Ground Fault Protection Applications in Low Voltage Motor Control Systems for Process Industries

Matthew R. Hussey
Member, IEEE
Eaton Corporation
2900 Doc Bennett Rd.
Fayetteville, NC 28306 USA
MatthewRHussey@eaton.com

Steven Drzymala
Electrical Engineer
BAE Systems, Inc. | OSI
114 Peppers Ferry Road
Radford, VA 24141
steven.drzymala@baesystems.com

Abstract – **Continuous processes require motor control systems to maintain uptime in a variety of installed system types. New capabilities in low-voltage (LV) motor protective relays have enabled ground fault protection to be specially tuned for these process needs. This paper will examine several design alternatives for engineers considering site ground fault protection needs in low voltage motor control systems for commonly applied power system types including ungrounded, solidly grounded and resistance grounded). The importance of application in motor life, fault detection, motor failure examples due to ground fault and electrical safety will be considered. Typical methods of ground fault protection in LV motor control centers and common challenges for ground protection schemes including residual, zero sequence and high resistance ground (HRG) pulse detection systems to achieve fast fault detection and ground fault protection for LV motor control centers (MCCs) will be addressed. Finally, a case study involving an industrial project technology review and installation of a HRG pulse detection system for a newly installed LV MCC will be reviewed.**

Index terms: Continuity of service, process industries, fast fault detection, ground fault protection, motor control centers, high resistance grounding

I. Introduction

In recent years, a focus towards prevention through design has provided a new platform for system design engineers in considering how personnel safely interact with energized electrical equipment. From understanding the severity of arc flash hazards, to recognizing the risks to personnel present during the operation and maintenance of electrical equipment, an effort to eliminate exposure is omnipresent. Phase to ground faults are commonly understood and these have historically contributed to over 80% of electrical faults. These faults occur throughout a variety of power systems and can originate in a myriad of different ways. This in turn calls for a diverse suite of techniques to address arc flash events initiated by phase to ground faults in industrial and commercial power systems.

However, identification, isolation and protection against ground faults have generally presented a difficult challenge in application of low voltage motor control centers. Often requiring sensitivity at lower pickup settings than traditional phase overcurrent protection, ground fault protection methods can be prone to nuisance tripping due startups and switching currents for large loads. Additionally, with protection methods commonly deployed in upstream systems, it can be very difficult to locate a ground fault amidst the vast quantity of distribution and motor loads served. Lastly, while costs of ground fault protection may be nominal with switchgear systems, the feasibility of incorporating layers of ground fault protection into MCCs may be less justifiable.

Currently, low voltage motor protection relays have become increasingly more capable, allowing more users to address these historical safety and system reliability issues. Simple motor overcurrent protective devices of the past that have used heat to model current and mechanical actuation in the event of a motor overload condition have been replaced by advanced solid state microprocessors that have made ground fault protection ever more accessible in overload relays.

This paper will discuss how traditional overload relays have progressed to tackle ground fault protection applications in low voltage MCCs, improving worker safety in a variety of industrial and commercial power systems, enabling operations and maintenance teams to achieve greater system reliability.

II. Background Of System Grounding Configurations

Low voltage MCCs are commonly applied throughout industrial and commercial power systems to serve a variety of process and facility loads. Ground faults are caused by contact between ground and an energized phase conductor, such as a motor cable and the grounded MCC enclosure. These faults have the potential to release a large amount of electrical energy and can be dangerous to equipment and people [1]. Traditional system grounding methods employed include ungrounded, solidly grounded and resistance grounding. Each type of system has the potential to experience a ground fault and each requires an understanding of system dynamics so the fault can be addressed appropriately.

An ungrounded system has no intentional connection to ground. However, the capacitance present through the phase conductors establishes the system coupling to ground (see Fig. 1).

