Application of Next-Generation Motor Management Relays to Improve System Reliability in Process Industries

David B. Durocher
Senior Member, IEEE
Eaton Corporation
26850 Kinsman Road,
Wilsonville, OR 97070 USA
DavidBDurocher@eaton.com

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

Luigi Rizzi
Buzzi Unicem USA Inc.
100 Brodhead Rd.
Bethlehem, PA 18017 USA
Luigi.Rizzi@buzziunicemusa.com

David Belzner, ISA CAP
Member, IEEE
Buzzi Unicem USA Inc.
100 Brodhead Rd.
Bethlehem, PA 18017 USA
David.Belzner@buzziunicemusa.com

***Abstract* – This paper describes advances in functionality of motor management relays in terms of both motor protection and predictive diagnostics. Network connectivity of these devices via high-speed Ethernet-IP allows real-time monitoring of system parameters, providing analytics to allow process industry users to better manage system processes to improve reliability, efficiency and safety. A case study of a recent application of new motor management relays in included in the paper, offering producers a specific example of how new motor management relays are applied and outlining details involved to leverage the latest technologies.**

***Index Terms*—Motor protection, motor management relay, motor control center, network connectivity, programmable logic controller, distributed control system, predictive diagnostics.**

I. Introduction

Over the past decade, advances in the functionality of motor and circuit protective devices have accelerated rapidly, easily doubling technology development for these same devices over the past century. Protection of three-phase low-voltage and medium-voltage induction motors 40 years ago included a motor overload relay that consisted of a resistive heater element in the current path, deflecting a bi-metal (two dissimilar metals fused together) during motor overcurrent conditions — which then mechanically engaged a trip bar to disconnect the source voltage before a motor overload failure. Today's motor protection/motor management relays are based on sophisticated electronics. Current designs have evolved to become intelligent motor protective devices that continuously monitor positive and negative sequence motor currents to establish a precise thermal model of the machine's windings. These deliver an order of magnitude of improved motor protection, functionality and oftentimes complexity. This paper will discuss a common sense approach for leveraging the benefits of enhanced functionality in motor control and motor control centers (MCCs) through plant automation, while optimizing the level of complexity, to ensure cement plant maintenance and operations continue to maximize operational productivity.

II. Background

Motor overload protection is at the heart of newer design protective relays. Integral current transformers sense load current in each of three phases, converting motor load current to a logic level signal sensed by microprocessor controllers which use algorithms to develop a thermal model of the driven motor load. The electronic protection model is designed to ensure the motor load condition does not approach the damage curve of the machine as published by the manufacturer. Although the level of protection has significantly improved, the basic response of a protective trip on thermal overload prior to machine damage has not changed. With individual phase current sensing, a host of other advanced protective features are now also routinely available, including protection for phase current unbalance, loss of phase and ground fault current protection. As an additional capability, some load-specific protective features, such as undercurrent or overcurrent, allow users to program alarm or trip conditions should the motor load fall outside an anticipated operational parameter. Some new motor protective relays also include the capability to accept and continuously monitor phase voltage inputs. Of course, adding voltage inputs also allows for additional protective functions, such as phase loss, phase reversal, voltage unbalance and under-voltage trip. Although many of these added protective features are included as "nice to haves," each will typically require users to commit some degree of time and effort to setting up specific protections. For instance, if the underload protection is desired, an underload current level for alarm and/or trip needs to be pre-programmed.

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In addition to protective functionality, a host of monitoring/metering capabilities are also included in today's motor protective relays. In pyro-processing and a few other more critical process load applications, the availability of instantaneous and historic information for values such motor phase currents, real energy (kilowatt-hours), power (kilowatts), motor efficiency and motor starts per hour can also be important. This new functionality offers a marked improvement over older legacy systems that required additional current transformers (CT's) or kilowatt (kW) transducers which added cost and space in MCC cubicles. The ability to trend parameters such as current or kW in the plant control system offers plant maintenance personnel a powerful trouble shooting tool. Trends indicating abnormal fluctuations or consistently higher or lower than normal values help to isolate process or mechanical issues. Again, legacy systems required an electrician to connect instruments to manually measure current and kW values at the motor controller, exposing them to potential arc flash hazards – an important safety risk discussed in [1] and [2] that should be considered. Some more advanced relays include time clocks that include a time stamp to mark trip conditions in real-time and capture critical values of voltage and current at the time the trip event occurred. Pre and post-trip oscillography in some designs allows experienced power systems engineers to view and analyze current and voltage waveforms prior to the trip event and diagnose a probable cause of failure. Unlike trip settings, monitoring of electrical and other system parameters typically does not require setup prior to operation. This said, care must be practiced when the new relays are installed, since the required added terminations for voltage increase the chances of making a wrong connection which in turn will likely result in a device trip or incorrect metered values.

