Convert Operational Data Into Maintenance Savings

Mark Zeller
Schweitzer Engineering Laboratories, Inc.

This paper was presented at the 2014 IEEE Rural Electric Power Conference and can be accessed at: http://dx.doi.org/10.1109/REPCon.2014.6842205.

For the complete history of this paper, refer to the next page.

Presented at the
IEEE Rural Electric Power Conference
Fort Worth, Texas
May 18–21, 2014

Originally presented at the
Power and Energy Automation Conference, March 2013

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Mark Zeller
Member, IEEE
Schweitzer Engineering Laboratories, Inc.
2350 NE Hopkins Court
Pullman, WA 99163, USA
mark_zeller@selinc.com

***Abstract*—Electrical protective relays contain a great deal of equipment condition monitoring data. Multiple systems are available to read this information for use in both operations and maintenance. This information can then be used to improve operation and maintenance efficiencies, such as:**

- **Reading key equipment data from the relay, and displaying or generating work instructions.**
- **Reducing unscheduled downtime from equipment failures.**
- **Improving maintenance effectiveness by working on equipment based on condition instead of on a time basis.**

Moving operations and maintenance from reactive to proactive activities lowers cost and improves efficiency. Selecting and converting the right information to timely work instructions can ease overall workload by focusing on activities that have the highest payback. Protective relays offer insight into operating characteristics, key equipment statuses, and maintenance indicators. Establishing communications channels between distributed control systems or maintenance work systems with existing protective relays provides vital information at little or no cost. This paper focuses on turning this existing relay information into scheduled work activities that achieve real cost savings.

***Index Terms*—Asset Management; Broken Rotor Bar; Condition-Based Maintenance; Cyclic Loading; Event Analysis; Motor Protection; Overload; Predictive Maintenance; Protective Relay; Reliability-Centered Maintenance.**

I. Introduction

Electric power system protection has seen a dramatic transformation in the last 20 years because of the application of microprocessor-based protective relays. This technology, initially developed by Dr. Edmund O. Schweitzer, III, for the protection of transmission lines, has been applied in all areas of power system protection. The microprocessor-based modern protective relay converts analog signals to digital information and performs complex mathematic algorithms to determine the operating conditions of the power system. These data, while initially collected to monitor and protect the power system, have valuable information that can be used to improve the safety, reliability, and economy of the processes powered by the electric system. This paper focuses on turning this existing relay information into scheduled work activities that achieve real cost savings.

II. Information Sources

The modern process control plant uses multiple sources of information, both analog and digital. Often, valuable information gathered for one primary purpose can have a substantial benefit when applied in ways not initially intended. Modern digital protective relays are an excellent example of this benefit when the data collected for electrical protection are also used for operational control and troubleshooting.

The information gathered to perform electrical protection must be sampled at a much higher frequency rate than is typically needed for process control. The sample rate for a modern protective relay is typically between 4 and 16 samples per ac cycle. The relay uses this information to quickly detect abnormal electrical conditions and disconnect the section of the circuit with the problem. When not used to protect the circuit, most of this information is discarded after evaluation.

Reading this information from the protective relay, which is installed to protect the circuit, for use in process evaluation can provide valuable information at a very low cost. Most modern digital protective relays include some form of communications interface. Collecting data from these relays is often as easy as configuring the port and defining the information packets to the protocol of choice.

The information stored in a protective relay is well defined by the relay manufacturer, but often, the protection engineer does not discuss the information available in the protective relay with operations or process control colleagues.

The processing power in modern digital protective relays is not only capable of separating protection functions from communications processing time, but is also designed to operate the protection on a fixed scan rate, independent of communications processing. Drawing information from a modern protective relay requires no more than a normal communications setup, and it does not impact the protection functions of the relay.

Sharing relay information among operations, protection, automation, and reliability personnel should be encouraged wherever possible.