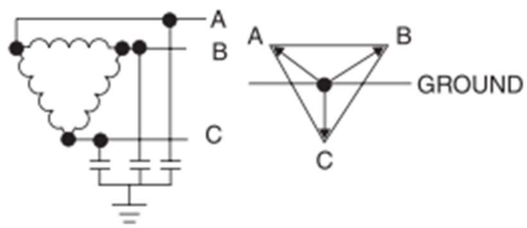

Fig.1 Ungrounded system [2]

Given the ability of an ungrounded system to maintain service after a phase conductor is unintentionally grounded, industry favored ungrounded systems in three phase, three-wire low voltage systems through the 1950's. A first ground fault would be at relatively low levels, thereby falling below the trip threshold of overcurrent protective devices, preserving continuity of service. However, a prolonged first ground fault on this system is difficult to find and an eventual second phase to ground fault would establish a phase-to-ground-to-phase fault condition of much greater magnitude. Secondly, with system grounding present through capacitance, the inability to discharge fault current presented dangerous transient voltage escalation caused by restrike conditions, ultimately leading to catastrophic insulation failure (see Fig. 2). While some ungrounded low-voltage systems are still present today, most new systems incorporate solidly grounded or high-resistance grounded methods in favor of ungrounded systems [2].

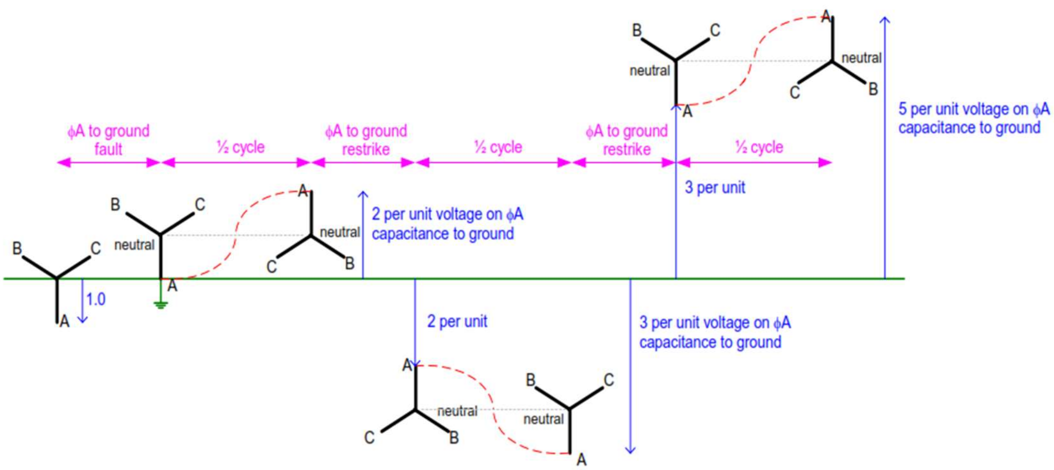

Fig.2 Escalating overvoltages on ungrounded systems [1]

Solidly grounded systems are directly connected to earth ground with no intentional additional impedance in the circuit. The presence of a neutral provides flexibility in application voltage, commonly utilized for lighting, heating and other single phase loads (see Fig. 3).

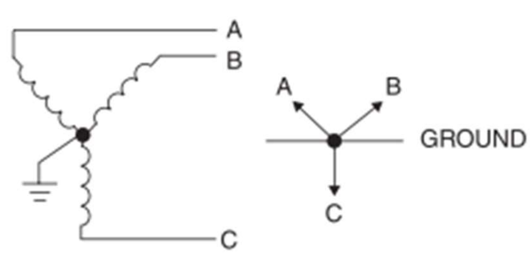

Fig. 3 Solidly grounded system [3]

During the 1960's and 1970's, industry began moving from ungrounded to solidly grounded systems throughout industrial and commercial power systems given this system's ability to minimize over-voltages with a means to locate ground faults quickly. However, with the very low impedance path to ground, high fault currents presented new challenges that needed to be addressed. Ground fault events could result in total equipment destruction and affect personnel safety with the heightened arc fault energy levels. As new ground fault protections methods became available, these systems would also yield unfavorable service interruptions due to lack of coordination [2].

