Challenges and Solutions of Protecting Variable Speed Drive Motors

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***Abstract*—Variable frequency drives (VFDs), also known as variable speed drives, provide significant advantages for the operation of induction motors. These advantages include reduced starting currents, adjustable speed control, and improved energy efficiency. However, VFDs create additional challenges for motor operation and protection that are not present in line-connected motors. The protection challenges are solved by new protection elements available in an electronic motor protection relay.**

Traditional motor protection elements use fundamental frequency measurements for operating current. VFD-operated motors have a fundamental frequency that changes rapidly in response to speed adjustments. Additionally, the synthesized sine waves produced by the VFD contain significant harmonic content. The new protection elements use true rms (fundamental plus harmonics) operating current. True rms measurements are not dependent on having a fixed fundamental frequency. True rms measurements properly account for the motor heating caused by harmonic currents.

Conventional single-speed motor protection uses a fixed value for the full-load amperes (FLA) of the motor. This single FLA assumes that a fixed cooling rate is available to the motor. Commonly used low-voltage motors have shaft-coupled cooling fans that spin at the same speed as the motor. At reduced operating speeds, the cooling air provided by the fan is significantly reduced. In order to prevent overheating of the motor, the protection elements should compensate for the reduced cooling. The new protection elements dynamically compensate for the reduced cooling available at reduced speed operation.

VFDs are typically installed in motor control centers (MCCs). Because of the large available fault current, MCCs can have significant arc-flash hazard potential. The safety of VFD-operated motors can be improved using arc-flash protection elements.

VFDs are often installed in large numbers at industrial facilities. This makes it impractical to manually monitor and control each motor as a standalone device. A centralized motor management system solves this problem.

This paper describes novel protection elements that accommodate the unique protection, monitoring, and control challenges of VFD-operated motors.

I. CONVENTIONAL MOTOR PROTECTION

In order to evaluate the protection requirements for variable frequency drive-operated (VFD-operated) motors, this paper first reviews the basic operating principles and compares them to across-the-line motor operation. A conventional across-the-line-connected motor is operated using a short-circuit protective device (SCPD), usually a circuit breaker or fuses; a motor controller, commonly known as a contactor; and an overload protection device, referred to as a motor overload protection relay (MOPR) in this paper. This method is shown in Fig. 1 using a simplified content diagram that meets the standards of National Electric Code (NEC) Article 430.

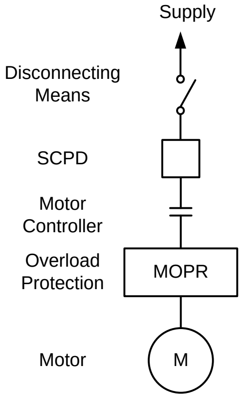

Fig. 1. NEC Article 430-compliant motor protection

The SCPD provides protection against fault currents in excess of the motor locked rotor current, typically six to seven times the full-load amperes (FLA). When the contactor is closing for starting, we expect to see locked rotor current at the moment the contactor is closed. As the rotor spins up to operating speed, the current decreases to or below the FLA for a properly loaded motor.

For currents above FLA, but less than the trip rating of the SCPD, the MOPR trips according to its overload protection curve. This can be caused by several conditions, including the following:

- Locked rotor.
- Jam or stall.
- Continuous overload.

Advanced MOPRs may include the following additional protection functions:

- Overvoltage and undervoltage.
- Phase unbalance.
- Loss of phase.
- Earth fault.
- Overfrequency and underfrequency.
- Loss of load.
- Starts per hour.

The SCPD and MOPR must be coordinated so that each trips for its appropriate protection range. The contactor is typically rated for interrupting currents up to ten times its continuous rated current. Therefore, it is important that the SCPD operates before the MOPR for currents above the contactor rating. Otherwise, the contactor could be damaged as it tries to interrupt the large-magnitude fault current.

The voltage and current waveforms in these applications are assumed to be single-frequency (50 or 60 Hz) sinusoidal ac systems. Classic sinusoidal circuit analysis techniques are used to evaluate the performance and protection requirements of the system. Any harmonics in the system are often assumed to be negligible for the purposes of protection, measurement, and control.