III. Operating Time

Protective relays include internal clocks and can also be synchronized to external time sources. Most protective relays include a function that tracks the time circuits that are energized. For motor-driven equipment, a motor protection relay logs when the motor is started and the amount of time the motor has operated since the accumulator was reset.

A. Correlate Maintenance Activities With Operating Time

The length of time that equipment has been operating can be a good indication of when required maintenance is due to be performed. Many maintenance activities as well as operation checks should be performed at intervals dependent on operational time. Examples such as adjusting pump packing, cleaning cooling vents, changing filters, monitoring vibration, inspecting for leaks, and completing other visual checks are standard operating procedure. In applications where the process can be configured using alternate equipment configurations, inspections on equipment that is not in operation or has not reached inspection intervals waste operation and maintenance time. By triggering inspections and work orders based on operating times, activities can be performed when specific intervals are achieved. This is like the oil change warning light coming on in a car, indicating the mileage has reached the interval specified to change the oil. An example operating time report is shown in Fig. 1.

```
Unit 3 FD FAN 2
3-532-CB-B10

Operating History   (elapsed time in dd:hh:mm)
Last Reset Date     04/11/2009
Last Reset Time     04:50:45
Running Time        30:02:04
Stopped Time        > 84:20:17
Time Running (%)    26.2
Total Mwhr (Mwhr)   197.9
Number of Starts    46
Emergency Starts    0
```

Fig. 1. Typical operating time and number of starts log information.

B. Balance Operating Time Between Redundant Equipment

Many critical process applications have multiple backup systems installed that decrease downtime by using spares, redundant systems, or additional equipment that is only used during occasional peak demand periods. Operating the backup system is the best way to ensure the unit is functioning properly and is ready when needed. Tracking the operational time on each unit provides criteria to balance the wear on the equipment. Many strategies exist for optimizing the operating times of redundant systems, such as equal operating time or one-third to two-thirds scheduling, but in each case, an indication of actual operating time is used to implement the scheme. Protective relays provide an easily accessible run-time measurement.

C. Indicate Unusual Operating Configurations

The operating times of equipment can also be used to trigger alarms or work orders when the operating times of backup systems exceed normal expectations. These times can also indicate when incorrect process configurations are operated, causing undue wear on equipment and additional energy costs. An example is when two pumps are operated in parallel even though the system is designed to operate on a single pump. Some operators operate both pumps because they feel it provides more flow, better stability, or more reliable operation. These are opportunities to teach operators about process control and save money on maintenance and energy. Using the operating times instead of instant alarming on parallel operation provides a buffer that allows some brief operation in parallel for testing and adjustments without undue notifications issued.

IV. Number of Starts

One of the most damaging periods a motor experiences is the starting cycle. The motor is subjected to electrical, mechanical, and magnetic stress that, in most cases, exceeds what the motor experiences during operation. In order to get the initial rotation of the shaft, current is applied to the stator and a magnetic field is generated, propelling the rotor and output shaft.

A. Winding Stress

The inrush of starting current puts stress on the windings and causes mechanical movement that damages the insulation of the windings over time. This insulation is critical to the operation of an electric motor. In addition to the surge of current, the temperature of the motor when started can contribute to the electrical stress on the windings. Limiting the number of starts in a period of time has been a rule of thumb for protection engineers for many years. Modern digital protective relays have advanced calculations to monitor the actual heating of the motor and protect against thermal damage. This is discussed further in Section IX.

B. Magnetic Coupling

Electrical energy is transformed into mechanical energy through a magnetic field. The motor stator generates the field linking the stationary stator to the rotating rotor. This magnetic field is proportional to the current passing through the stator. Subjecting the stator to excessive starts can, over time, diminish its ability to generate the magnetic field and produce torque in the motor. Monitoring the starting characteristics, as discussed in Section X, can result in a motor with reduced starting torque.