Resistance grounding involves the addition of a fixed impedance to the ground path through the use of a neutral grounding resistor (see Fig. 3). Methods employed include low-resistance and high-resistance grounding. For low voltage systems, high-resistance grounding methods are typically used and these will be considered for the purposes of this paper.

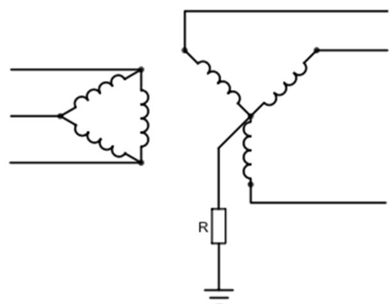

Fig. 4 High-resistance grounding system [3]

The use of high resistance ground (HRG) systems has been prominent in process industry applications for industrial and commercial power systems for the past several decades. HRG systems are commonly applied because of their ability to maintain continuity of service while minimizing fault current during a phase-to-ground condition. The added resistance is sized so that in the event of a downstream phase conductor fault to ground, a current of less than 10 amperes is present on the system. This level of fault current effectively reduces equipment damage and also reduces arc flash hazards to personnel. While additional care/training may be required to operate and maintain this system, equipment downtime is essentially minimized [3].

III. Typical Ground Fault Protection Techniques In Low Voltage MCCs

Historically, protection for low voltage motors involved simple bimetallic overloads with heaters to safeguard against overcurrents. Additionally, protection techniques for ground faults on industrial and commercial power systems traditionally have come at the cost of nuisance tripping conditions. Ground faults in motors typically occur as the result of insulation breakdown in windings, conductive foreign materials, or moisture buildup. The level of damage experienced in low voltage motors due to ground faults is proportional to the magnitude of the respective ground fault current. Only minor damage to windings may be seen at low level ground faults, whereas high ground fault levels can cause severe damage to the motor. Therefore, the ability to detect and clear these faults before significant damage has occurred will have a direct impact on facility operating uptime and resulting equipment damage.

For ungrounded systems, fault location and protection is typically challenging. Known protection methods involve the addition of individual motor ground detectors which enunciate the voltage imbalance following a phase to ground fault present in the system. These detectors usually involve lights or voltmeter relays connected from each phase to ground. Section 250.21of the U.S. National Electrical Code (NEC) states the required installation of these devices for ungrounded ac systems as permitted operating between 120 volts and 1000 volts and to be connected as close as practicable to where the system, receives its supply. In low voltage MCCs, a unit is connected to MCC bus with a set of potential transformers (PTs) arranged in wye to wye configuration to step down the voltage and a series of lights are connected on the secondary. Under normal conditions each light is dim. With a ground fault on one of the phases, the grounded phase will drop in voltage the other 2 will rise, causing one indicating light to go out and the other two lights to go bright. This effectively determines that the ground fault is located within the loads fed from that lineup, however it does not further identify which load the ground fault is on. It is then up the operator to locate the faulty load, usually by de-energizing various loads until the detector returns to its normal state [4].

With the potential for very high fault currents in solidly grounded systems, extensive damage can be caused to low voltage motors. Additionally, section 230.95 of the NEC outlines the requirement for the use of ground fault protection for systems rated up to 600V for service disconnects of 1000A or more. For low voltage MCCs, molded case circuit breakers or fuses are typically suitable for providing ground fault protection of motor loads. However, a common issue of mis-coordination exists when large motor loads are present. For continuous industrial processes among others, this can result in increased safety hazards and has led to a number of exceptions due to these types of applications. Usually the ground faults on these large loads can exceed the pickup level on the MCC main or upstream circuit breaker located in low voltage switchgear and cause an unwanted trip before the branch protective device clears the fault. This loss in selectivity is pictured in the image below (see Fig. 5). For this reason, additional dedicated relays or protective schemes would need to be employed to provide proper selectivity. While this provides the selectivity required, it also introduces additional space requirements in the MCC and adds to both the complexity and the installed cost of the system.