II. VFD MOTOR OPERATION

VFDs, by definition, operate over a variable frequency range. This is in contrast to the fixed 50 or 60 Hz operation of across-the-line-operated motors.

The SCPD is installed on the supply side of the VFD, so that it will still operate on a 50 or 60 Hz system. The MOPR operates on the load side of the VFD, exposed to the entire frequency range of the VFD. A fixed frequency system can no longer be assumed. The overload protection device must be able to operate correctly at any allowed operating frequency of the motor. Because the motor can be subjected to abnormal frequency levels, overfrequency protection should be provided.

A. The Effect of VFD Technologies on Voltage and Current Waveforms

VFDs feature a significant number of ways to synthesize the variable frequency voltage waveform in the dc-to-ac inverter section of the drive. For low-voltage (LV) drives, the most common method uses dc-to-ac conversion with pulse-width modulation (PWM). PWM is a versatile technique because the frequency, phase angle, and amplitude of the ac output can be varied as needed by modifying the pulse pattern of the device. This pulse pattern can be readily generated by a microprocessor-based algorithm. Fig. 2 shows the sequential positive and negative pulses produced by a PWM inverter.

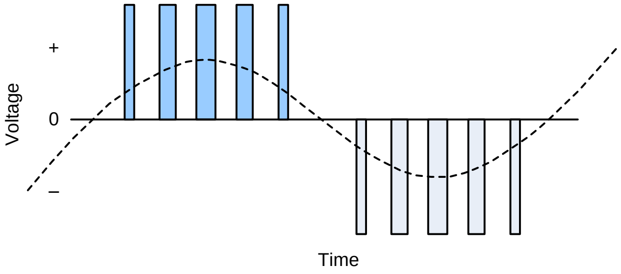

Fig. 2. Sequential positive and negative pulses produce a low-frequency sinusoidal waveform component

In many VFDs, PWM switching is performed by a high-speed semiconductor switch, such as an insulated-gate bipolar transistor (IGBT). A carrier frequency of at least ten times the desired output frequency is used to establish the PWM switching intervals. A carrier frequency in the range of 2,000 to 16,000 Hz is common for LV VFDs. A higher carrier frequency produces a better sine wave approximation but incurs higher switching losses in the IGBT, decreasing the overall power conversion efficiency.

Looking at the PWM pulse train, it is hard to visualize the sinusoidal voltage component. Once the carrier frequency and higher frequencies are filtered out, we are left with a mostly sinusoidal voltage waveform, shown as a dashed line in Fig. 2.

If we were using the unfiltered PWM output to power a resistive load, we would expect the current waveform to be identical in shape to the pulsed voltage waveform. However, the appropriately named induction motor provides an inductive load. Because the current in an inductor cannot be instantaneously changed, current continues to flow in the motor even when the PWM output switches off. This results in a sinusoidal current waveform with a clearly visible fundamental frequency. Fig. 3 shows the current and voltage waveforms for one phase of a 100 hp, three-phase motor operating at 40 Hz. The red vertical lines are the PWM voltage. The sinusoid is the current waveform.

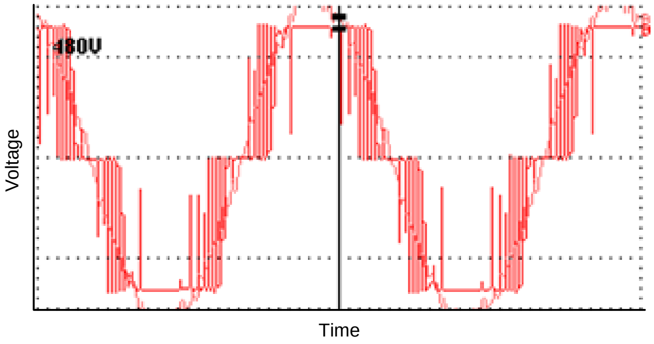

Fig. 3. Voltage and current waveforms for a VFD operating at 40 Hz

B. The Effect of Harmonics on Overload Protection for VFD Operations

In across-the-line (non-VFD) motor protection, positive- and negative-sequence components are used as inputs to the first-order thermal model from which the rotor and stator heating are calculated [1]. In this case, the fundamental frequency is isolated using cosine filtering, thereby excluding any harmonic frequencies [2].