A quick note regarding adjustable frequency drives (AFDs) and motor protection. These devices offer the ability to control both voltage and frequency to an induction motor, delivering infinite speed control. Many process areas in cement apply AFDs for low and medium-voltage motors. Because drives include real-time instantaneous control of motor torque across a span of multiple frequencies, motor protection for induction motors is best managed by microprocessors included in the AFD regulator. AFD controllers typically include protective, monitoring and metering functions discussed here - along with several others – so a stand-alone motor management relay is rarely applied for AFD driven machines. If motor overload protection external to the AFD is required for applications where for instance a single VFD is controlling multiple motors, the frequency specification of the intelligent motor protection relay must be considered.

III. SELECTING THE RIGHT NETWORK

With a host of new monitoring and metering functionality in today's motor protection, perhaps the most important consideration is selection of a suitable network to ensure information is accessible across the facility, and for multi-site cement producers, across the enterprise. For new installations, networks based on open architecture have almost completely replaced earlier proprietary networks supported by single suppliers. According to recent industry data [3] Industrial Ethernet networks account for 46 percent of global installations with an impressive annual installed growth rate of 22 percent. Fieldbus networks account for 48 percent of global installations, but these are growing at only 4 percent per year. Wireless networks account for the balance of 6 percent of installations, with a growth rate of 32 percent. An undisputed trend for industry applications including cement is a shift away from Fieldbus networks such as DeviceNet and PROFIBUS and toward Ethernet-based networks such as Ethernet/IP, Modbus TCP and PROFINET. Cost per point and throughput are the drivers fueling this growth, along with industrialization of the physical network components themselves. Ethernet switches designed for industrial environments include conformal coated circuit boards and MTBF ratings in excess of 20 years. This combined with support of the latest IEEE 802 standards for reliable messaging, redundancy implementation and robust security, make industrial application of this hardware increasingly more to practical.

Today's advanced motor protection relays generally include network connectivity to a host of popular networks. The trend is away from a device that is compatible with only one network and toward a modular approach where the relay can support a host of different communication cards that are compatible with the most frequently applied industrial networks. The primary value proposition behind industrial networks was historically wire savings. Input/output (I/O) modules of Programmable Logic Controllers (PLCs) could easily be located near field devices, and a network facilitated information "transport" back to a host computer with minimal wires. Today, networks provide connectivity from communicating field devices such as advanced motor protection relays and AFDs along with discrete I/O to upstream supervisory Distributed Control Systems (DCS), Supervisory Control & Data Acquisition (SCADA) systems, and PLCs to control plant processes. In the industrial Internet of Things (IIoT) world, information is ubiquitous and high-speed networks offer the means to share information needed to improve system efficiencies, reliability and workplace safety.

A simple block diagram of a commercially available advanced motor management relay is shown in Fig. 1. A modular design provides mounting flexibility in the MCC withdrawable unit. The design includes a base control module, a measurement module and an optional user interface module. The measurement module is connected downstream of the incoming overcurrent protective device (shown as a circuit breaker) and the motor contactor (M). Embedded current transformers in the measurement module provide motor current measurement and terminals at the top accept direct voltage inputs for each of the three phase voltages. Motor measurement data is passed electronically to the base control module where motor management, protection and network communications are performed. The plant user can optionally send networked

