages to perform routine tasks on this equipment. When the equipment is switchgear feeding large processes, the downtime cost of a task such as racking in and closing a power circuit breaker can be tens of thousands of dollars.

Medium Voltage (MV) current limiting fuses, used on transformer primaries, have reliably fulfilled the protection objectives of isolating failed transformers from the electrical system, protecting the transformer from large through-faults and protecting cables connected to the transformer. Current-limiting Medium Voltage fuses have been particularly effective at limiting the damage that occurs from transformer primary faults such as winding failures, bushing failures and insulation breakdown [1]. For these faults MV current-limiting fuses dramatically limit the destructive energy delivered to the fault by clearing in less than ½ cycle while preventing the fault current from reaching its first ½ cycle peak value. This dramatically reduced energy results in arc flash incident energy calculations of less than 1 cal/cm^2. Current-limiting fuses also have the high ampere interrupting ratings needed for fault current levels typically found in industrial power systems.

Arc faults on the LV secondary of the transformer can yield primary currents below the current-limiting threshold of the MV fuse resulting in clearing times in excess of 2 seconds for most of these fuses. The difficulty in using MV fuses to limit low voltage arc flash energies arises from selection of ampere ratings and time current curves to ensure that magnetizing inrush currents do not cause nuisance openings when the transformer is energized and to ensure coordination with secondary overcurrent protective devices (OCPD).
With the proper relaying, the new Mersen Medium Voltage Controllable Fuse (MVCF) overcomes the shortcomings of traditional primary fuse protection against secondary arc flash events while maintaining all the advantages of primary current limiting fuse protection. This Tech Topic will provide information on the construction, operation and proper application of these devices. Examples with various low voltage protection schemes will be presented to assist in making the optimum selection of relays and settings.

II. PRIMARY FUSE ADVANTAGES

Equipment Protection

In some of today's industrial medium voltage power systems available fault currents have reached values exceeding 50kA. At these power levels damage can occur very quickly in the event of an arcing fault in medium voltage equipment. Although there is published research showing a relationship between arc energy (W_{arc}) and levels of equipment damage, little has been written on the maximum allowable W_{arc} to ensure that MV equipment would be easily repaired. [2][3]

The following arc fault tests show the superior short protection of current limiting fuses for MV faults.

An arc fault was created within a 15kV disconnect switch by placing a trigger wire on the line side of the switch. The first test used an upstream 100E current limiting fuse as the protection. A 14.4kV source was closed onto the circuit. With an available fault current of 18kA, the fuses opened within 7.6 ms. A total arc energy of less than 200 kWs was measured. The peak power was limited to less than 13 MW. The photos of Figure 1 show the location of the 18AWG trigger wire (l) and the damage after the event(m). Since very little damage occurred, the equipment could have been cleaned, tested and put back into service with minimal effort.

The same event as above was created but with no fuse protection and the station circuit breaker set to trip at 5 cycles (83 ms). With the trigger wire placed at the same location, the damage shown in the photos of Figure 1(r) was observed. The actual clearing time of the station breaker was 96 ms. A peak power of 42 MW was measured. The energy delivered to the arc exceeded 2,200 kWs. The insulators and interface barriers appear to have been impregnated with the copper vaporized from the electrodes of the arc. These would likely need to be replaced as well as any other component impregnated by copper.

Figure 1. Trigger Wire Location (l). Damage with Current Limiting Fuses (m). Damage at 96 ms (r)

People Protection

Although calorimeters were not used in the scouting tests discussed above, calculations using the bolted fault currents and measured clearing times were used in calculation with IEEE 1584 equations. With a working distance of 24”, a worker standing by the switch handle; would be exposed to a calculated incident energy of 0.3 cal/ cm^2 with the current limiting fuse. With a clearing time of 96 ms, the incident energy calculation rose to 4.5 cal/cm^2.

A high speed video camera in the lab control room was used to record both events. A GoPro® Camera was placed closer to the switch to better gauge the reach of the plasma by-products. Video captures from both perspectives are shown in Figure 2.

Figure 2. Reach of arc flash with E-Rated Fuse (l) and 5 cycle opening (r)

System Protection

Equipment fed from connection points on the line side of the protective device will experience voltage disturbances based on the performance of the protective device. Figure 3 illustrates the potential impact of a bolted fault on the MV power system. In this example, the voltage was measured just upstream of the protective device during bolted fault tests.