C. Mechanical Stress

When the motor is started, the rotor is accelerated from a standstill to full rotational speed in seconds. The motor bearings experience significant loading, both axial and thrust. Motor bearings are the highest failure mechanism in electric motors [1]. Most process industries pay considerable attention to the condition monitoring of bearings. Operators have recognized significant savings by optimizing the life of bearings in rotating equipment. This same focus on bearings can be extended to overall motor condition monitoring by analyzing the data in the electrical protective relay.

Minimizing the number of starts can help extend the life of the motor. Monitoring and controlling the starting conditions can also significantly improve the motor life. Improper motor start conditions include starting an overheated motor, a motor that is still spinning (both forward and reverse rotation can damage a motor), a motor with a locked rotor, a motor under low-voltage conditions, or a motor without proper lubrication. These are just a few of the most common ways to damage a motor that can be detected and avoided using digital relays working in conjunction with a control system.

V. Time to Start

The amount of time it takes a motor to reach operating speed can be an excellent indicator of the condition of the process. Extended start periods (periods that exceed the normal or average start time) provide a window into the process. For example, large fans are a common high-inertia load that can push a motor to its start limits. The system design puts the start current curve very close to the motor damage curve many times. Changes in either the process or the motor power supply can push the start process into the protection region and prevent the motor from completing the start cycle, leaving the entire process stopped. Monitoring the current voltage or slip, as shown in Fig. 2, indicates when the motor has transitioned from start to run.

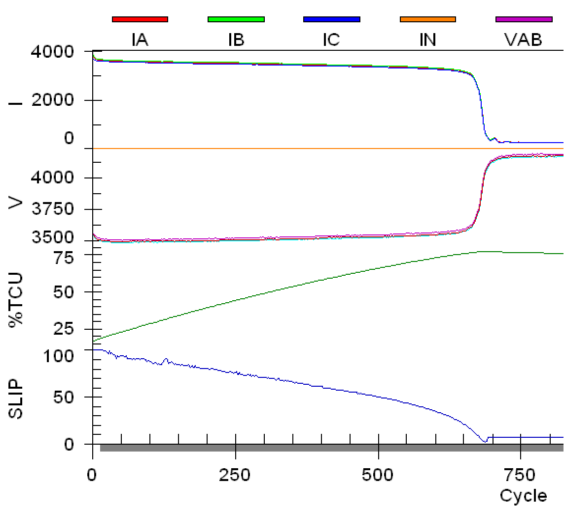

Fig. 2. Measuring motor start time from the start report.

A. Motor Condition Change

Low starting voltage can significantly reduce the amount of torque the motor can deliver to the load. If sufficient torque is not developed by the motor, it fails to reach operating speed and stalls. Winding failures can occur within the winding itself, resulting in one phase with a different number of turns. The failure can be a winding-to-winding fault or a catastrophic open circuit. This unbalance can be seen in the current signature. All motors have some level of unbalance. If this level suddenly changes, it is an indication of a turn-to-turn winding failure. Exercise caution when evaluating the current unbalance in a motor. When operating at no-load or very low-load conditions, the current unbalance can swing dramatically. Always evaluate current unbalance when the motor is operating above 50 percent loading.

Comparing motor parameters during common operational conditions can also indicate changes in motor condition. If the motor current is higher than has been experienced for the same operating conditions, this could be an indicator of a motor problem. It could also be an indication that something has changed in the process and needs further investigation (see the next subsection for examples).

B. Process Condition Change

Many times, changes in the process can be first detected by monitoring the motor information. Monitoring the motor parameters during a normal operating condition provides a baseline from which to evaluate the system for process changes during later comparisons. Process instrumentation, such as flow rate, temperature, valve and damper position, and material consistency, can all be logged for normal operation and a simple matrix used to crosscheck the validity of any one feedback parameter. Motor parameters such as current and horsepower read from the protective relay can play an important part of this validation and testing system. Most of the anticipated variations can be predicted with basic process analysis. The power of this type of evaluation system lies in its ability to find problems before they elevate to a failure level. Feedback systems can be recalibrated, positioners can be maintained before failure, and maintenance activities that require a process shutdown can be scheduled for the next available outage.

