

# A TESTED METHOD FOR MITIGATING ARC FLASH HAZARDS IN EXISTING LOW VOLTAGE MOTOR CONTROL CENTERS

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Paper No. PCIC-(do not insert number)

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**Abstract** — This paper develops a practical, cost-effective method of retrofitting existing low voltage motor control centers to reduce the arc flash energy for open door work to a much safer level. These self-extinguishing solutions are designed to reduce the arc flash energy from a calculated value in excess of 40 calories per square centimeter ( $\text{cal}/\text{cm}^2$ ) at an 18 inch working distance to an average tested value of less than 1  $\text{cal}/\text{cm}^2$ .

The research presented focuses on the low voltage motor control center where technicians perform troubleshooting tasks on a daily basis with the motor starter door open and the circuit energized. The paper discusses engineered and tested modifications that will greatly improve the safety of the low voltage motor control center with little procedural change for the technician in the field. These solutions allow the process owner the option of upgrading existing equipment to extend the operating life of the equipment while addressing safety issues and reducing mean time to repair.

**Index Terms** — Low Voltage Motor Control Center (LVMCC), Personal Protective Equipment (PPE), Safety by Design, Retrofit, Open Door Testing, Motor Control Unit (bucket), Self-Extinguishing, Arc Flash Risk Assessment

## I. INTRODUCTION

Many advancements have been made in the last forty years in electrical safety for the industrial worker. There is no denying that newer, safer equipment is available and has saved lives. Unfortunately, very little research and development has been considered in retrofitting existing low voltage motor control centers (LVMCC) to make them safer with the motor control unit (bucket) doors open, as is necessary when troubleshooting equipment.

Industrial process units, such as refineries and chemical plants run 24/7, scheduling work often years in advance for turnarounds. LVMCCs are commonly energized during the troubleshooting process. These constraints make de-energizing the equipment nearly impossible in an industrial complex. The arc flash exposure levels calculated for an arc fault on the line side of the individual bucket's circuit breaker or fused disconnect switch in a petrochemical facility is a high energy zone. The calculated arc flash energy often exceeds 40 calories per square centimeter ( $\text{cal}/\text{cm}^2$ ) at a working distance of 18 inches (in) for an installation with upstream coordination interval from 200 milliseconds (ms) for a power circuit breaker with an integral electronic trip unit to 300 ms for an electromechanical

trip per corporate standard. To reduce the risk to an acceptable level on a 480 V industrial system, popular modern solutions are to add a maintenance switch on the upstream circuit breaker and put workers in 40  $\text{cal}/\text{cm}^2$  personal protective equipment (PPE).

The maintenance switch typically requires a new trip unit in the upstream circuit breaker, or the addition of a shunt trip and an independent relay, to limit the energy by adjusting the instantaneous setting. This, however, compromises selective coordination and can compromise load integrity by isolating the entire LVMCC if a fault occurs in a single starter unit.

The 40  $\text{cal}/\text{cm}^2$  PPE makes troubleshooting work very difficult, if not impossible.

Engineered solutions are recognized as being 70 to 90% effective at eliminating hazards while procedural solutions are considered 10 to 50% effective [1]. Relatively simple modifications to older style LVMCC can greatly reduce the incident energy exposure, while assuring minimum interruption to the process.

This project focuses on third party testing of actual equipment retrofitted with an engineered solution which reduces potential incident energy exposure for workers performing typical work in a motor control center bucket with the door open from a calculated 55  $\text{cal}/\text{cm}^2$  to a measured value of 1  $\text{cal}/\text{cm}^2$ . In addition, the modifications maintain existing selective coordination allowing process integrity. The changes also reduce the mean time to repair (MTTR) for an arc fault in the rear of the LVMCC significantly.

## II. HIGH-ENERGY ARCING FAULTS

Typical causes of high-energy arcing faults in a LVMCC are:

1. An electrical technician troubleshooting a combination motor starter that is failing to pull-in on a start command. The technician has energized the cubicle with the door open, after checking that there is voltage to the field controls, a jumper is temporarily installed across the field control system at the bucket to confirm the problem is in the field. While working with the jumper, the technician makes a mistake and ends up causing an arcing fault.
2. An electrical technician, after troubleshooting and changing out a bad overload, powers up the bucket with the door open to confirm operation. As a last step, the technician checks for a loose connection in all current carrying terminals with a non-insulated screwdriver that makes contact phase-to-ground.

3. An insulation failure of the leads between the bucket's protection device and the riser bus stabs. This fault is typically the principal opportunity for a high energy phase-to-phase or phase-to-ground fault due to movement between the conductors, conductors rubbing during starts, insulation embrittlement over years of service, or sheet metal rubbing on the leads connecting the line side of the primary protective device.
4. Misalignment issues not uncommon with early bus stab jaw designs in NEMA LVMCC. Over the years, stab issues from the connection of the bucket to the riser bus have contributed to many hot spot failures and insufficient clamping force during through-faults. Both hot spots and reduced clamping force can result in arcing faults. Properly engaged buckets rely on:
  - a. The pre-insertion centering of the bus stab jaws.
  - b. The bucket being square, both vertically and horizontally.
  - c. Uniform pressure on all sides of the bucket as the technician slides or forces the bucket onto the riser bus.
  - d. The bus stab spring being in good condition.

The research presented in this paper builds on two previously published papers with testing completed in Test Series 1 in 2013 [2][3]. Additional testing was conducted during Test Series 2 in July of 2015 [14] on two samples of three vertical sections each of LVMCC. Test Series 3 [15][16] concluded the Proof of Concept Testing of the final enhancements in November of 2015 and was also conducted on two LVMCC samples consisting of three vertical sections each. All the equipment was front access only with an insulated 3200 A main bus. The 600 A riser bus insulation varied between factory insulated, field insulated, and bare riser bus.

### III. NEW TESTING: SERIES 2

The focus of the second series of testing was the high-energy section of the LVMCC bucket, between the line side lugs of the motor control unit's molded case circuit breaker (MCCB) and the bus stabs mounted in the glass polyester stab assembly (clamshell). As in Test Series 1, these tests were conducted with the bucket door open to simulate an energized maintenance task being performed. The research utilized physical barriers to extend the distance of travel beyond the arc's practical limits for the driving voltage and the free electrons generated by the specified ignition source. Braided shield wire over the flexible leads was also used to force a ground plane in close proximity to energized components, preventing maximum arc energy transfers to the air that result in high incident energy events. The braid selected is an open weave and the length is short enough to have no impact on the continuous current rating of the combined motor control unit.