In figure 3a the current (red) and voltage (blue) for C phase are shown. Notice that the voltage is near zero for most of the 100 ms duration of the bolted fault. For connection points near the fault, the voltage applied to plant equipment can be pulled to levels below their operating voltage. If this duration is too long, equipment on non-affected circuits will 'drop out.'

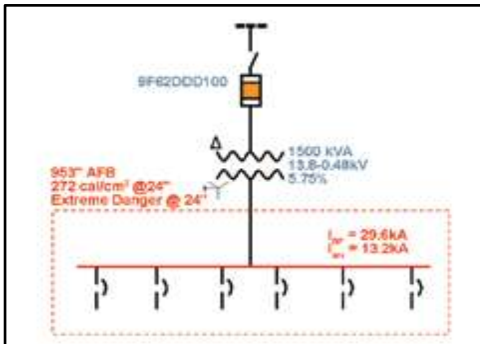


Figure 4: Switchgear with no main fed by 1500KVA Transformer. Short circuit protection for switchgear bus is provided by primary fuse.

This situation is less likely when fault current levels are in the current limiting range of the fuse protection and clearing times are less than 1/2 cycle. With current limiting fuse protection, the disturbance to the system voltage will be less than 1/2 cycle for faults above the fuse's current limiting threshold. As shown in figure 3b, the system voltage at fault initiation is near zero volts at the line side of the fuse switch until the fuse elements heat up and melt. When the elements melt, arcs are formed between the notches of the short circuit element causing the voltage at the line side to rise quickly. In this example, voltage has risen to a peak level in 1.9 ms after initiation of the fault. It is this rise in voltage that stops the increase in current. At this time, 'dropout' is not a concern as the voltage has risen above the system voltage due to the support by the voltage developed across the system reactance by the di/dt caused by the fuse operation. If the fuse meets the requirements of IEEE Standard C37.46 [4], this transient voltage will be below the Basic Insulation Level (BIL) of components connected to the MV system.

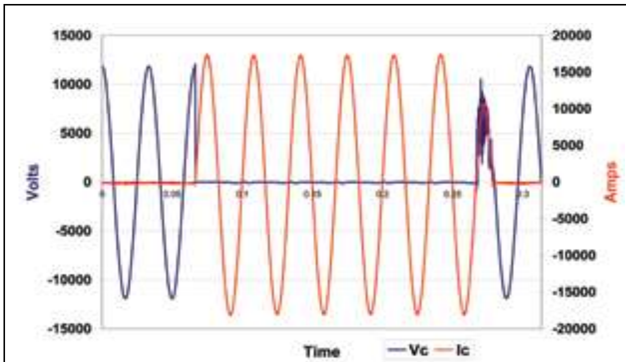


Figure 3a: Bolted Fault test with 5 cycle clearing time

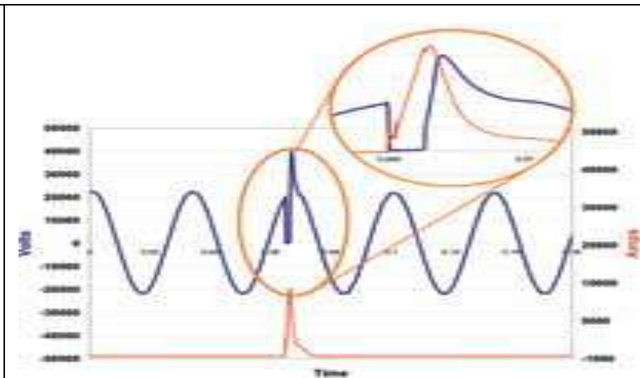


Figure 3b: Bolted fault with current limiting fuse protection. Clearing time 3.9 ms

III. TYPICAL PRIMARY FUSE PROTECTION ISSUES

The example depicted in Figure 4 highlights 480V switchgear where incident energy calculations exceed 40 cal/cm^2. In this situation, the switchgear should be de-energized by opening the transformer primary switch to perform many typical maintenance actions such as racking out a feeder breaker. Since opening the primary switch will de-energize all the circuits in the LV switchgear, the cost of downtime associated with this safety practice can be so costly that improvements have to be made to the protection scheme to drastically reduce the incident energy.