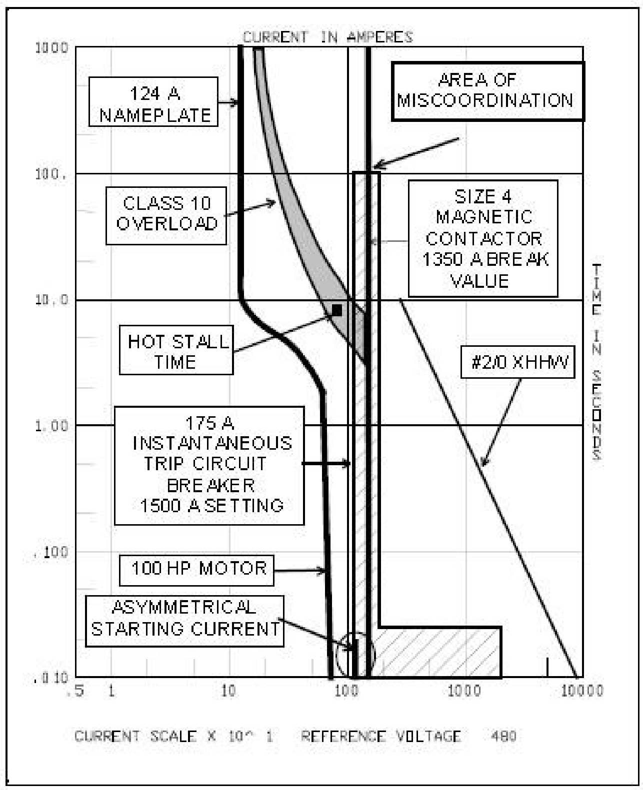

Fig. 5 Time-current curve with of motor starter showing mis-coordination[5]

With high resistance grounding systems, single line to ground fault levels are reduced to 10 amperes or below, so the effective damage to motors during a ground fault condition is greatly minimized. Protection methods exist today that include the capability to identify and isolate the motor load with ground fault before a second ground faults develops and creates a more severe condition. Rather than tripping the load following a ground fault, an alarm signal is developed by measuring a voltage across the grounding resistor and then a pulsing contactor switching in an additional resistance in the neutral to ground connection is introduced and utilized to locate the faulted feeder (see Fig. 6). This allows the site to continue to operate, while the fault is manually located and then cleared. Site maintenance personnel are typically tasked to find the pulsing current signal with a special clamp-on window type hand-held ammeter. MCCs serve as a common area to locate the fault, since this electrical assembly houses many of the load conductors in accessible wireways. Given the vast quantity of motor loads present downstream of low voltage MCCs, locating and clearing the ground faulted feeder circuit can be a very time consuming effort. This activity also presents an arc flash exposure risk to personnel as it requires use of the clamp-on hand-held ammeter while the process is running.

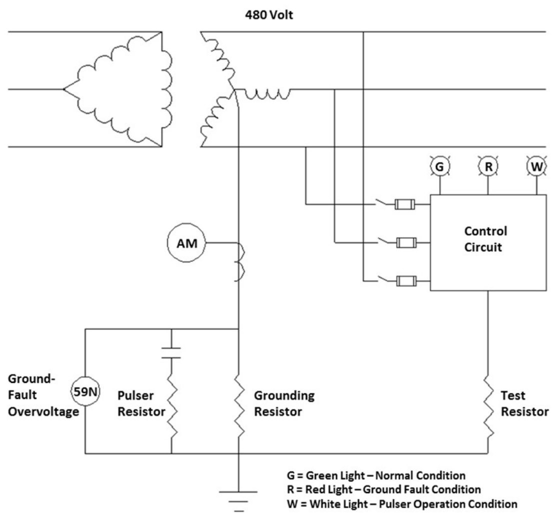

Fig. 6 Low-voltage pulsing high-resistance ground system schematic [6]

IV. Advancements In Low Voltage Motor Protection

Benefitting from the proliferation of microprocessor technologies, today's modern low voltage motor overload relay has evolved into a solid state motor management relay with multifunction protection capabilities. Recalling the increased awareness of arc flash hazard risks and the need for improvements in process availability, these devices are delivering benefits in both areas, serving as multi-function tools to support industrial and commercial power systems. Commonly these relays support the capability to sense individual phase currents and voltages, providing a suite of monitoring and protection functions such as motor jam, load loss, and low power conditions. As discussed in [6], today these devices now support extensive ground fault protection algorithms, enabling flexibility to be applied in a variety of power system applications (see Fig. 6).