C. Safe Stall Times

As noted in Section V, Subsection A, the failure of a motor to develop sufficient starting torque results in a stalled motor. The motor experiences high currents during high-load situations, including a stall scenario. This high current through the motor can cause serious damage or failure of the motor. The motor design is based on the amount of heat a motor can withstand before damage occurs. The heat is generated by a combination of motor current, resistance, and the length of time the motor has been subjected to the current. Also, it is important to note that the time needed to damage a motor is also dependent on the heat already in the motor before the overload condition is applied. In his book *AC Motor Protection*, Stanley E. Zocholl details the mathematics for a model that closely matches the heat and damage curves experienced by motors [2]. A heat memory is important for accurately protecting the motor and for optimizing the available horsepower from the motor without damage. Measuring and tracking the thermal capacity used in a motor provides optimized protection, but it can also be used for diagnostic evaluations of the process, as discussed in

Section IX.

Many high-inertia loading applications, such as large fans, refiners, crushers, and pulverizers, have starting load curves that nearly reach the damage curve of the motor. In these applications, it is critically important that all motor parameters be monitored and correctly evaluated. Modern digital protective relays are able to provide much more precise measurement and protection than electromechanical devices. The safe stall time of a motor is dependent on the heat generated during starting. The heat is derived by multiplying the current and the resistance. A dynamic resistance, which is calculated by advanced protective relays, also accounts for the changing resistance experienced by a motor rotor as its rotational speed or slip changes. This variation in a standard ac induction motor rotor resistance can be a factor of four or more. If this slip-based resistance is unaccounted for in the heat calculation, overestimating the heat results in premature tripping of the motor protection. In high-inertia applications, this error is unacceptable. Accurate heat calculation is imperative in optimizing the available safe horsepower of the motor.

VI. Starting Current

The current inrush of an ac induction motor is typically 6 to 10 times the normal rated current of the motor. This inrush is based on the ability of the system to supply current, as well as the motor design itself. Most electrical systems are designed to supply sufficient current to the load. If problems in supply are an issue, then a serious redesign of the system, including the motor starting characteristics, is needed. This is discussed further in Section VIII.

A. Current Amplitude

The current amplitude provides a good source of repeatable motor information. Assuming the process variations driven by a motor are relatively constant, the motor itself provides relatively consistent operating characteristics. The motor starting current amplitude is repeatable and consistent for the useful life of the motor. When variations of the motor current amplitude are observed, we recommend investigation. Motor current variation can be a result of motor problems (see Section V, Subsection A) or process changes. By monitoring the normal or average peak current, triggers can be established to alert operators of potential problems. Motors experiencing a higher than normal start current can indicate issues such as pump mechanical issues, process consistency variations, valve position problems, or process pipe blockage. Motors experiencing lower than normal current can indicate problems with couplings, pump shaft or impeller damage, or lack of pumping material. Current feedback is perhaps the most commonly used motor information. Monitoring and tracking variations in the starting current can provide valuable process information, even when the motor successfully starts.

B. Current Balance

Current unbalance during motor operation is the most significant contributor to motor overheating. The heating from negative-sequence current as a result of unbalance contributes typically 3 to 5 times more impact than the positive phase current. Current unbalance is, of course, integral to the voltage supply. Unbalance in voltage, even in a healthy motor, results in current unbalance, creating negative-sequence current. Voltage unbalance can cause current unbalance 6 to 10 times the magnitude of the voltage unbalance. Although this is not accounted for in many electromechanical protective relays, modern digital relays can accurately account for this extra source of motor heating. This measurement can also be a good predictive indicator that the motor or electrical feed systems are not functioning properly.

Some variation is to be expected, but when the levels are in excess of 15 percent, we recommend investigation. The instantaneous value of the current balance can be filtered to minimize false alarms. Typically, this unbalance alarm is averaged over a fixed period of seconds to provide a more indicative measurement.