In this example, the arc flash incident energy calculation for the low voltage switchgear is based upon the clearing time of the primary fuse. Referring to Figure 5, note that the 9F62DDD100 clearing time for a secondary arcing fault of 13.2kA at the 480V switchgear (459A through the primary fuse) will be near 10 seconds. The resultant incident energy calculation for a 24" working distance at the switchgear is 272 cal/cm^2. Using the 2 second limit mentioned in IEEE 1584, the incident energy calculation for the LV switchgear is still in excess of 40 cal/cm^2.

Even with the inverse time current curve of the 9F60HMH100, the incident energy calculation will typically be greater than the rating of daily wear PPE typically worn by electrical workers. See Tech Topic Arc Flash Note 6 [5] for more details on the limits to the application of this fuse.

IV. CONTROLLABLE FUSE DETAILS

Construction and Operation

The Controllable Fuse System is comprised of the Controllable Fuse (MVCF), the Actuator Module (CFAM) and the Interface Module (CFIM) as shown in the photo of Figure 6. Within the MVCF are three main components: The Main Fuse, The Controlled Fuse and the Bypass Switch (see Figure 7). The Bypass Switch is closed until it receives a pulse from the CFAM Module.

Operation begins when the CFIM receives a relay contact closure. It will then transmit a signal via fiber optic cable to the CFAM attached to the MVCF. The CFAM will then send a pulse to the Bypass Switch within the fuse body. This pulse will cause the normally closed Bypass switch to release, placing the Controlled Fuse in series with the Main Fuse. Being a much smaller fuse, it is designed to open significantly faster than the Main Fuse. The opening time of the fuse system is dependent on the relay scheme and the magnitude of the overcurrent.

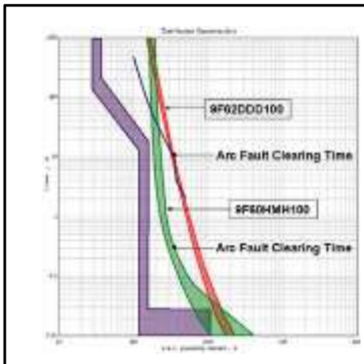


Figure 5: Time current curve for primary fuse.


Figure 6: Controllable Fuse System Components

In addition to sending a trip signal to the CFAM, the CFIM polls the CFAM to assess the health and status of the unit. LED lights on the CFIM can be used to alert personnel if there is a problem. Contact closures from the CFIM can be used to send alerts to remote locations. For more information on the operation of the Controllable Fuse System see Instructions for Installation, Operation and Maintenance of the Mersen Medium Voltage Intelligent Fuse System.

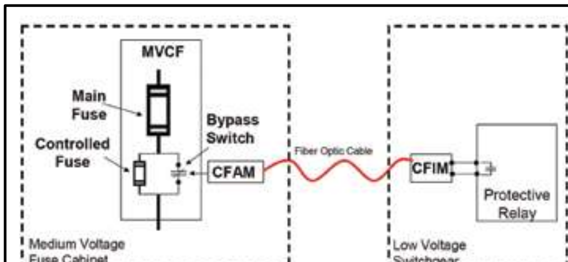


Figure 7: Controllable Fuse Diagram

Controllable Fuse Application Information

The example shown in Figure 8a demonstrates how to model the two fuse elements and Bypass switch of the Controllable Fuse in power system analysis software with conventional elements. In this diagram the 50P unit of the relay, wired to CTs on the secondary of the transformer, is shown connected to the Bypass Switch of the Controllable Fuse. When modeled in this manner, the time current curve of the Main Fuse would be used to assess the level of protection on the primary of the transformer and coordination with other overcurrent protective devices in the same manner as a conventional current limiting fuse (see red time current curve in Figure 8b). However, the time current curve of the Controlled Fuse is added to the operation time of the 50P relay (in this case 0.2 seconds) to assess protection and coordination on the secondary of the transformer.

Contact Technical Services for time current curves and more information on modeling the MVCF in analysis software.

When modeled this way with analysis software, the Controlled Fuse can be considered to be a 'virtual' secondary main. For arc flash analysis, the combination of the relay operating time and the time current curve of the Controlled Fuse (orange curve in Figure 8b) would be used to determine the duration of a LV switchgear arc flash in the incident energy calculation.