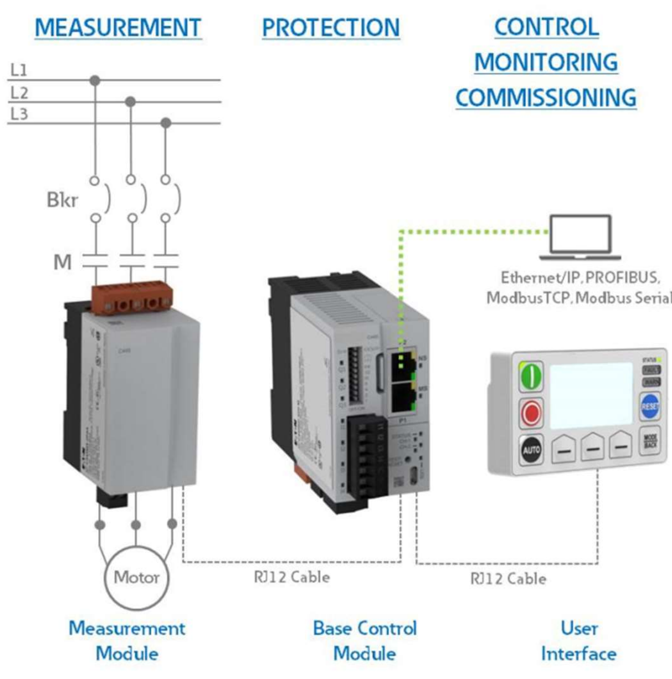

Fig. 6 Typical microprocessor based motor management relay [6]

Residual ground fault is one of the basic protection methods available with low voltage motor management relays. A vector sum of the 3-phase currents is calculated from each phase current transformer (CT). This signal is transmitted to a microcontroller for signal processing. Under normal operation, no ground current flows since the resultant current of the three CTs is zero. Once a ground fault condition is present, the ensuing ground current is compared against user programmed thresholds for magnitude and then reacts based on a prescribed delay time. While this feature in present in today's motor protection relays, the sensitivity to detect ground currents is limited by the CT ratio of the relay. Typically on larger motor loads in MCCs this presents a challenge as relatively high ground currents would need to be present respond on the faulted load. As previously described for solidly grounded systems, fault currents can rapidly develop into high magnitude conditions, so early detection and response is key.

To solve this problem, low voltage motor protection relays now also support zero sequence ground fault protections by allowing a core-balance CT input and adjustable set points. These relays automatically detect when a core balanced CT is connected to the microprocessor and a different set of user defined parameters is enabled with different set points. With millisecond response time capability, this method limits equipment damage caused by ground faults on solidly grounded systems. By leveraging the built-in capability of the motor protection relay, these settings can be coordinated with upstream overcurrent protective devices without requiring any additional relays. This effectively minimizes cost and space impacts to the MCC to achieve this protection technique.

Lastly, these same relays can be configured for ground fault pulse detection in high resistance ground systems. An algorithm in the microprocessor works in conjunction with the contactor pulse train from the HRG to detect the repetitive ground signal. When the relay detects a series of similar pulses at a pre-programmed pulse amplitude, it will indicate a ground fault has been located on one of the starters in the MCC. The pulse amplitude is a user settable parameter in order to accommodate various HRG systems and can be configured to warn or alarm when the pulse waveform is identified (see Fig. 7).