Fig. 1 Typical microprocessor based motor management relay

and/or local control signals directly to the device via a network, the user interface or on-board I/O instead of hardwiring discrete control circuits to the relay. The base control module considers both user configured protection and command inputs to control the motor contactor (M). An optional user interface module is the final systems module, which is typically door mounted at the MCC. This provides easy access for the operator to set and monitor all protection parameters and interrogate the base control module for data such as trip logs. Note for this particular offering, the base control module includes a plug-in communications module at the upper right. Depending on the specified network protocol, the user selects a different network card to meet the system needs. In this case, the network module shown is compatible with Ethernet/IP with Device Level Ring (DLR) communications. This is one frequently applied Ethernet configuration for process industries such as cement. Fig. 2 shows the concept behind Ethernet/IP with DLR. Ethernet is traditionally a "home run" topology where each communicating

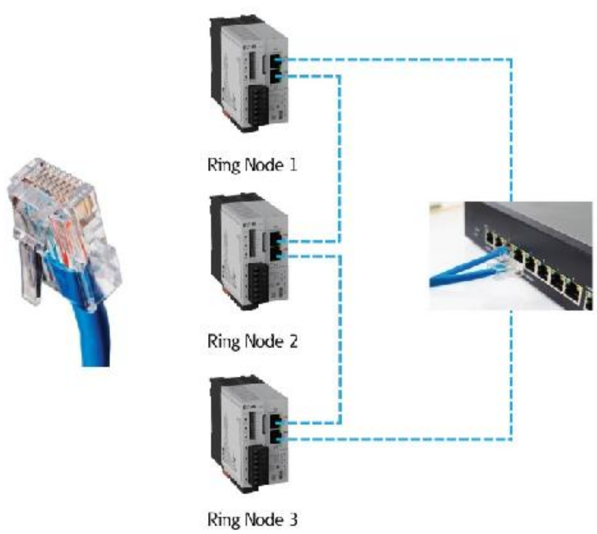

Fig. 2 At left, a typical RJ45 Ethernet connector used with standard Cat 5 cable media. At right, Device Level Ring Ethernet topology

device with a network address is connected via RJ45connectors and 600 volt rated Cat 5e shielded twisted pair cable to an Ethernet switch as shown. The DLR option allows a group of Ethernet nodes to be connected in a ring configuration, and wired back to an intelligent switch. This delivers the benefit of a self-healing network, meaning if one node should be removed or dropped from the ring, the network will continue to communicate to the remaining nodes in the ring tothe switch from the opposite direction. To support DLR topology, the base control module includes dual RJ45 connectors so one motor management relay with a unique Ethernet/IP address can be ring connected to an adjacent relay back to the Ethernet switch. One alternate application of DLR includes a home run connection to a central MCC Ethernet switch, then a ring connection between multiple MCCs in the plant. This topology is more tolerant of potential network disruption in systems where multiple starters are idled as spares or removed from the MCC for maintenance.

After the motor protective relays, drives, and other devices are connected to the network, software integration tools generate descriptive I/O tags, and then import and provide aliases for them in the form of generic tags that reside in the PLC. Users should look for devices offering time savings integration tools such as add-on-instructions, which make it easy to import all device tags and take care of scaling parameters automatically. Some recently developed protective relays include software tools that allow configuration with any PLC or DCS controller, supporting a variety of industrial networks, including Ethernet/IP, Modbus TCP, Modbus serial, PROFIBUS and PROFINET. When connected to Ethernet, each relay or drive includes web pages for configuring, monitoring and control.

Given the extensive amount of data available from the intelligent motor protection devices, first time users may elect to monitor as much operating information as possible back to the host controller. However, care should be taken when defining what specific information the end user is interested in as it is important to consider bandwidth limits and performance requirements of the selected industrial network. Not all devices will necessarily be configured to communicate the same information. Some assets may only require simple overcurrent protection and monitoring based data for non-essential loads, while mission critical applications might demand capabilities in power-based data/analytics or high-order fault algorithms.