All testing in [15] (Appendix A) was initiated as three phase faults due to the previous testing that indicated a phase-to-phase fault could propagate to all three phases of the bucket's MCCB. This is compliant with the proposed changes to IEEE C37.20.7 using three phase faults with #10 bare fine stand ignition wire [10].

All of the Series 2 tests were performed at 589 V, the voltage

required by the test lab to maintain the current profile identified in IEEE C37.20.7. The first four trials were conducted at a prospective current of 36 kA and the remainder of the trials at 50 kA. These trials validated the viability of the changes at a nominal voltage of 480 V. Obviously the higher driving voltage made arc extinction more difficult. The maximum allowable trip time was set by the test lab's backup circuit breaker at 300 ms. Appendix A lists the results of the July 2015 series of tests [14].

The faults were initiated as three phase faults using two methods for installing the ignition wire, each attempting to replicate a worst case real world incident. In the majority of the tests, the arc was not able to sustain the faults for longer than 25 ms and maximum incident energy observed was 2.3 cal/cm<sup>2</sup>. The remaining trials propagated through the stab assembly to the riser bus and resulted in faults that lasted 300 ms with a maximum incident energy of 4.5 cal/cm<sup>2</sup>. The test facility's backup circuit breaker cleared these faults. Appendix A shows the arcing current for each fault.

#### A. Test Series 2 Observations

Because of the short duration and indeterminate nature of the waveforms, the paper refers to peak values, rather than RMS.

Fig. 1 is the oscillography from Trial 13 of Test Series 2 (Appendix A) [14]. The trial was performed at a prospective current of 50 kA, resulting in a 41.6 kA peak and the arc being sustained for 10.8 ms. The phase currents demonstrate the typical collapse of the arc fault current for an HRG system. The test lab's circuit breaker closed and energized the test sample approximately 1.3 cycles after the data record started. The first 1/10th of a cycle is the time required to melt the #10 bare fine strand ignition wire. At this point the arc develops. A-phase collapses at the first zero crossing failing to re-establish when the anode and cathode swap polarity. Due to the collapse of A-phase, B and C-phases must reposition themselves to be 180 degrees out from each other and the current extinguishes at 2.05 cycles after the data started and 0.65 cycles after the arc began. The circuit remained energized for the full 300 ms to assure no restrike occurred. The arc lasted just over 10.8 ms and the maximum heat energy recorded was 1.14 cal/cm<sup>2</sup>.

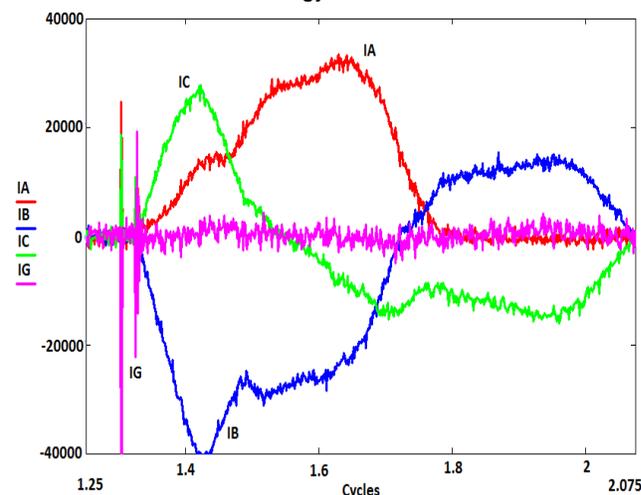


Fig. 1 Series 2, Trial 13 Current Oscillography

In Fig. 2, Trial 6 of Series 2 phase currents illustrate the

difference a solidly grounded system makes as opposed to an HRG system. This test was performed at a prospective current of 36kA, with a recorded arc fault of 37.9kA peak, with a 21.9 ms arcing time.

The solid ground contributes to sustaining the arc. The test lab's circuit breaker closes ~1.55 cycles after the data acquisition system starts. At 1.7 cycles, the ignition wire melts and the arc begins. C-phase has trouble re-establishing at each zero crossing. At the zero crossing of A-phase, the arc restrikes between A and B-phase with little ground involvement. At 2.25 cycles, the C-phase restrikes and the fault current involves phase A, C, and Ground before restriking to B. At 2.6 cycles, the A-phase arc extinguishes, followed by C-phase, so the fault for the last 1/8th cycle is B-phase arcing to ground.

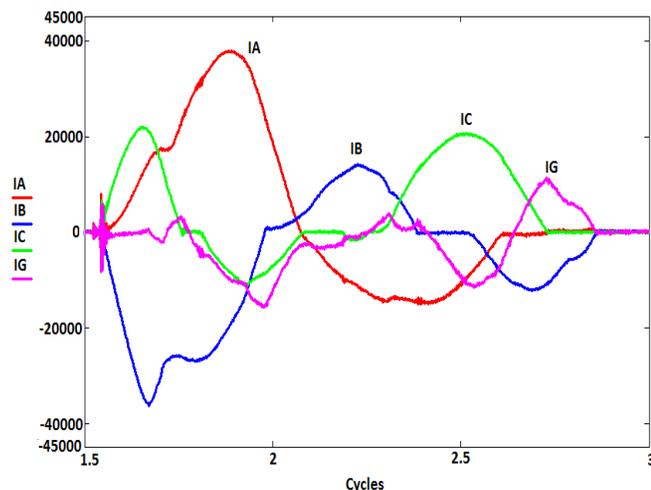


Fig. 2 Series 2, Trial 6 Current Oscillography

A-phase arced to the braid preventing the plasma field from developing sufficiently to sustain through the zero crossing. There was evidence of arcing between A and B-phase. The prospective current for this trial was 36kA rms, but the last 1/2 cycle of current crested at less than 20kA. The maximum incident energy recorded was 1.35 cal/cm<sup>2</sup>.

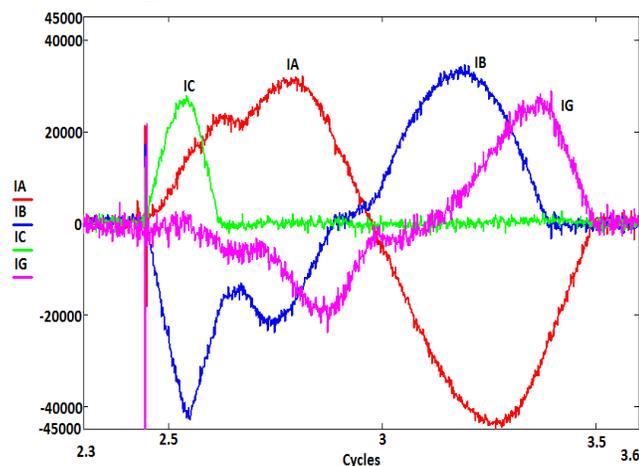


Fig. 3 Series 2, Trial 8 Current Oscillography

In the second trial of a solidly grounded system, (Fig. 3) the

arc fails to reverse polarity through the zero crossing at this voltage level for C-phase. Due to the proximity of the ground plane, the arc does not develop to a maximum energy transfer condition, as discussed in Paper 2 [3]. As the polarity shifts, it becomes impossible for a stable plasma field to re-establish over the resistance created by the bucket modifications.