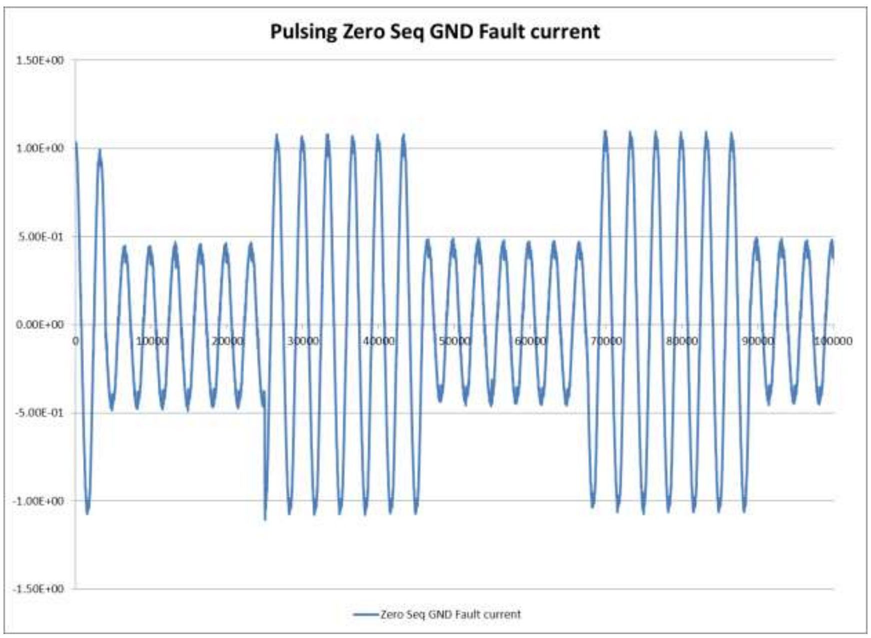

Fig. 7 Pulsing signal from high-resistance ground system

By leveraging the integral current sensors of the motor protection relay, this eliminates the requirement for additional core-balance CT and relay systems to be deployed to achieve similar detection capability. The incorporation of a localized user interface allows site operations to quickly locate and identify which MCC starter has the faulted load. This keeps personnel from needing to gain access to energized conductors within the MCC and completes the fault finding effort while assuring personnel are not exposed to energized conductors. Additionally, the support of network connectivity for these relays enables operators to visualize faults from plant control rooms or accessing from dashboards tailored to the needs of operations and maintenance personnel. These HMI panels can be located where suitable to simplify fault finding process, saving valuable time and maximizing productivity (see Fig. 8).