C. Motor Design Influence

Motor operating characteristics can be affected by the motor design. Fig. 3 shows standard design variations from the National Electrical Manufacturers Association (NEMA). Motor torque can be optimized or inrush current minimized through the mechanical and electrical design of the motor. Typical design characteristics are available from the manufacturer and are indicated on the nameplate. Misapplication of a motor design can cause serious process performance problems. A motor designed for high starting torque may not be suitable for an application requiring low inrush current. Make sure the motor design matches the process application needs.

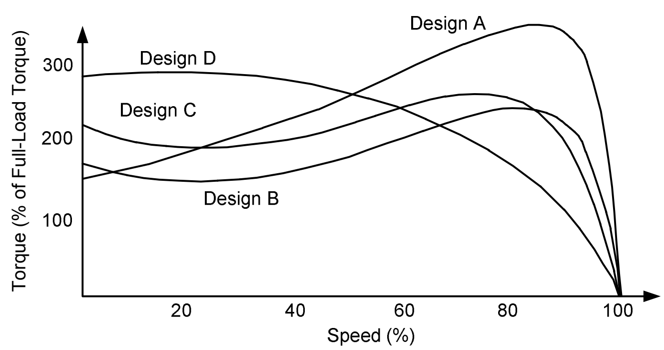

Fig. 3. NEMA motor speed torque curves.

Also, when changing a motor, verify that the design of the replacement matches the design of the original motor. Many hours have been spent troubleshooting why a motor does not start after an outage only to find the design characteristics of a replacement motor did not match the original.

VII. Current Signature Analysis

One of the advantages of a modern digital protective relay is the extensive computing power available. One of the capabilities of the digital relay is the transformation of a signal from the normal time domain to the frequency domain. Basically, this allows a signal to be analyzed with respect to its frequency content. In the case of motor current signature analysis, variations in frequency centered on specific points are strong indicators of motor problems. This transformation is typically accomplished using a Fourier transform function.

A. *Fourier Transform Function*

The Fourier transform function is based on the premise that all signals are composed of a set of sine waves. By breaking any signal into its series of sine waves, the contribution from each sine wave can be evaluated.

B. *Frequency Domain Analysis*

The analysis of the current signal in the frequency domain results in some commonsense graphical representations. The sine wave with the most influence on a typical ac motor operating in the United States is centered around 60 Hz. This is the expected result based on the motor power source being transmitted at 60 Hz. The interesting and profitable information is derived from the signals not at the 60 Hz interval. As described in [3], analysis of the current signature reveals broken rotor bars contributing to the current signature at fixed frequencies, as shown in Fig. 4. When one or more bars break, upper and lower sidebands appear at $(1 \pm 2s)f_o$, where s is the motor slip frequency and f_o is the system frequency.

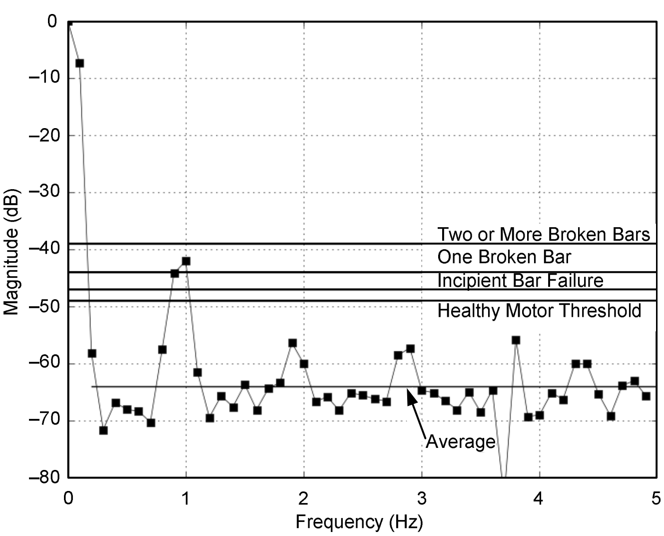

Fig. 4. Frequency domain graph of a motor with broken rotor bar.