IV. MCC CONFIGURATIONS

Current designs of low-voltage MCCs offered in North America and built to ANSI and UL standards, as well as those offered in South America, Europe/Middle East/Africa and Asia Pacific built to IEC standards are available with advanced motor protection relays. Fig. 3 shows a current design IEC assembly with a withdrawable module that includes the modular motor management relay shown in Fig. 1. Factory assemblies will include network communication modules based on the producer’s selected network. One best practice is to specify factory acceptance testing (FAT) of MCCs with networked motor management relays. During the factory test, communication cables and network addresses can be set to ensure functionality as expected prior to installation in the field. If the PLC planned for use in the process is available, factory acceptance testing can also include some rudimentary tests to ensure the system program functions as expected. One should take advantage of a scheduled FAT to perform these tests with the automation group or systems integrator as this extra step will greatly reduce the required time for field commissioning.

Fig. 3 Typical IEC low-voltage motor control center showing starter module with integrated motor protective relay

Although the basis for this discussion assumes a new assembly is installed, some manufacturers of MCCs can supply replacement motor starter modules to be retrofitted into existing MCC structures. This allows existing incoming power and motor cables to remain in place, along with the legacy steel structure and copper bus, while controls are updated with the latest functionality, extending the useful life of the existing control assemblies.

V. Case Study

A global cement producer recently installed low-voltage MCCs with updated motor management relays for a new baghouse project at one of their facilities in the mid-Western United States. The project was part of an existing facility process system equipment upgrade that would also assure environmental compliance as required by Federal regulators [4]. Included as a part of the project, new medium-voltage switchgear, power transformers, medium-voltage motor control and variable frequency drives along with the new low-voltage motor control centers were installed. The project team for the producer was led by a central engineering/management group at the U.S. headquarters in Eastern Pennsylvania. Although the project was not yet commissioned at the writing of this paper, the new baghouse, supplied by a European integrator, is shown in Fig. 4. The structure is now in place and tie-ins for mechanical and electrical systems are in final stages of completion. This current installation serves as an excellent case study: a unique opportunity to discuss installation and best practices surrounding the newly installed motor control centers and processes employed by both the central engineering group and the plant operations team to assure a successful project.

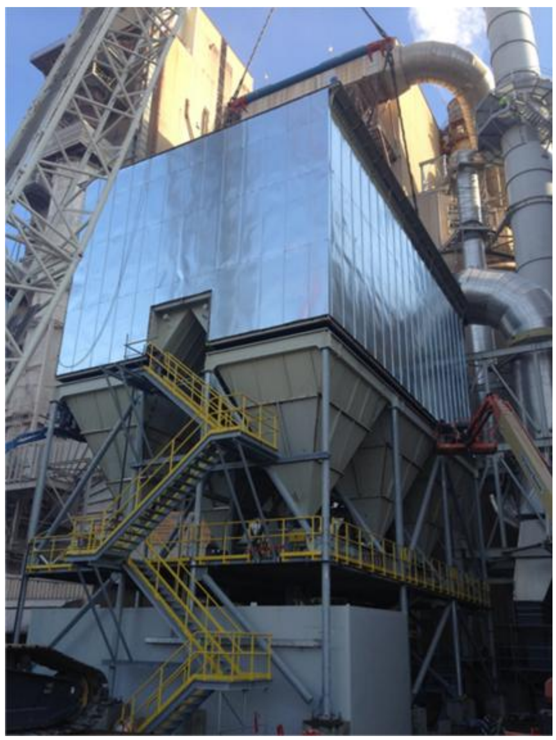

Fig. 4 New baghouse structure installed at the existing cement plant

A. *MCC Configuration at the Factory*

Traditional scope of supply for the equipment supplier on a major project addition such as this might include not only the mechanical assemblies but also the electrical equipment used to power the process. In this case, the central engineering group of the plant owner decided to specify and purchase the electrical equipment directly from the supplier. In Europe, suppliers of electrical equipment offer products that are manufactured and tested to International Electrotechnical Commission (IEC) Standards. For instance, low-voltage motor control centers in Europe are manufactured and tested to IEC61439-1 [5] while MCCs in the United States are manufactured and tested to UL 845 [6]. Because the baghouse project was planned for installation in the U.S. where in-country installation standards [7] prevail, the project team opted to locally source the required electrics directly from the manufacturer. On similar projects, some IEC assemblies have found their way into U.S. markets, but oftentimes, not without significant challenges. Because these assemblies are manufactured and tested to different standards, local inspecting authorities have the right to reject such installations, requiring the assemblies be field tested and labeled before they can be energized.