For systems with a secondary main, Figure 9a, the MVCF can be used to provide arc flash incident energy reduction for the main breaker compartment and backup protection for the main. See Figure 9b for insight into the flexibility possible with the controllable fuse system with different settings in the relay.

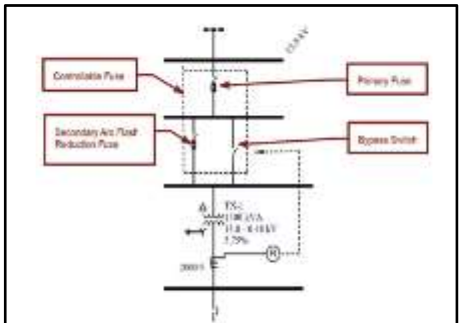


Figure 8a: Modeling the MVCF for arc flash calculations.

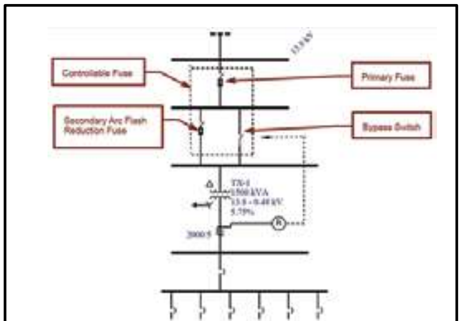


Figure 9a

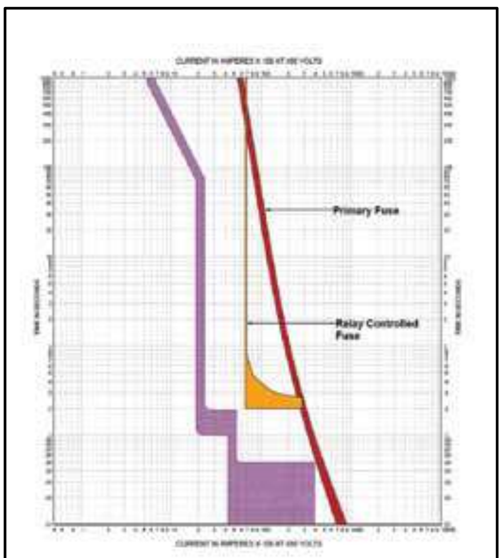


Figure 9b: Time Current Curves of Controlled Fuse with 700 ms delay

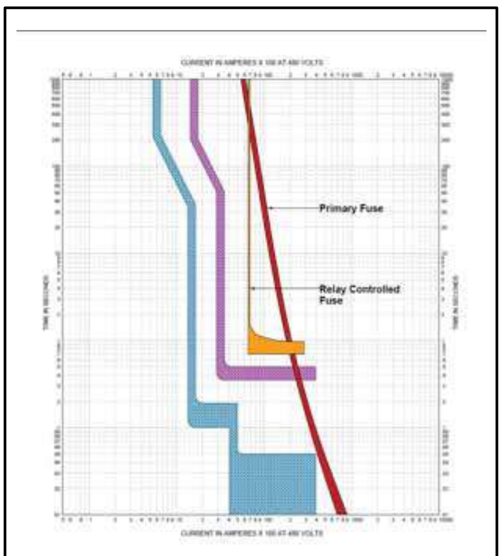


Figure 8b: Time Current Curves of Controlled Fuse with 200 ms delay

V. IMPROVING ARC FLASH PROTECTION OF LV SWITCHGEAR APPLICATIONS

With the MVCF, it is now possible to reduce incident energy on the low voltage switchgear to much lower values than conventional primary fuses. The following discussion is intended to highlight ways that a controllable fuse can be used with relays and other devices to reduce incident energy calculations to less than 8 cal/cm^2.

Selection of the ampere rating of the MVCF is the same as a conventional MV current limiting fuse. The ampere rating is chosen based upon the consideration of transformer characteristics, NEC requirements, conductor protection and coordination. Refer also to [1], [5] or [6] for additional guidance on the considerations for proper ampere rating selection.