By sealing the stab assembly with silicone caulk, the ability of the plasma to move into the back plane, allowing the fault to propagate to the riser bus is virtually eliminated.

Based on observations made when the LVMCC side cover was removed for post trial inspection, special care needs to be taken to boot the end of the main bus run at the last vertical section. The end of the main bus is a natural location for the plasma field to initiate a secondary arc to the side cover. The test results also demonstrated that allowing a fault to propagate to the riser bus and travel to the bottom of the section resulted in a maximum allowable fault time that heavily damaged the entire test sample. The damage observed led the team to investigate incorporating an arc flash detection relay (AFDR) as a method of minimizing damage and MTTR.

#### B. Selected Enhancements for New Test Series 3

Based on the observations of these previous tests, five arc-extinguishing modifications were selected for the Test Series 3 trials in November of 2015. (Fig. 15)

1. MCCB Cover – The MCCB cover appeared to limit the ability of the arc to propagate within the motor control unit by placing a barrier that stretched the arc length between the breaker terminal and metal surfaces.
  - a) The MCCB cover also minimizes the opportunity to start a fault where phase-to-phase distances are close enough for the fault to be sustained.
  - b) The holes for the lead wires in the MCCB cover are only large enough for the leads to enter the breaker lugs, making it improbable for a conductive part larger than 1mm to reach an energized surface from the top of the MCCB.
  - c) The MCCB cover was secured with a heavy-duty cable tie that prevented the cover from popping off during the fault, thus further reducing the energy forced to the front of the bucket.
2. Silicone Caulk – Simply sealing the line leads at the glass polyester clamshell provides a barrier for the plasma field and prevents propagation of the arc fault to the riser bus.
3. Grounded tinned copper braid – The tinned braid protects against arc propagation if the leads blow out at the top of the MCCB. As mentioned before, the ground plane works to kill the arc by making the low impedance path a ground fault. The braided tinned copper sleeve draws any faults to ground, rather than allowing faults to develop into phase-to-phase faults. Further, the braid shortens the arc path and limits the free electron/plasma field created. In the case of the HRG, this results in a 5A fault, and in the case of the solidly grounded system, the reduced impedance to ground prevents the fault from surviving the next zero crossing since the energy is too low to sustain the plasma field.

4. Proper torquing of the MCCB terminals - The lead wire needs to be torqued with a torque wrench to the specification on the front of the circuit breakers to ensure the lead is not blown out of the MCCB terminals. These torque values are to ensure the terminal retains the lead wire and cannot be reproduced with a simple screwdriver.
5. Increasing insulation at the end of the main bus away from the source - Factory insulation may be present but needs reinforcing to prevent the end of the main bus from becoming a terminal point for arc faults travelling away from the source. To increase the bus insulation a half lap layer of elastomeric electrical tape was added to the main bus end away from the source.

**IV. EQUIPMENT & TEST SETUP**

*A. Ignition Wire Installation Methods:*

During testing, several methods were developed to secure the bare #10 fine strand ignition wire used to initiate the arc. The most effective method removed the line side terminals from the MCCB to be drilled and tapped for the terminal screw to receive an 8-32 screw after reinsertion into the breaker. For line side faults this method used a 1-1/2 in., 8-32 zinc machine screw, (2) #8 flat washers, and (2) 8-32 nuts as shown in Fig.4. The bare #10 fine strand ignition wire was secured to the machine screws by clamping a loop of the ignition wire between the two nut and washer combinations. The machine screw head was then cut off as close as possible to the nut.



Fig. 4 Bus stab ignition wire connection

To perform the bus faults, the ignition wire was wrapped around each of the bucket stabs, as shown in Fig. 5. The combination starter unit was then stabbed onto the riser bus and the calorimeters were mounted 18 inches from the front of the unit with the door open.



Fig. 5 Bus stab ignition wire connection

*B. Arc Flash Detection Relays:*

The arc flash detection relaying scheme requires the addition of relay class current transformers (CT) in the LVMCC feeder circuit, a trip signal from the arc flash detection relay to the LVMCC feeder circuit breaker at the low voltage switchgear, and the installation of a bare fiber loop with associated supports and bulkhead fittings (Fig. 6 and 7). The light sensing fiber is installed in the rear bus compartment by removing only the two side panels of the LVMCC and using screw together fiberglass pulling rods (fish sticks) to pull in the fiber. During testing, three donut style CTs were installed on the incoming bus and one donut style CT was installed on the grounding conductor. The ground CT was used only for data gathering and was not part of the AFDR relaying scheme. The AFDR trip outputs were wired into the test facility's backup circuit breaker to interrupt faults detected by the relays. Only one AFDR was actively tripping during any test but both AFDRs were in service and recording fault data. Both AFDRs worked well and as expected throughout the tests.

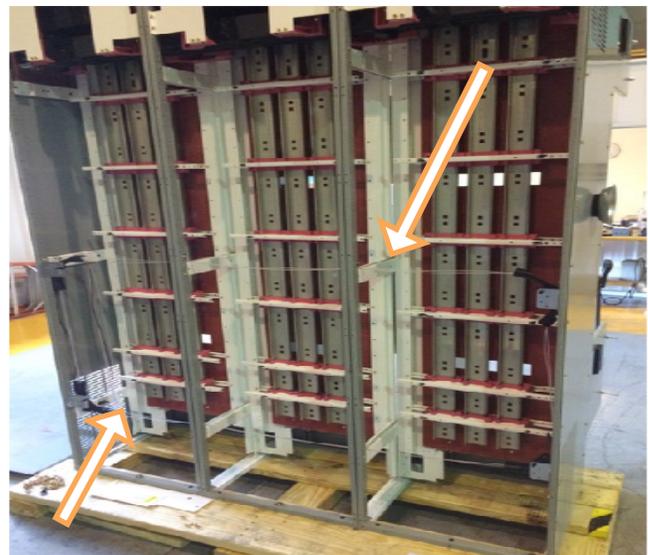


Fig. 6 Bus compartment fiber optic loop installation from bulkhead fitting in the bottom left of picture over lower support brackets and return over midway support brackets. (Rear panels removed for clarity)

The light detection element (AFD) of the AFDR is supervised by an overcurrent element (50) to prevent false tripping due to inadvertent exposure to bright light. The current pickup was set based on the load current rating of the horizontal bus and the locked rotor current of the largest motor that would be installed on the low voltage system, 250 HP ( $3200A + 6(1.25 \times 250) \approx 5000A$ ). The time delay (62) is used for tripping security to allow the arc extinguishing modifications and the MCCB to control fault current extinguishing or clearing times in the bucket or the downstream circuit. Therefore, the AFDR will only send a trip signal to the upstream circuit breaker for a fault in the bus section of the LVMCC.