The project team executed careful planning in specifying configuration of the low-voltage MCC before the assembly was shipped from the factory to the plant site. MCC manufacturing facilities by most major suppliers are typically well versed in understanding the requirements of network connected assemblies. In the case of this project, the central engineering team requested that the MCC plant prepare the assembly by setting all of the network IDs for each motor management relay prior to shipment. Ethernet/IP was the selected protocol for the project so in this case, each device was preset with specific internet protocol network address based on the producer's instructions. As discussed in Section IV of this paper, oftentimes the producing plant can bring the system logic controller to the MCC supplier's plant prior to shipment as a part of the factory acceptance testing. Including this activity as a part of the FAT is considered a best practice. In the case of this project, time constraints and an expedited schedule resulted in the central engineering group's decision to forego the factory test as the focus was on installing and wiring the MCC in the electrical room first.

B. Becoming Familiar with the Hardware and Software

The existing cement plant maintenance group included 15 electricians deployed during various production shifts. At this site, all of the electricians were already familiar with the selected PLC hardware and software as these were installed across other processes in the facility. Although site electricians were typically not involved in changes of PLC programming, activities such as disabling an interlock from the PLC program during troubleshooting was a common practice. The addition of the new MCC with motor management relays for each starter was new to plant operators. The project execution group from headquarters deployed an engineer to the site to finalize the PLC programming and configure network communications for each device. He too was unfamiliar with the new hardware being installed.

Before the MCC shipped from the factory, a local site engineer from the supplier met with the controls engineer from headquarters along with the local electrical technicians at the plant to plot the best path forward to assure both groups came up to speed quickly regarding configuration and network communications with the new intelligent devices. A decision was made to immediately ship a sample of all new components including the measurement module, control module and user interface module described in the Section III above. A web conference was scheduled with the supplier's application specialist at a nearby controls operation center after the sample components arrived at site. The corporate controls engineer was very experienced and had commissioned several similar projects. Using preprogrammed control logic based on operation of a type of machine such as a bucket elevator or a screw conveyor, he was able to add the project specific requirements, then assign inputs and outputs to each device. Fig. 5 shows a typical function block for each device where PLC inputs and outputs can be