Achieving incident energy levels below 4 cal/cm^2 is possible for 1500kVA transformers (or smaller) with standard impedances by using relaying schemes that provide trip signals in less than 1 cycle. Two schemes gaining greater acceptance in industry are discussed in the following examples.

1. Maintenance Mode Switch and Instantaneous Relay (50P)

2. Arc Flash Relay with Instantaneous Relay (50PAF) and light sensors

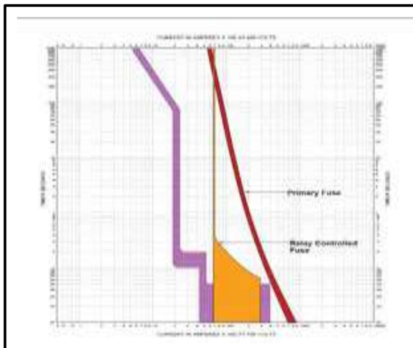


Figure 10: Time current curve of controlled fuse with no delay.

In the following examples, the performance of the MVCF with these protection schemes is reviewed with the resultant arc flash calculations.

Example 1 Maintenance Mode Switch

In this scheme, relay operation is faster when the position (state) of a switch is changed to maintenance mode. This switch can be of several forms such as a keyed switch, the output of a motion detector or the output of a light curtain. The resultant lower incident energy is only during the time that the switch is in maintenance mode. The two modes of operation of the relay to be considered with this scheme are discussed below.

Normal Mode. In the example shown in Figure 8a, the relay is programmed to have a time delay for its 50P instantaneous overcurrent function. The 0.2s delay ensures coordination with the downstream feeder breaker. This delay added to the time current curve of the Controlled Fuse is shown in Figure 8b. The incident energy on Bus 4 for this example is calculated to be 10.4 cal/cm^2 at 24 inches. For the example of Figure 9a, the incident energy calculation for Bus 4 is 27 cal/cm^2 at 24” due to the 700 ms delay in the relay instantaneous setting to coordinate with the main breaker.

Maintenance Mode. In both applications, switching to Maintenance Mode Switch removes the time delay of 0.2s and 0.7s respectively from the 50P instantaneous overcurrent function. The CFIM will receive a trip signal in less than 0.01s in the event of a fault. The resultant trip curve of the relay and Controlled Fuse components is shown in Figure 10. The incident energy calculation for the incoming bus for both applications is reduced to 3.7 cal/cm^2 at 24" when in maintenance mode.

Since this scheme relies on worker interaction, some companies apply arc flash labels with only the incident energy calculation of Normal Mode to the LV equipment. Utilizing lower rated PPE while interacting with the LV equipment in Maintenance Mode would be part of a documented work procedure. Note that protective device coordination is lost if not returned to Normal Mode after work is complete.

<u>Example 2 Arc Flash Light Sensors</u>

In this scheme, relay operation occurs only upon detection of light by arc flash light sensors located within the protected equipment and a simultaneous pickup of the 50PAF function. Minimal delay from the relay is added to the clearing time of the controlled fuse for the incident energy calculation. For this example, the incident energy on the bus is calculated to be 3.7 cal/cm^2. The combination of light and overcurrent prevents tripping for faults downstream of the breaker; hence there are no coordination concerns with this setting. The appropriate curves are shown in Figure 11.

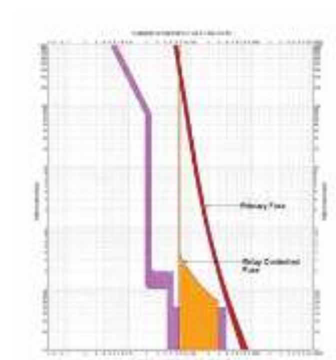


Figure 11: Time current curve of controlled fuse with arc flash sensors and 50PAF relay

When using light sensors in circuit breaker cubicles of Low Voltage Power Circuit Breakers (LVPCB), take the necessary precautions to prevent nuisance operation of the arc flash relay. With improper placement of the light sensor, the arc flash relay can be triggered by a breaker interruption of a downstream fault. The combination of the overcurrent and the light emitted from the arc during the circuit breaker interruption can fool the relay into interpreting the event as an arc flash in the cubicle. See [7] for more information on the best placement of light sensors in circuit breaker compartments.