VFDs produce significant harmonics in both current and voltage outputs. As a result, the thermal model is more accurate for VFD operation when true root-mean-square (rms) measurements are used instead of fundamental frequency sequence components. True rms measurements include both fundamental and harmonic content. The thermal model is modified as follows:

- Use true rms magnitudes for motor currents to account for harmonics in the current waveform.
- Use average magnitudes of the true rms currents in place of the positive-sequence current.
- Assume the negative-sequence current magnitude is zero.

C. The Effect on Torque for VFD Operation

When comparing across-the-line motor operation with VFD operation, the VFD-operated motor can run hotter than its across-the-line equivalent because of increased heating from harmonic effects and reduced cooling from low-speed operation. As a result, the continuous torque available from a VFD-operated motor is often lower than with a line-connected motor.

1) Torque Derating Due to Harmonics

VFDs are available with a large variety of topologies. Within PWM inverters, there are many pulse patterns used that can vary with the operating frequency. Consequently, it is not feasible to make global characterizations of the VFD output harmonic content.

Voltage and current harmonics create iron and winding losses in the stator and rotor. The effect of any given harmonic on motor heating is affected by the motor design variants. These variants include rotor materials (i.e., copper, aluminum, or brass) and slot geometry (i.e., deep or shallow bars and double cage).

Given the large variety of VFDs and motors, there is no easy way to calculate the torque derating. These deratings are dependent on the particular combination of VFD and motor. References [3] and [4] give example values for some specific VFD and motor combinations.

2) Torque Derating Due to Reduced Cooling

The most common types of LV motors use shaft-coupled fans to provide speed-dependent cooling for the motor. Two common types of motors using this cooling method are the totally enclosed, fan-cooled (TEFC) and the open drip-proof (ODP) motors. Operation of these motors at low speeds results in reduced cooling air being provided to the motor and a subsequent increase in the operating temperature. At very low speeds, these motors may only have 20 to 50 percent of their full-speed cooling. When operating a motor at reduced speeds, this reduced cooling can affect the motor torque.

Motors using speed-independent cooling do not rely on motor shaft rotation for cooling. These motor types include totally enclosed, nonventilated (TENV) and totally enclosed, blower-cooled (TEBC) motors. A TEBC motor uses a separate fan motor to provide cooling air independent of the speed of the primary motor. Independently cooled motors are better suited for sustained low-speed operation.

Reference [3] provides torque derating curves for motors, as shown in Fig. 4. These derating curves are very conservative in that some National Electrical Manufacturers Association (NEMA) motors are capable of continuous operation down to 5 Hz without torque derating using commonly available constant-flux PWM VFDs.

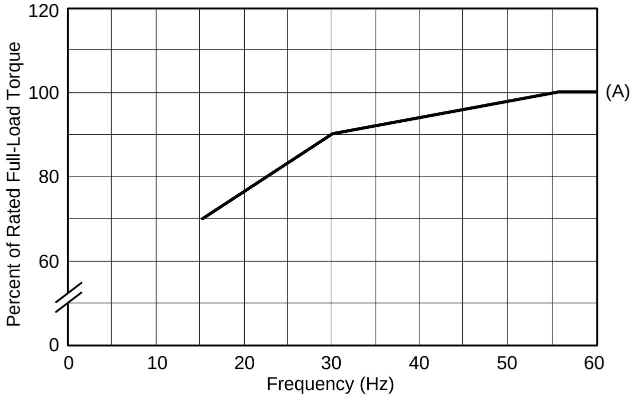

Fig. 4. NEMA MG1 effect of reduced cooling on the torque capability at reduced speeds of 60 Hz, NEMA TEFC motors

D. The Effect of Cooling on Overload Protection for VFD Operation

The thermal model for line-connected motors does not account for the increased heating due to harmonics and the reduced cooling from low-speed operations. This is because the harmonics are negligible and operating speed is always near rated speed for the line-connected motors.