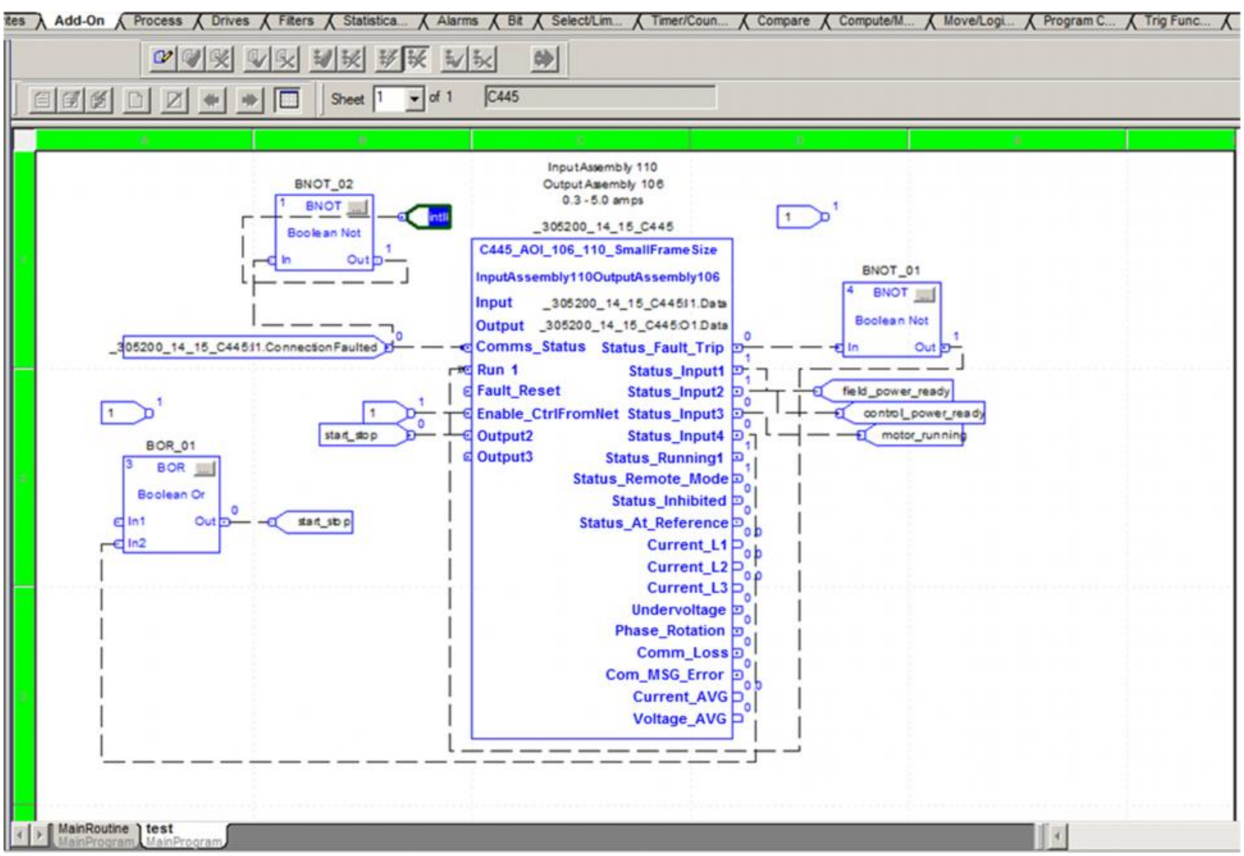

Fig. 5 Typical function block of the motor management relay showing inputs and outputs assigned to the PLC program

preassigned. Settings for each device including parameters such as motor full load amperes and overload trip class, are set in PLC registers and these values are overwritten to the device via the network communications when the host controller establishes a connection. The corporate controls engineer was very pleased with the ease in which the new system was seamlessly integrated into the PLC software which was supplied by a different manufacturer. At first there was a concern that the configuration software would be difficult to work with and that a license would be required to configure the system. It turned out that the configuration software was available free from the MCC manufacturer as was the sample hardware components used for training and the technical assistance to assure both the corporate controls engineer and site electricians were comfortable navigating between the PLC program and the intelligent devices in the motor control center.

Fig. 6 shows the new low-voltage MCC while still being installed and wired prior to project commissioning. The inset photos at the left and right include door-open views for two of the individual MCC units. At the left is a view of an across the line reversing starter unit. Note that the measurement module is mounted/wired just below the starter unit incoming circuit breaker. Phase conductors are routed through the embedded current transformers in the measurement module that continuously monitor motor phase currents. A smaller control gauge wire for each of three phases is connected from the load terminals of the circuit breaker to the orange terminal block at the top of the measurement module to monitor phase voltages. The control module is mounted just to the right of the measurement module. Note here that the blue Ethernet cable is connected here and this communications cable extends through the MCC structure vertical wire-way to the Ethernet switches should in the inset photo at the right. This photo shows that a home-run network connection was selected where multiple starter units are individually wired to the Ethernet switch. This approach requires a higher density of communication cables than the device level ring (DLR) daisy-chain connection between starters in a given structure using both RJ45 connectors at the communication module as described previously. Because of the system design, there were many starters in the MCC assigned as spares or futures. Using the DLR topology for each structure in this case was not practical since dropping off two starters in a given ring could disrupt the process due to loss of communication with functioning starters. Instead, the project controls engineer elected to set-up a network ring at the Ethernet switch level. This design approach assured network integrity at a higher level since for this configuration, two Ethernet switches would need to be dropped from the network before communications were lost. Using this system configuration assures that failure or malfunction of only one Ethernet switch still assures that communication with all starter units remains intact. In this system there are two sources of control power. Individual starter units include a 480Vac to 120Vac control power transformer used to power the contactor coil and door-mounted indicating lights. The Ethernet communications requires 24Vdc power which is derived from a redundant power supply unit in the low-voltage MCC which is not shown in the image for Fig. 6.