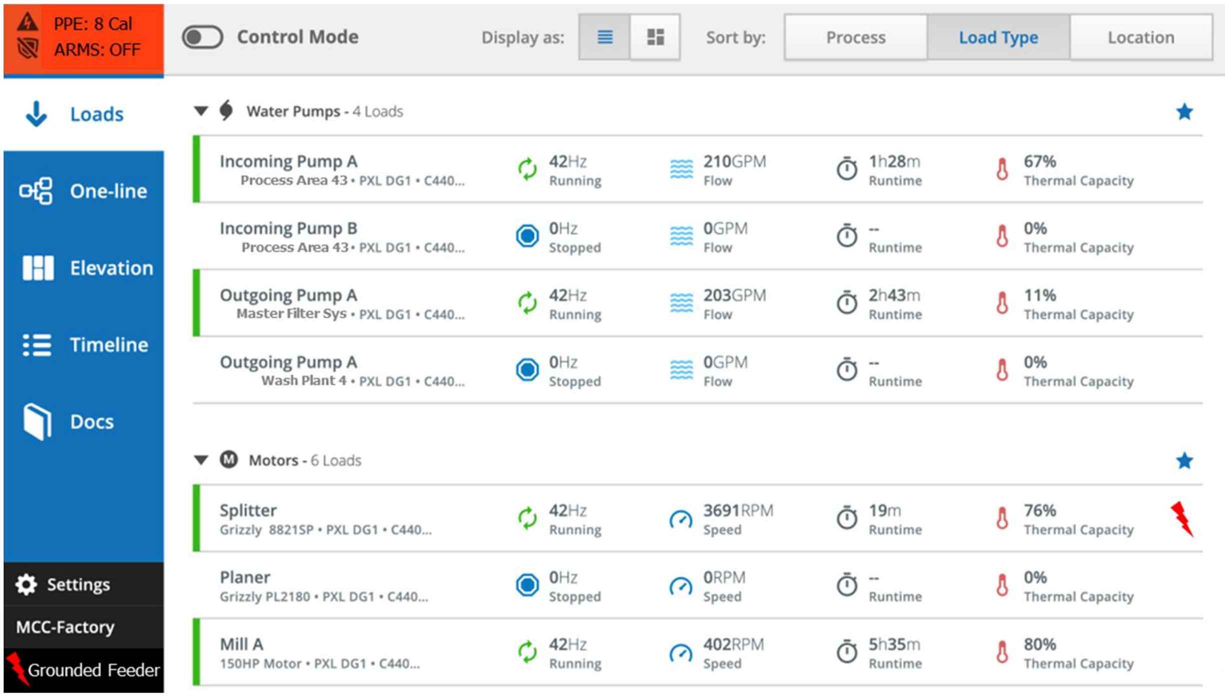

Fig. 9 Example of a simple MCC Dashboard designed to deliver useful information to plant electrical system owners [6]

V. Case Study

Recently, a global defense provider considered the new capabilities of today's motor protection relays for a project including the installation of a MCC in a new facility. As is common in today's process industries, high resistance grounding systems were selected as the basis of design as discussed previously regarding methods and relevant codes and standards. With this setup, the selection of a low voltage motor protection relay with capability to provide pulsing ground fault detection simplified the project, improving both system reliability and operator safety. Furthermore, these relays were deployed in a network connected fashion to a number of higher level plant control systems, tapping into the ability to control and monitor the process with rich system data.

VI. Conclusions

With recent emphasis on prevention through design in safety standards such as NFPA-70E-2018 [7] and IEEE-1683 [8], new techniques have emerged that address electrical safety in the workplace. By focusing on the required tasks during the operation and maintenance of low-voltage MCCs, previous challenges can be looked at with fresh eyes and novel concepts can be introduced. Development in low voltage motor protection relays have opened the door to new solutions in this area. Embedded microprocessor technology and network communications within these relays has improved industry's ability to address a host of new applications to maintain reliability and safety. Improved techniques to provide protection against ground faults can be applied for a variety of system grounding methods.

Moreover, the intelligent capability of these motor protection relays must also consider simplicity and ease of use from the operator perspective. Deploying these solutions cannot be considered "smart" unless it empowers the user to take meaningful action to drive improvements in productivity and safely. When executed appropriately, these added functionalities can prove to be useful in a number of industrial and commercial power systems. The benefit of added safety and improved asset management can be realized by understanding and addressing the needs of plant personnel responsible for supporting these intelligent devices. The incorporation of modern motor protection relays can be instrumental in providing solutions to historical difficulties in process reliability and arc flash safety for low voltage motor control centers.

VII. REFERENCES

[1] J. Bowen, “Grounding for Industrial Systems,” 2011 IAS Tutorial

[2] IEEE-242, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems

[3] IEEE-142, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems

[4] NFPA 70, National Fire Protection Association, National Electrical Code (NEC), 2017

[5] IEEE 3004.8-2016 Recommended Practice for Motor Protection in Industrial and Commercial Power Systems

[6] Durocher, D.B., Hussey, M.R., Belzner, D., Rizzi, L; “Application of Next Generation Motor Management Relays to Improve System Reliability in Process Industries”, IEEE Transactions on Industry Applications, March/April 2019.

[7] NFPA 70E, National Fire Protection Association Standard for Electrical Safety in the Workplace, 2018 Edition

[8] IEEE 1683-2014; “IEEE Guide for Motor Control Centers rated up to and including 600 V AC or 1000 V DC with Recommendations Intended to Help Reduce Electrical Hazards”