To account for the reduced cooling at low-speed operations, we have modified the thermal model to include the multiplier KVF to provide a compensated FLA rating for the motor.

As shown in Fig. 5, KVF is defined by the minimum frequency for full load (FREQ_FL) and the maximum load allowed at the zero speed (LOAD_ZS). For frequencies above FREQ_FL, KVF has a value of 1. For frequencies below FREQ_FL, KVF varies linearly between LOAD_ZS and 1.

As shown in Fig. 5, the value of KVF changes dynamically with the frequency. KVF is used to compensate the trip threshold for both the rotor and stator thermal models.

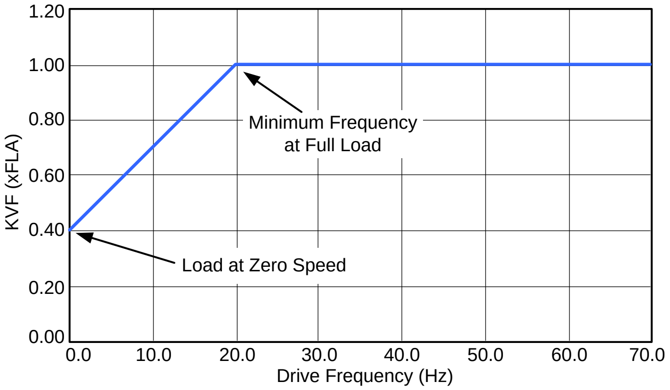

Fig. 5. KVF factor versus VFD output frequency

E. The Effect of Low Frequencies on Current Transformers (CTs) for VFD Operation

Typically, the CT capability is proportionally reduced at lower frequency operation. This requires careful selection of magnetic CTs, both external and internal to the protective relay [5]. The use of Rogowski coils in the relay eliminates the need for external CTs for most LV applications and offers linear characteristics over a wide range of both the frequencies and currents, making Rogowski coils ideally suited for VFD applications [6].

F. Multiple Motors Using a Single VFD

For applications requiring multiple motors to operate at the same speed, it can be advantageous to use a single VFD with multiple motors operated in parallel. Each of these motors is connected to a common bus and has the same voltage and frequency applied.

Typical VFDs provide overload protection for a single motor. A VFD senses the total current provided to the motor bus. If one of the motors is drawing too much current, the VFD cannot sense this overload among the total connected load. As a result, when multiple motors are connected in parallel, each motor requires its own independent thermal overload protection device and SCPD, as shown in Fig. 6.

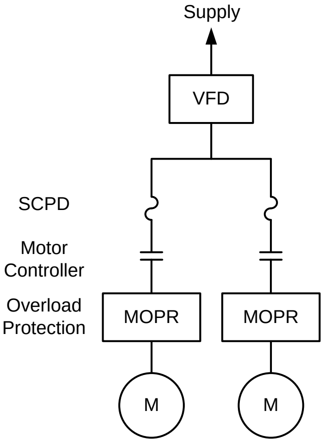

Fig. 6. One VFD for the control of multiple motors

G. VFD Bypass

VFD bypass contactors are used in situations where it is necessary to have the option of running the motor from either the VFD or directly across the line. The following are two major applications of VFD bypass:

- Isolation of the VFD for maintenance while allowing the motor(s) to operate directly across the line.
- Sharing one VFD among several motors for soft starting. Once a motor is at full speed, it is switched to operate across the line.

Fig. 7 shows an example application in which a three-contactor arrangement allows the VFD to be bypassed. The connected motors can operate from either the VFD or directly from the line, depending on the contactor states. Two of the contactors are used to isolate the VFD. The third contactor provides across-the-line power to the motors.