<u>Other Relay Options</u>

Zone Selective Interlock (ZSI). Another possibility with a relay controlled fuse is a ZSI protection scheme. In this scheme, a trip signal from the relay to the CFIM is dependent upon both a pickup of the 50P function and the absence of a blocking signal from all of the feeder breaker trip units [7]. A short time delay in the 50P is added to allow for the downstream trip units to sense a fault on their circuit and create a contact closure blocking signal. Without a blocking signal the combination of relay settings and fuse time current curve are shown in Figure 12. Incident energy at the low voltage bus of figure 8a is reduced to 5.1 cal/cm^2 at 24". If the relay receives a blocking signal from any of the feeder breakers, the relay switches to a slower backup instantaneous settings such as shown in Figure 13. If the overcurrent is not cleared in a timely fashion (e.g. breaker failure) the relay will send a trip signal to the CFIM according to the slower settings.

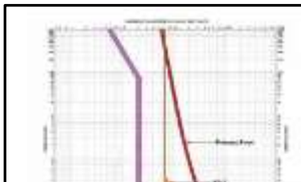
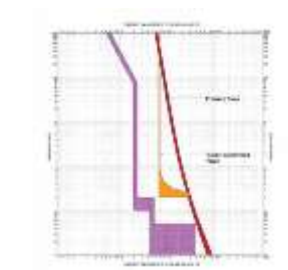


Figure 12: Tripping characteristics of controllable fuse without a blocking signal

Figure 13: Tripping characteristics of controllable fuse with a blocking signal



The advantage of this approach compared to the use of a manual maintenance mode switch is that low incident energy can be obtained at the low voltage bus without compromising coordination or relying on personnel to put the system into maintenance mode. Unlike the maintenance mode approach, arc flash labels with only the low energy need to be applied since the protection scheme does not rely on the proper interaction by a worker. For more information for using a ZSI scheme refer to the manuals for the trip units and relays being considered.

Differential Relaying Protection. Although it is not typically very economical for the application discussed in this paper, the MVCF system can be used in a differential relaying scheme.

This protection scheme would require dedicated CT's on the load side of each feeder breaker and on the secondary bushings of the transformer. For any faults within the protected zone (i.e. between the transformer CTs and any feeder CT) tripping would be instantaneous. For faults beyond the feeder CTs, the differential relay will not trip.

Like the ZSI scheme, low incident energy can be obtained at the low voltage bus without compromising coordination or relying on personnel to put the system back into maintenance mode. For more information for using a differential scheme, contact Technical Services or the relay manufacturer.

VI. SUMMARY

The controllable fuse offers all the advantages of a current limiting transformer primary fuse with the flexibility of various protection schemes for improved protection against arcing faults in the Low Voltage Switchgear. Several relay schemes were presented that have the possibility of reducing incident energy to levels below the arc rating of many electrical workers' daily wear. Although there are many variables to consider when choosing a scheme, settings and timings, it is now possible to have dramatic reductions in incident energy with this new technology.

Whether de-energizing circuits on the MV or LV system, the act of placing equipment in electrically safe work condition puts workers in the position of interacting with energized equipment. It is critical that employers do a hazard analysis to ensure that workers have adequate PPE for the task.

VII. REFERENCES

1. IEEE Standard 242, "IEEE Buff Book Section 10.2," IEEE, September 2002.

2. Schau, H. and Stade, D. "Requirements to be met by protection and switching devices from the arcing protection point of view." Proceeding of 5th International Conference on Electric Fuses and their Applications, Technical University of Ilmenau, Germany, Sept 1995, pp 15-22

3. Gammon, T. and Matthews, J. "Conventional and Recommended Arc Power and Energy Calculations and Arc Damage Assessment," IEEE Trans. Ind. Applic. Vol. 39 pp 594-599 May/June 2003

4. IEEE Standard C37.46, "Standard for High-Voltage (>1000 V) Expulsion and Current-Limiting Type Power Class Fuses and Fuse Disconnecting Switches," IEEE 2010.

5. Tech Topic Arc Flash Note 6: Reducing Arc Flash Energies on Transformers Secondaries

6. Mersen Advisor 111, Section P page P33

7. Roscoe, G., Valdes, M.E. and Luna, R. “Methods for Arc Flash Detection in Electrical Equipment” Proceedings,” IEEE PCIC Annual Meeting Sep 2010.