A 30 ms dropout timer was added to the light detection element to "latch" the light pickup due to the instability of the arc, ensuring the light detection input remains asserted in case of a AFD failure before the overcurrent delay times out. (Fig. 8)



Fig. 7 Supports for bare fiber loop installation both manufacturers' relay loops routed together.

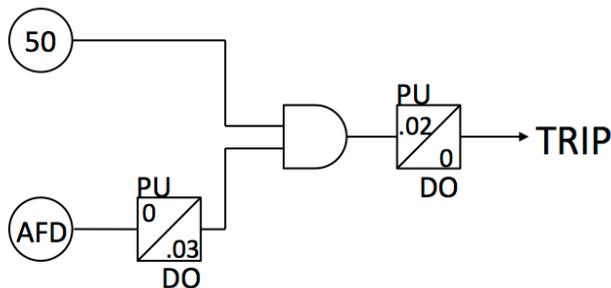


Fig. 8 Tripping Logic for one AFDR used

The manufacturers of the two AFDR used in the Test Series 3 use different methods for monitoring light intensity and setting the sensitivity of the Arc Flash Detection element. One manufacturer's AFDR uses a scale of 0-100% of light sensor saturation. The second relay uses a sensitivity adjustment on a scale from 1 to 9 corresponding to 9 klux minimum and 25 klux maximum setting. Prior to the start of fault trials, a number of light only simulations were conducted using a camera flash positioned in different locations including both the front and rear section of the LVMCC to verify operation of the light detection elements.

The AFD pickup for the first relay was set at 3% while the

second relay's element was set at 9 for maximum sensitivity. The light magnitude recorded by the relays never approached the minimum pickup settings of the relays for a fault initiated in the bucket or for a MCCB clearing a bolted fault on the load side. All arc faults in the bus section of the LVMCC emitted enough light to provide a maximum light magnitude in both relays. In fact, even when the light detecting fiber loops were not replaced and allowed to be coated with decomposed polymer residue from the previous trials, the light from the arc fault was still able to provide a maximum light magnitude reading on both relays. This being said, the research recommends that the light sensing fiber loop be replaced after any fault in the rear of the LVMCC even when the relay provides a positive light sensor self-check.

## V. NEW TESTING: SERIES 3

The next stage of the testing in November 2015 (Appendices B and C) [15] [16] confirmed the repeatability of the arc extinguishing modifications in the bucket and the added arc flash detecting relay (AFDR) to the main and riser bus area of the LVMCC functioned as expected without false tripping. The focus of the testing was to verify repeatability of the final arc extinguishing bucket modifications and the ability of an arc-detecting relay to coordinate with these features.

It was observed in Test Series 1 and 2 that very little energy from a fault in the bus section in the back of a LVMCC that lasts 200, 300, or even 500 ms makes it to the front of the equipment. In both insulated and uninsulated riser bus arrangements, the fault traveled to the bottom of the riser bus and rooted, vaporizing several inches of the riser bus and contaminating the entire sample with copper and decomposed polymer (Smoke) residue from the pyrolysis of the insulation as seen in Fig. 9.



Fig. 9 Remaining rear compartment after 300ms 50kA fault

The intention of the AFDR is not to reduce the incident energy at the front of the LVMCC but to limit the damage, thus reducing MTTR if a fault develops in the bus area. The system requires the installation of a set of current transformers in the switchgear, the mounting of the AFDR, installation of the fiber optic sensing loop and installation of an externally powered shunt trip on the feeder breaker if the breaker has only an integral trip unit. The existing protection system does not

require any other modifications and will act as it has in the past. (Fig. 10)

A method of detecting and determining if the arc fault is occurring in the bus and not the bucket area is essential. The primary benefit of combining the AFDR with the proposed LVMCC bucket enhancements is that the arc-extinguishing features eliminate tripping the entire LVMCC for a bucket fault and minimizes the MTTR for a fault in the bus area. After analyzing both light detection and current detection systems, it was determined the best solution is a combination of light and current detection with a time delay of 20 ms. This time delay value was chosen based on the maximum fault clearing time for both line side and load side faults in the motor control bucket.

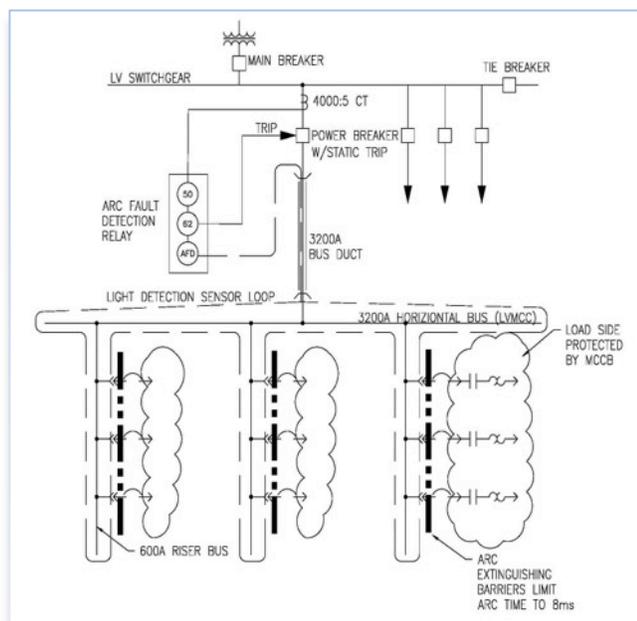


Fig. 10 Arc Flash Detection Protection One-Line Diagram

#### A. Series 3 Test Development

The tests were designed with the installed base of LVMCC in mind and the solution had to be implemented without rear access. All tests were completed with the bucket door open and the prospective fault currents of 36, 50, and 63 kA, representative of typical 1500 kVA, 2000 kVA and 2500 kVA transformers, respectively. Using IEEE Standard 1584 [8] calculations, with prospective short circuit fault currents of 36, 50, and 63kA, result in calculated incident energy observed should be on the order of 48, 69, and 90 cal/cm<sup>2</sup>, respectively, at a distance of 18 in and a maximum clearing time of 200 ms. The test samples for Test Series 3 had single loops of fiber optic "light pipe" added to the LVMCC, one for each of the relays utilized. Point sensors were used for benchmarking but not considered practical due to the level of disassembly required to cover a 20 vertical section LVMCC. The fiber loop could be added with the simple removal of the two LVMCC side panels.