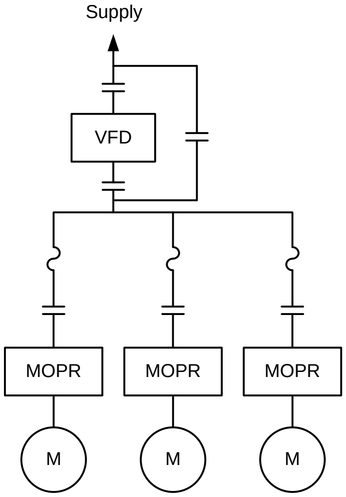

Fig. 7. VFD bypass with multiple motors

When VFD bypass mode is used, several issues must be considered, including the following:

- The motor must be suitable for both VFD and across-the-line operation. Some inverter-duty motors are not approved for across-the-line operation.
- The motor and loads must be capable of continuous full-speed operation.
- Any possible reversing arrangements must be considered to ensure that both VFD and VFD bypass modes will operate the motor in the correct direction.
- Motor overload and short-circuit protection must be provided to support both VFD and VFD bypass operations.

III. ARC-FLASH PROTECTION

As described in [7], an arc-flash detection (AFD) element in a protective relay can provide a significant reduction in the hazardous incident energy from an arc fault. The light produced by an arc flash provides a large-magnitude signal that is used in conjunction with overcurrent sensing to securely and reliably detect an arc fault. Upon detection of the arc-fault condition, the relay initiates high-speed tripping of an upstream breaker to minimize the arc-fault duration and resultant incident energy. In the system described in this paper, the MOPR is capable of providing the entire arc-flash protection function, including light sensing, overcurrent sensing, and high-speed tripping.

The typical motor control center (MCC) implementation is vulnerable to arc faults upstream of the MOPR, for example, on the contactor, fuse, busbar, or breaker. Consequently, it is also advantageous to sense the arc-fault overcurrent on the incoming feed to the motor bus while still sensing the light flash within the MCC bucket. Furthermore, LV MCCs typically use fuses or magnetic breakers within the buckets. These fuses and breakers cannot be tripped by a protective relay. As a result, it is necessary to trip the incoming motor bus breaker to reliably clear the arc fault. A typical scheme for such a system is shown in Fig. 8.

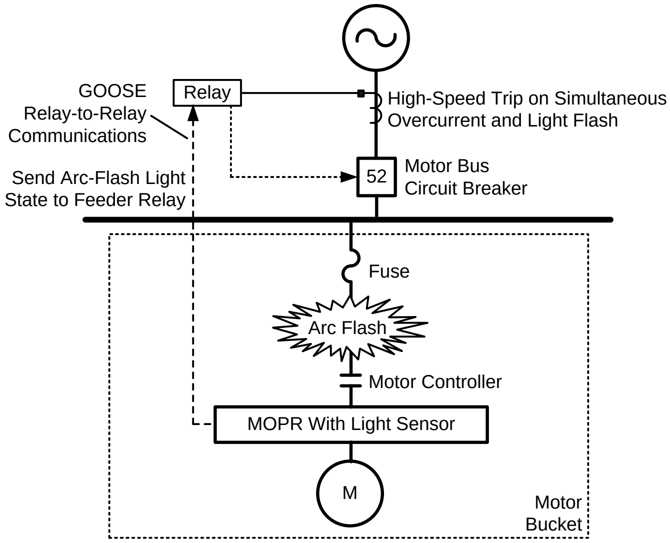

Fig. 8. Use of relay-to-relay GOOSE messaging for arc-flash protection

When a light flash is detected in an MCC bucket, high-priority IEC 61850 Generic Object-Oriented Substation Event (GOOSE) messaging is sent from the MOPR to an upstream relay associated with the motor bus circuit breaker (52). If the upstream relay detects an overcurrent condition coincident with the MCC bucket light flash, a high-speed trip is initiated on the motor bus circuit breaker to minimize the arc-fault duration.