The PLC control cabinet was installed in the same electrical room as the MCC and this is shown in Fig. 7. Note that each PLC includes a communication card that is wired to a local Ethernet switch. This switch includes a connection to two Ethernet cables which are essentially the "beginning" and "end" of the network ring. The PLC cabinet also includes local input & output cards which are connected to field based devices.

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Fig. 6 Installed motor control center showing a starter unit at right and home-run connection to Ethernet switches at left

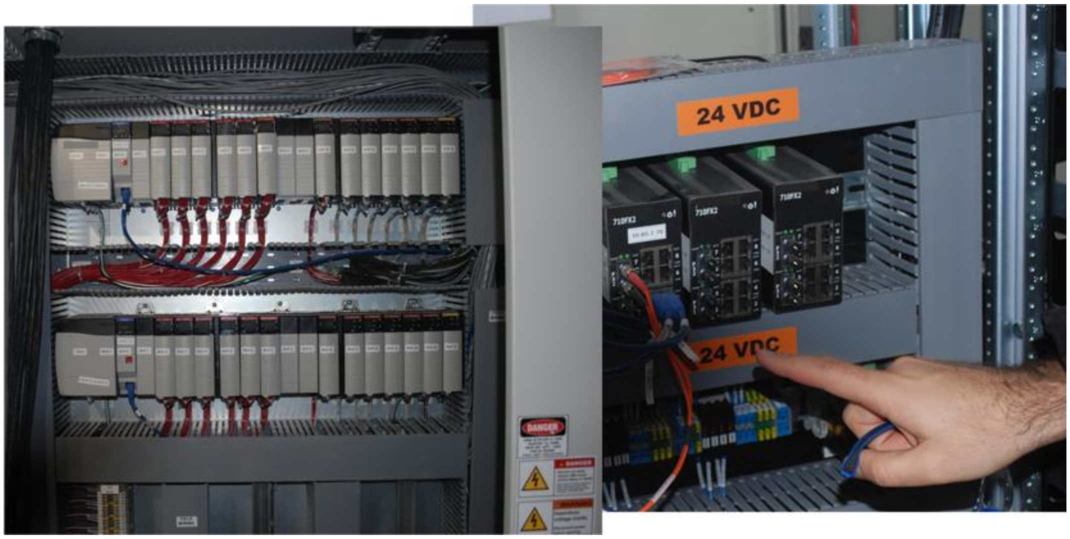

Fig. 7 At left, programmable logic controller panel with EthernetIP communication cards and input/output cards to support local field devices. At right, beginning and end of the network ring connection to the MCC

C. Leveraging Technology with Improved Functionality

Addition of the motor management relays delivered some unexpected functionality that was a benefit to the user. The new baghouse project included a high-resistance pulsing ground system for the new 480Vac system. Fig. 8 shows a typical schematic of the installed pulsing ground system for the low-voltage system. The use of these systems in process industry applications are well understood and described in [8]. The basic principle in these systems includes connection of a fixed resistance between the transformer Wye connected neutral secondary. Typically, the resistance value in ohms is selected so that in the event of a downstream phase conductor fault to ground, the maximum amount of current that will flow through the plant ground grid back to the source is 4 or 5 amperes. When a downstream fault occurs, the pulsing high-resistance ground (HRG)