The testing covered routine open door operations by qualified electricians troubleshooting operational issues commonly found in process industries. The results show the modifications allow the technician's standard 8 calorie AF

clothing an acceptable risk level for these open door tasks in the risk assessment. Operations such as stabbing a bucket onto the riser bus are not included in the test plan and would still require an arc flash risk assessment consistent with NFPA 70E [7].

The final test plan was designed to determine the effectiveness of the installation of the modifications and the ability to coordinate the arc flash detection system. The AFDR needs to be blind for the flash of the MCCB clearing and the light associated with an arc flash due to a fault on the line side of the MCCB. The coordination will allow the arc extinguishing modifications to perform but be sensitive to faults on the LVMCC bus. The ruggedness of the light detection system was also to be determined after being contaminated from bus faults and the repeatability of our coordination strategy.

#### B. Series 3 Test Observations

Appendices B and C show the results of Test Series 3 from November 2015 [15][16]. In all cases, the test results from faults initiated on the load, line, and bus stabs were very consistent.

1. Fig. 11 shows the typical extinction pattern witnessed in the line side faults. The B-phase would be the first to collapse at approximately 3 ms followed by A-phase and the final arc would be C-phase-to-ground. This sequence appears to be the result of the geometry of the magnetics and its impact on the arcing fault.

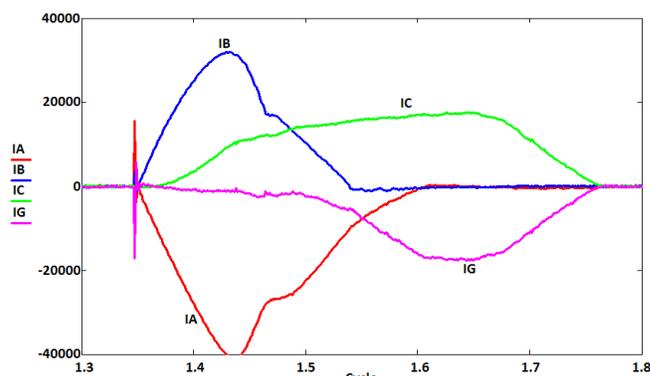


Fig. 11 Typical 63kA prospective line side fault extinguishing pattern for solidly grounded system

2. Load side initiated faults were all interrupted in less than ½ cycle by the MCCB in all cases but one, where a poor bus stab connection resulted in a riser bus fault that was cleared by the AFDR tripping the test lab circuit breaker. The use of the AFDR provided a distinct advantage in mean time to repair with arc faults in the bus section of the LVMCC. (Fig 12)
3. Both the operation of the buckets' MCCB under fault condition and the line side bucket fault existing until extinguished by the bucket modifications generate a flash of light. The AFDR event report in Fig. 13 (line side fault, door closed) shows the fault clearing in approximately 7 ms with the light detected in the rear of the LVMCC at less than 1% of the maximum light detection level of the relay. The arc fault self-

extinguished with no action by the upstream circuit breaker.



Fig. 12 Minimal bus damage after riser bus fault cleared by AFDR

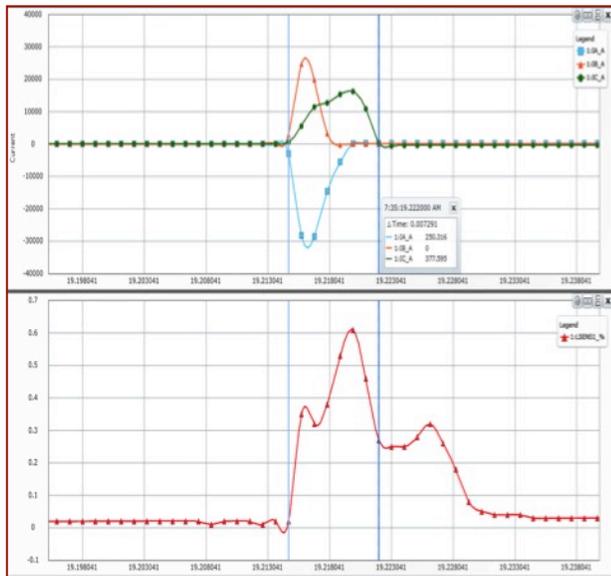


Fig. 13 63kA Prospective current, line side fault with door closed. The top graph shows the current oscillography for the 7msec the fault lasted and the bottom graph show the light buffer internal to the AFDR as reported by the relay software.

4. The fault recorded in Fig. 14 (line side fault, door open) lasted just over 10ms with a maximum light detection of approximately 1.5% of full scale and no other device acted to clear the fault. The arc self-extinguished as was typical for this series of tests.
5. Figs. 13 and 14 show AFDR oscillography for the line side faults with door closed and door open. Consistently, the bucket faults in various locations of the LVMCC frame recorded less than a 1% increase

over the background light level for the flash created by the breaker interrupting a non-arcing fault. For an arcing fault generated on the line side of the bucket circuit breaker, a sensor level of 1.5% over the background light detection level was the maximum recorded.

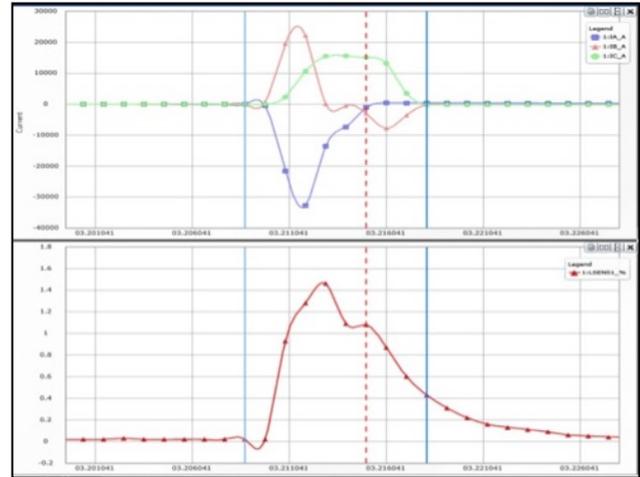


Fig. 14 63kA Prospective current line side fault with door open. The top graph shows the current oscillography for the 10msec the fault lasted and the bottom graph show the light buffer internal to the AFDR as reported by the relay software.