Tests during live arc-flash events with multiple relays prove that the careful design of relays is required so they can survive the harsh environment of an arc-flash plasma cloud. This environment includes very high temperatures, bright light, ionized air, strong magnetic fields, flying molten metal, and mechanical shock. Table I shows the end-to-end detection and trip times as measured in arc-flash testing at a high-current laboratory. The test methodology is similar to that described in [7] but with an MOPR instead of a feeder relay.

TABLE I
SUMMARY OF GOOSE ARC-FLASH TRIP TIMES

	Trip Time (milliseconds) From Application of Current
Minimum	4
Maximum	13

The MOPR must survive an arc-flash event long enough to trip upstream breakers. Significant testing of the relays must be done in real arc-flash environments to ensure survival. Typical testing methods are shown in Fig. 9.

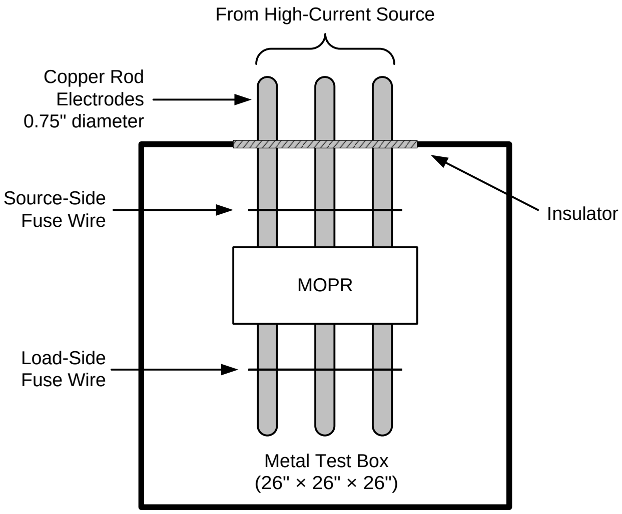

Fig. 9. Arc-flash test box

Controlled tests have proved that even in a catastrophic arc-flash event test, at least four GOOSE messages indicating the arc-flash event are sent within 16 milliseconds. The variance between 4 to 13 milliseconds, shown in Table I, is caused by the asynchronous processing cycles of the MOPR and Ethernet switches.

IV. EVENT DIAGNOSIS

The ability to diagnose and understand motor overloads, short-circuit trips, motor starts, and all other relay operations has proved to be critical in the protection industry. Synchronized time signals to all the relays in the MCC and throughout the plant provide the ability to have comparable power system fault and disturbance event reports (oscillography), Sequential Events Recorder (SER) records, and time-accurate reporting for supervisory control and data acquisition (SCADA) analog and state-change records (sequence of events [SOE]).

Being able to do time-deterministic root-cause analysis of system events and combine report data from different relays to calculate in real time the timing between occurrences related to the same incident have proved to be invaluable.

The types of event reports commonly provided by an MOPR include the following:

- Oscillographic recording with a built-in oscilloscope – an oscillography report of every event for post-event analysis.
- SOE capture – the binary state of change of inputs, outputs, and internal digital variables.
- Total harmonic distortion (THD) measurement.
- Load profile report – the storage of metering quantities captured every few seconds into nonvolatile memory, replacing slow sample, long-duration strip-chart recording devices.
- Motor operating statistics report – includes summarized information such as running data, start data, and alarm and/or trip data.
- Motor start report – a special oscillography recording of every motor start. An example of this is shown in Fig. 10.