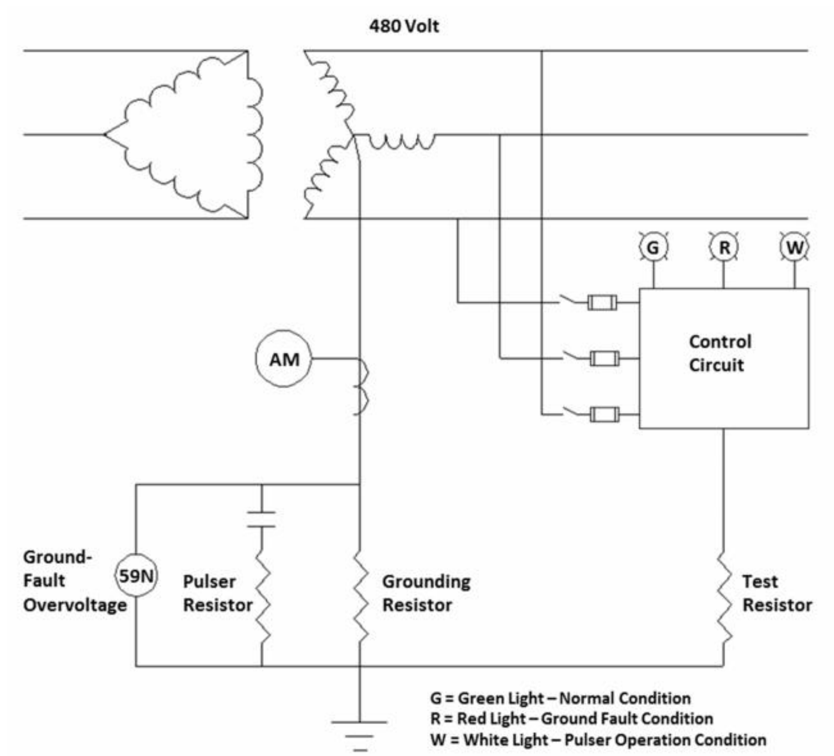

Fig. 8 Low-Voltage pulsing high-resistance ground system

system will measure the current flow through the grounding resistor and typically sound an alarm. Service to the process loads is continued as the current in the ground plane is not high enough to trip any system overcurrent protective device. While service is continued, the plant operators are responsible to identify the motor feeder where the ground fault originated and clear this fault from the system. Finding the location of the faulted feeder can prove an onerous task. In order to locate the load where the fault exists, the HRG system is equipped with a pulsing system that includes a single pole contactor and an additional resistor. When the "pulser" is initiated by the user, the contactor switches the additional resistance in and out of the circuit on a 2 to 3 second interval. The added resistance switched between neutral and system ground changes the current in the ground plane by a few amps. Site operations can then apply a special clamp-on window type hand-held ammeter at each of the feeders to check for the change in ground current. This process allows the owner to isolate the faulted feeder.

The new motor management relays installed in the low-voltage MCC at the site were designed with future considerations for the application of high resistance pulsing ground systems. The microprocessor in the relay will be capable to identify the pulse train generated by the HGR system. Since the Measurement Module of each relay includes three integral current sensors, special functionality of the new relay can be added to recognize when the HRG pulser has been activated, and then report not only which motor feeder but also which phase of the faulted feeder has a ground fault. This capability obviously saves the plant operators time in locating and clearing the fault and also improves the plant's electrical workplace safety as defined by industry standards [9] since operators are not exposed to energized electrical conductors in the fault finding process. Because the pulsing HRG detection function of the motor management relay was in development during the project, a decision was made to modify the existing relays with this additional capability during the next scheduled outage. As the required sensing hardware is inherently integral to the Measurement Module of the relay today, future field modification of this capability is possible through updating the device firmware of the on-board microprocessor via a configuration and monitoring software tool.

VI. Conclusions

There is no argument that the added functionality of newer motor management relays offers improved motor protection and access to a host of electrical parameters that ultimately improve plant reliability and productivity. New device algorithms in development use electrical motor current signature analysis to detect electrical and mechanical system problems. Developments focused on detecting both motor and load issues including broken rotor bars, stator failures, pump cavitation and looming impeller failures, will all be made possible through a host of predictive diagnostics capabilities, collectively referred to as a complete "system diagnostics" portfolio. Industrial networks coupled with the IIoT will allow information to become a driver toward automation solutions improving plant safety, efficiency and productivity. With the advantage of a new plant, or when a new process is added, an opportunity exists to take advantage of the latest technology. Conversely, older plants that have expanded over several decades likely will contain several vintages of multiple disparate systems that represent more of a challenge.

Improvements in operations, asset protection, safety, reduced installation and savings over conventional I/O hardware should justify the incremental cost for selection of intelligent motor protection hardware vs conventional overload relays and hardwired control systems interface. As with any new technology, management will need to recognize the need to invest in human assets and provide the required training for local plant maintenance personal responsible to support this new technology. The case study described in this paper offers an excellent step by step roadmap outlining the required steps to plan and execute a successful project employing the latest in motor management technology.

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