6. In Fig. 15 and Fig 16, the result of a fault in the rear of the LVMCC recorded a light level of 100% of the relay light detection range and in the case of one manufacturer's AFDR, the lux level was consistently high enough to drive the light detection transducer into saturation.

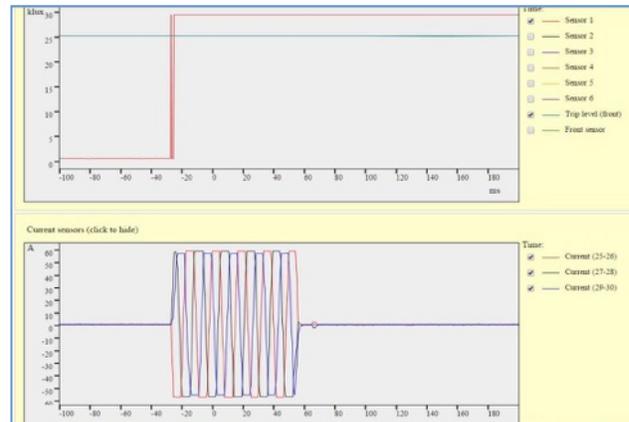
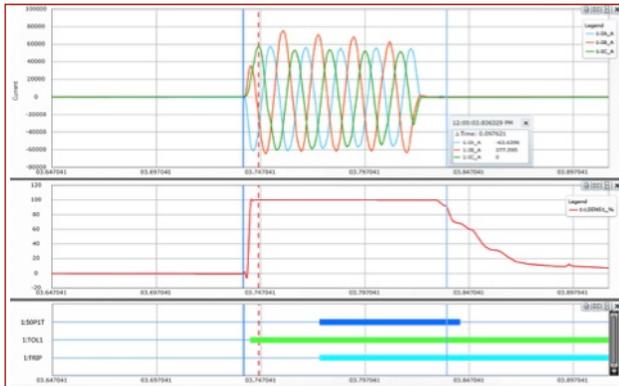


Fig. 15 Typical waveforms for Arcing Fault in Bus section as reported by one of two different AFDRs

The summary of the results of the faults initiated on the line side of the LVMCC bucket's MCCB and cleared by the arc extinguishing modifications (line side) and the faults initiated at the stabs and cleared by the AFDR (bus faults) are shown in the Fig. 17. The results clearly show that for the 35 trials in

Test Series 3, no results indicated an average calorimeter reading greater than 1 cal/cm<sup>2</sup>.



- Fig. 16 Typical waveforms for Arcing Fault in Bus section as reported by second of two different AFDRs

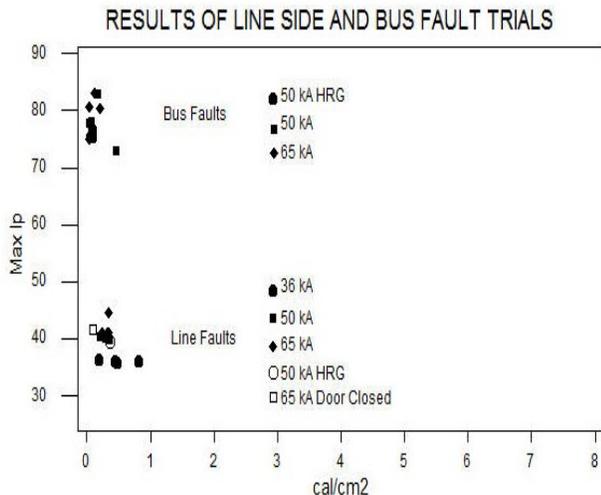


Fig. 17 Final results of riser bus fault and bucket line side fault trials

## VI. APPLICATION CONSIDERATIONS

The safety modifications discussed in this paper can play an important role in any LVMCC asset management program. The cost benefit of life extension of older LVMCCs is an alternative often overlooked. The life extension can increase the return on investment of the overall LVMCC/Cable/Motor load system.

The evaluation of replacing existing LVMCCs must include not only the cost for the hardware change but also project scope escalation. The most significant of these is the possibility of damaging existing motor power and control conductors during the change-out process. The cost and schedule variation is dependent on the condition of the conductors used and whether the LVMCC is fed from conductors in an underground duct bank, type TC or MC cable in overhead cable tray, or type THHN or THW conductors in overhead conduit. The cost impact of repairing or replacing damaged motor power and control conductors could reach 3 to 10 times the cost of the LVMCC change-out and the impact of the added schedule

could result in adding multiples of that cost.

An LVMCC reaches its end of life when spare parts are not available and servicing is impossible or prohibitively expensive. Typically it is when the MTTR becomes unacceptably long that action is forced upon the user depending on the operating conditions. [17]

The cost benefit of life extension with individual component change out of older LVMCCs is often overlooked. The vertical section and the associated bus structure are well within the process unit life expectancy. The primary concerns such as stabs and MCCBs can be addressed with safety and component upgrade projects.

When the asset's life extension is evaluated accordingly, and with the possibility of modifying the existing LVMCC to allow open door troubleshooting using the techniques highlighted in this paper, the evaluation becomes much simpler. The estimated savings of a life extension project over a complete change out are significant.

Getting buy-in from plant management to replace an asset that is still performing is difficult to justify. The problem is that the LVMCC is an asset component that must be considered along with the motor and the power and control conductors. When evaluating from a process profitability perspective, a strategy that permits replacement of the cables as they fail and component repair or retrofit of the LVMCC is typically preferable to the wholesale change out of the LVMCC system. From an overall plant electrical system strategy, each component of the asset must be evaluated based on the end of life and life extension of the dominant component. In this case the dominant component often is the power and control conductors feeding the motor load in the field.

## VII. CONCLUSION

NEMA LVMCC is a metal enclosed design (one large metal enclosure) that requires very different safety related work practices, since so much of the work is performed with equipment doors open and the bus energized. This paper presents an effective method of extending the life of existing LVMCC. The modifications were designed to:

1. Selectively coordinate with existing relay settings
2. Reduce the arc flash risk of open door work to a acceptable level
3. Reduce the shock hazard during open door work
4. Be cost effective to retrofit
5. Reduce MTTR for faults in the rear compartment

The design concepts work well in LVMCC, taking advantage of normal phase spacing, low driving voltages at the arc and the instability inherent in low voltage arcs due to the magnitude of the resistance injected into the circuit during an arcing fault. The test series finalized a set of design modifications. (Fig. 18 shows the bucket modification)

1. Glass polyester breaker cover on the MCCB secured with a heavy-duty cable tie.
2. Grounded braided tinned copper sleeves added to line side leads between the stab assembly and the line side of the MCCB.
3. The stab assembly was sealed with silicone caulk.