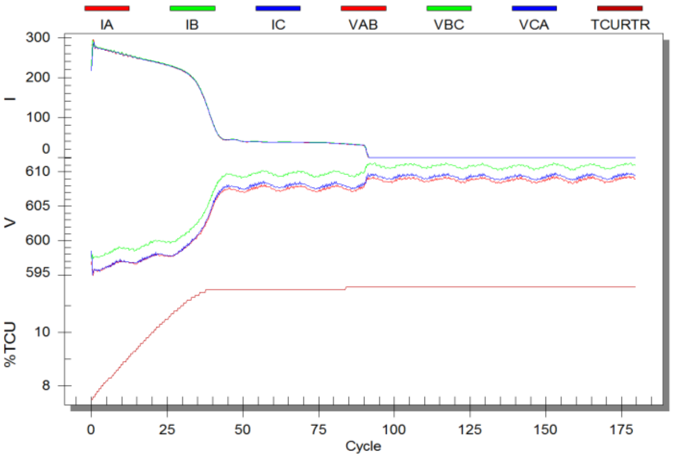

Fig. 10. Motor start report oscillography

V. MOTOR CONTROL SYSTEMS

Many industrial processes involve dozens to hundreds of motors operating together to provide the mechanical power needed by the particular process system. In these large systems, it becomes impractical to hard-wire process interlocks and control connections due to the large number of motors involved.

To address this issue, a centralized smart motor control system (CSMCS) is recommended to provide a fully integrated, plug-and-play package. The CSMCS is an out-of-the-box engineered solution for MCCs. The CSMCS replaces extensive cabling between relays, programmable logic controllers (PLCs), remote terminal units (RTUs), and other controllers with a minimum count of industrially hardened, purpose-built intelligent electronic devices (IEDs). Communication to each MOPR is done with a single Ethernet cable, implementing IEC 61850 GOOSE and manufacturing message specification (MMS) messaging from each relay to a centralized managed switch.

The CSMCS shown in Fig. 11 provides immediate real-time information on motor performance, centralized touchscreen human-machine interface (HMI) access to IEDs throughout the MCC lineup, and historical reporting and analysis. This networked CSMCS solution integrates the latest MOPR and incoming feeder relays for advanced motor protection, control, metering, and process automation.

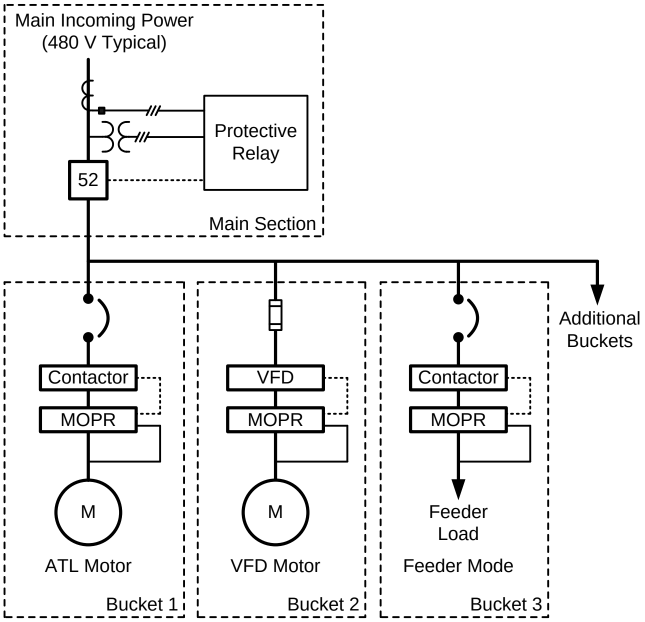

Fig. 11. CSMCS overview

Valuable system process data are automatically gathered, consolidated, and made available simultaneously to process control systems (PCSs), power management systems (PMSs), and asset management systems. Fig. 12 shows the simplified communications hierarchy of the CSMCS.

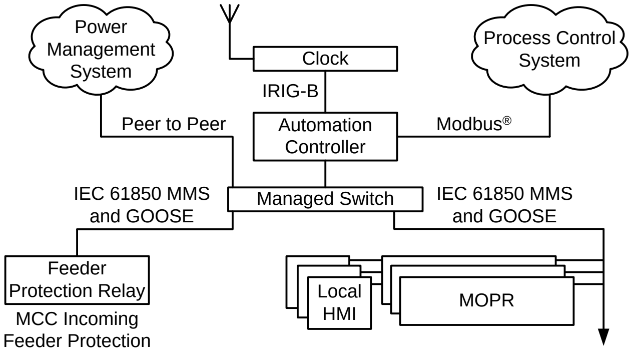

Fig. 12. CSMCS communications block diagram

The CSMCS is also a complete protection, control, and monitoring solution for an MCC. It provides process diagnostics that simplify maintenance by allowing users to detect and correct problems before they become critical, preventing damage and minimizing process downtime.