4. Insulate main bus ends away from the source at the side panel.
5. Install AFDR and the associated ancillary equipment to detect arc faults in the bus zone

It was beyond the scope of these tests to develop an effective method to account for the variations in geometry associated with withdrawal and reinsertion of a bucket. This task, if performed with the equipment energized, should be conducted per the NFPA 70E risk assessment process.

When viewed in the overall system one-line diagram, (Fig. 10) this paper introduces an effective method to reduce the risk of open door work to an acceptable level while eliminating fault propagation between the bucket and the rear compartment riser bus. Further, the solution offers high-speed protection for faults when they do occur, while limiting the shock hazard locations available.

The modifications allow the process owner to keep this equipment deployed, much like a motor rewind. When combined with component retrofit the LVMCC remains in the asset management plan with increased safety and reliability, rather than absorbing the cost of a wholesale replacement.



Fig.18 Final Bucket Modifications (1) breaker cover with cable tie, (2) grounded braid sleeve, (3) caulked stab assembly

## X. ACKNOWLEDGMENTS

The authors wish to thank the following people for their contributions: Kevin Lippert (EATON); Ariana Hargrave (SEL); Ajay D. Pathak (LITTLEFUSE); John Nelson (NEI); Richard McLaughlin and George Khoury (KEMA POWERTEST LABORATORY); Michael Wactor (POWELL INDUSTRIES).

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## XII. VITAE

**James E. Bowen (Fellow)** earned a BSEE degree from Texas A&M University in 1976. After working for SIP Engineering as a power engineer for three years, he joined Exxon Chemicals in 1979. His duties included maintenance, project design, construction follow-up and commissioning for the petrochemical and cogeneration processes in the USA and Europe.

In 1997, Mr. Bowen joined Powell Electrical Manufacturing Company as the Technical Director where he provided leadership in the application and design development of low voltage and medium voltage switchgear and circuit breakers. In 2009, Mr. Bowen joined Dashiell Corporation in the position of vice president of Advanced Technical Services. In 2010, Mr. Bowen accepted a position with Aramco Services Company as Power System Technologist. His current role includes investigating technologies that can be applied by Aramco to improve safety, reliability and profitability. He is a professional engineer in the state of Texas and was elevated to the rank of IEEE Fellow for his pioneering work in Safety By Design.

**Andrew Ackerman (Senior Member)** graduated from the United States Merchant Academy in 1991 and sailed aboard

merchant vessels as Third and Second Engineer until 1997 when he began work for Bolder Technologies, an advanced battery design manufacturer, as a facility engineer. In 2000, Mr. Ackerman joined NEI Electric Power Engineering, Inc. and earned his MBA from the University of Colorado, Denver. His experience at NEI includes the design, testing and commissioning of large utility and industrial substations through 230kV as well as design and commissioning of industrial systems at Medium and Low Voltage. He is currently a Principal Engineer and Vice-President of NEI Electric Power Engineering, Inc. Andrew is a registered Professional Engineer in the states of California, Colorado, Florida, New Hampshire, Utah, and Wyoming.

**Dane A. Martindale (Member)** received the BSEE from Texas A&M University, College Station, TX in 2007 and a MEEE from the University of Idaho, Moscow, ID in 2015. Upon graduation from Texas A&M, he worked for the Dashiell Corporation, where he specialized in the design and construction of high voltage substations and transmission lines. In April 2013, he accepted a position in the Power Engineering group of Aramco Services Company, Houston, TX, USA. His current role includes investigating technologies that can be applied by Aramco to improve safety, reliability, and profitability.

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**Thomas Malone (Member)** received his BSEE from the University of Maryland in 1980 and is currently Owner and President of MMT Services Inc., Houston, TX. Previously, Mr. Malone was employed by the Westinghouse Electric Corporation where he held positions as Area Sales Engineer, expatriate positions in Saudi Arabia and Amman Jordan as Regional Product and Applications Engineering Manager - Mid East Area. After the acquisition by Eaton/Cutler Hammer - he held positions as Product Manager for Molded Case Breakers, Bechtel Alliance Manager and SixSigma Black Belt. Mr. Malone was President of Protect Controls Inc. in Houston and was IEC Product Line Manager for Powell Electric, which led to a position as Commercial Director and Regional Director for Alstom/Areva in the Houston area. He was a key player in establishing Isolux Ingeneria USA and was VP and Business Development Director, participating in the CREZ transmission and substation project for Wind Energy Transmission Texas. He was recently the VP-Operations for Powerline Services Inc. before returning to MMT Services Inc. full time in 2015. He is a member of the IEEE and IAS.

## APPENDIX A

## TEST MATRIX SERIES 2 TESTING (JULY 2015)

KEMA Trial #	Test Number	Equipment	Bucket #	Starter Size	Modifications	Grounding	Expected Test Fault Current	Ignition Wire	Fault Location	Cal/cm2	Arc Duration msec	Peak Current kA	Avg RMS Current kA
1	CAL												
2	CAL												
3	A	Sample 1	631-2	1	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ glastic barrier	Solid Gnd	36kA	Method 1	2	0.67	315	50.5	28.1
4	B	Sample 1	632-2	1	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ glastic barrier above breaker	Solid Gnd	36kA	Method 1	2	0.94	8.8	36.5	-
5	C	Sample 1	629-2	1	a) Normal NRFVS b) w/ silicon caulk at cable transition c) silicon on breaker cover to keep in place	Solid Gnd	36kA	Method 1	2	0.86	8.9	36.0	-
6	D	Sample 1	630-2	1	a) Normal NRFVS w/ shielded cable b) w/ glastic barrier above breaker	Solid Gnd	36kA	Method 1	2	1.35	21.9	37.9	-
7	F	Sample 1	631-1	3	a) Normal NRFVS w/ shielded cable b) w/ glastic barrier above breaker	Solid Gnd	50kA	Method 1	2	0.50	5.5	40.9	-
8	G	Sample 1	630-1	3	a) Normal NRFVS w/ shielded cable b) w/ glastic barrier above breaker c) w/ silicon caulk at cable transition	Solid Gnd	50kA	Method 1	2	1.12	17.5	43.9	-
9	H	Sample 1	628-1	3	a) Normal NRFVS b) w/ glastic barrier above breaker c) <b>wire inserted into terminal screw access</b>	Solid Gnd	50kA	Method 2	2	2.32	28.2	53.7	-
10	I	Sample 1	629-1	3	a) Normal NRFVS b) w/ glastic barrier above breaker c) silicon caulk at cable transition d) <b>wire inserted into terminal screw access</b>	Solid Gnd	50kA	Method 2	2	1.65	321	71.1	35.6
11	J	Sample 2	632-1	3	a) Normal NRFVS b) w/ glastic barrier above breaker c) <b>wire inserted into terminal screw access</b>	Solid Gnd	50kA	Method 2	2	4.47	325	66.8	33.3
12	K	Sample 1	627-2	1	a) Normal NRFVS w/ shielded cable b) w/ glastic barrier above breaker c) w/ silicon caulk at cable transition d) <b>wire inserted into terminal screw access</b>	Solid Gnd	50kA	Method 2	2	1.74	319	66.8	42.0
13	L	Sample 1	628-2	1	a) Normal NRFVS w/ shielded cable b) w/ glastic barrier above breaker c) w/ silicon caulk at cable transition	HRG	50kA	Method 1	2	1.14	12.1	42.3	-
14	M	Sample 1	627-1	3	a) Normal NRFVS w/ shielded cable b) w/ glastic barrier above breaker c) w/ silicon caulk at cable transition	HRG	50kA	Method 1	2	0.50	6.2	41.6	-
15	N	Sample 1	627-1	3	Ignition Wire on Breaker Stabs	HRG	50kA	Method 3	3	0.54	323	81.0	36.3

## Fault Location

- 1 - Load Side of Molded Case Circuit Breaker
- 2 - Line Side of Molded Case Circuit Breaker
- 3 - Motor Starter Control Unit Bus Stabs

APPENDIX B

TEST MATRIX SERIES 3 TESTING (NOVEMBER 2015)  
36KA AND 50KA FAULTS

KEMA Trial #	Test Number	Equipment		Starter Size	Modifications	Grounding	Test Fault Current	Ignition Wire	Fault Location	AvgHeat Cal/cm2	Arc Duration msec	Peak Current kA	Avg RMS Current kA
1	CAL												
2	CAL												
3	A	Sample 2	023-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	36kA	Method 1	1	NA	6.5	28.4	-
4	B	Sample 2	023-1	1	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	36kA	Method 1	1	NA	5.9	28.4	-
5	C	Sample 2	022-2	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	36kA	Method 1	1	NA	5.7	19.0	-
6	D	Sample 2	021-1	1	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	36kA	Method 1	1	NA	5.9	19.2	-
7	F	Sample 2	023-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	36kA	Method 2	2	0.437	8.2	35.6	-
8	G	Sample 2	022-2	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	36kA	Method 2	2	0.810	14.2	35.7	-
9	H	Sample 2	021-1	1	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	36kA	Method 2	2	0.448	7.9	35.9	-
10	I	Sample 2	023-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	36kA	Method 2	2	0.187	7.8	36.1	-
11	J	Sample 2	021-2	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	50kA	Method 1	1	NA	5.5	30.0	-
12	K	Sample 2	021-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	50kA	Method 1	1	NA	88.2	67.3	26.1
13	L	Sample 2	022-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	50kA	Method 1	1	0.211	6.0	40.1	-
14	M	Sample 2	021-2	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	HRG	50kA	Method 2	2	0.358	7.0	39.5	-
15	N	Sample 2	022-1	1	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	HRG	50kA	Method 2	2	0.286	7.2	40.0	-
16	O	Sample 2	011-2	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	HRG	50kA	Method 2	2	0.288	6.5	40.3	-
17	P	Sample 2	013-1	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	HRG	50kA	Method 2	2	0.358	8.8	39.3	-
18	Q	Sample 2	023-1	1	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	HRG	50kA	Method 3	3	0.092	83.2	75.8	41.7
19	R	Sample 2	022-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	HRG	50kA	Method 3	3	0.083	83.0	76.6	-
20	S	Sample 2	021-2	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	HRG	50kA	Method 3	3	0.049	83.0	75.3	32.6
21	T	Sample 2	022-1	1	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	HRG	50kA	Method 3	3	0.091	83.0	75.4	43.8
22	U	Sample 2	023-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	50kA	Method 3	3	0.069	86.0	78.2	42.3
23	V	Sample 2	023-1	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	50kA	Method 3	3	0.176	85.6	83.0	43.2
24	W	Sample 2	011-2	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	50kA	Method 3	3	0.459	86.0	73.0	42.6
25	X	Sample 2	022-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	50kA	Method 3	3	0.032	64.6	77.8	42.2

- Fault Location  
 1 - Load Side of Molded Case Circuit Breaker  
 2- Line Side of Molded Case Circuit Breaker  
 3- Motor Starter Control Unit Bus Stabs

## APPENDIX C

TEST MATRIX SERIES 3 TESTING (NOVEMBER 2015)  
63KA FAULTS

KEMA Trial #	Test Number	Equipment	Bucket #	Starter Size	Modifications	Grounding	Test Fault Current	Ignition Wire	Fault Location	Avg Heat Cal/cm2	Arc Duration msec	Peak Current kA	Avg RMS Current kA
1	CAL												
2	A	Sample 1	011-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	65kA	Method 2	2	0.333	7.4	44.6	-
3	B	Sample 1	012-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	65kA	Method 2	2	0.331	6.8	41.0	-
4	C	Sample 1	012-1	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	65kA	Method 2	2	0.314	6.3	41.0	-
5	D	Sample 1	011-1	1	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	65kA	Method 2	2	0.244	6.7	41.1	-
6	E	Sample 1	012-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	65kA	Method 3	3	0.200	66.0	80.6	46.9
7	F	Sample 1	011-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	65kA	Method 3	3	0.121	72.0	83.1	46.2
8	G	Sample 1	011-1	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	65kA	Method 3	3	0.033	75.0	80.8	46.6
9	H	Sample 1	012-1	1	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	65kA	Method 2	2	0.041	64.0	75.2	46.5
10	I	Sample1	013-3	3	a) Normal NRFVS w/ shielded cable b) w/ silicon caulk at cable transition c) w/ Breaker Cap	Solid Gnd	65kA	Method 3	2	0.079	16.7	41.5	-

## Fault Location

- 1 - Load Side of Molded Case Circuit Breaker
- 2 - Line Side of Molded Case Circuit Breaker
- 3 - Motor Starter Control Unit Bus Stabs