The CSMCS uses standard integration and communications techniques refined through decades of electric power protection experience. Some of the attributes of the CSMCS include the following:

- AFD in the main section and built into each MOPR initiates an upstream breaker trip signal in less than 13 milliseconds from the detection of an arc-flash event anywhere in the MCC.
- All system communication consolidated onto an Ethernet network, reducing the wiring associated with present MCC hard-wired or distributed I/O methods.
- Feeder protection at the main incoming section.
- Control and monitoring of individual loads.
- Complete status and metering data from each load and the entire motor bus.
- Preconfigured bidirectional communication and interface to the PMS and PCS of the plant.
- Preconfigured HMI systems that provide basic system visibility.
- Factory preconfigured and programmed relays, controllers, and managed switch devices specifically for the CSMCS application.
- Remote PMS monitoring capability.
- Subcycle remote trip operation response from remote PMS load-shedding schemes.
- Engineering access to every relay on the Ethernet network.
- Centralized event diagnostic software.
- Instantaneous power metering from every relay to give real-time feedback about process operation.
- Metering for tracking process energy costs and improving energy usage.
- Standard data that include system faults, annunciation, motor thermal capacity used, motor load current, bus voltage, power and energy, motor operating statistics, motor start reports, and relay-stamped SER records.

VI. CONCLUSION

True rms measurements account for harmonic content in the current waveforms of VFD-operated motors. New protection elements use true rms magnitudes to properly account for the motor heating caused by harmonic currents.

The speed-dependent cooling of ordinary TEFC and ODP motors results in impaired ventilation for continuous operation at low speeds. The KVF factor dynamically adjusts the overload trip level to account for the impaired cooling that is due to low-speed operation.

As part of an MCC, VFDs are susceptible to arc-flash hazards. An AFD protection element in the MOPR can provide a significant reduction in incident energy, thereby improving safety.

A CSMCS provides a way to manage all of the protection, control, and automation information provided by the dozens to hundreds of motor relays found in large industrial facilities.

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VIII. BIOGRAPHIES

Angelo D'Aversa received his B.S.E.E. degree in 1990 and an M.S.E.E. degree in 1994 from Drexel University. After graduation, he developed distribution relays for General Electric for nine years. In 1999, he joined Schweitzer Engineering Laboratories, Inc. (SEL) as a test engineer, and since joining SEL, he has spent many years developing firmware for a variety of protective relays. Presently, he is a research and development manager for the industrial systems group at SEL. The industrial systems group specializes in motor and generator relays for industrial applications and utilities.

Bob Hughes received his B.S. in electrical engineering from Montana State University in 1985. He is a senior product manager in the protection systems department at Schweitzer Engineering Laboratories, Inc. Mr. Hughes has over 20 years of experience in electric power system automation, including arc-flash protection, SCADA/EMS, distribution automation, power plant controls, and automated meter reading. He is a registered professional engineer and a member of IEEE.

Subhash Patel received his B.S.E.E. and B.S.M.E. degrees from the Maharaja Sayajirao University, Baroda, India, in 1965 and 1966, respectively. He worked for Brown Boveri Company in India before coming to the United States in late 1967. He received an M.S. (E.E.) degree from the University of Missouri - Rolla, in 1969 and joined Illinois Power Company in Decatur, Illinois, where he was primarily responsible for power system protection. He was with General Electric from 1979 to 1999, during which time he had various assignments in the field of protection and control as well as gas turbine package power plants. In 1999, Mr. Patel joined Schweitzer Engineering Laboratories, Inc. (SEL) as a field application engineer and currently is a principal power engineer in Pennsylvania. Mr. Patel is a life senior member of IEEE, a member of SC-J and several working groups of PSRC, a registered professional engineer in the states of New Hampshire and Illinois, and an author of several protective relay conference papers.

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