This evaluation of the current signature has also been shown to be a reliable predictor for problems including pump cavitations, motor rotor eccentricity, bearing problems, and even belt misalignment. This type of signal analysis is the basis for many predictive maintenance programs evaluating the rotating equipment condition by monitoring the signal emitted by the bearings.

The advantages of performing this analysis in the protective relay include the available processing power, existing access to the current signal, continuous availability, and operator alarming capability. Predictive maintenance technology is just beginning to emerge as a key attribute in the protection and monitoring of an ac motor.

VIII. Starting Voltage

The voltage measurement of an ac induction motor is a strong indicator of the ability of the power system to deliver energy to the motor, often referred to as electrical stiffness. Significant drops in the applied voltage have a direct impact on the ability of the motor to deliver torque.

A. *Voltage Amplitude*

The voltage available to start and run an ac induction motor is supplied by the electrical distribution system. This system is dependent on many pieces of power supply equipment, such as transformers, breakers, and generators. Drops in supply voltage can occur because of an overloaded system, improperly set transformer ratios, long distribution lines, and multiple simultaneous motor starts. Monitoring the normal minimum starting voltage and comparing it with the actual start voltage can indicate changes or defects in the system. System voltage can be monitored continuously and alarms can be sent even without the motor operating.

Reduced starting voltage has an effect on both the torque delivered and the start time, as shown in Fig. 5 and Fig. 6.

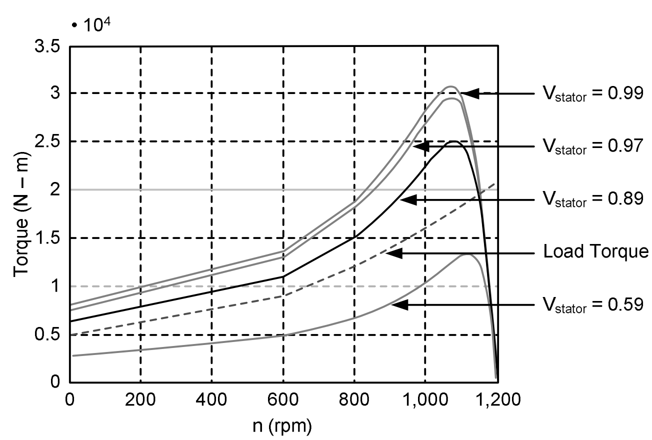

Fig. 5. Variations in torque with reduced voltage applied.

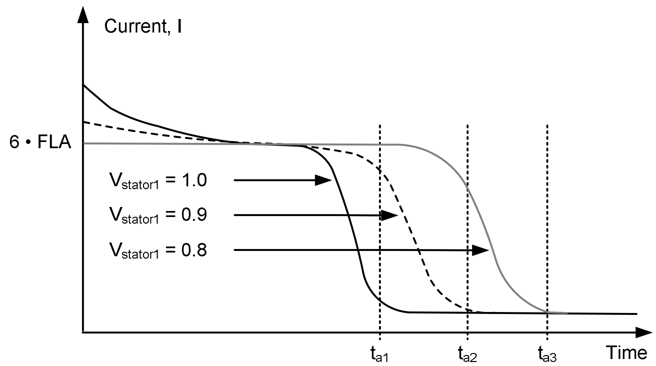

Fig. 6. Variations in start time with reduced voltage applied.

B. *Voltage Balance*

Balanced three-phase voltage is essential to the proper operation of an ac motor. ANSI C84.1, ANSI Standard for Electric Power Systems and Equipment, recommends power system operation with a maximum voltage unbalance of 3 percent. Voltage drop during starting should be even across all phases and should drop and recover together. Voltage unbalance results in extra heat generated in the motor. The temperature rise is about twice the square of the percent voltage unbalance [4].

Fig. 7 shows a motor start report with a voltage unbalance.

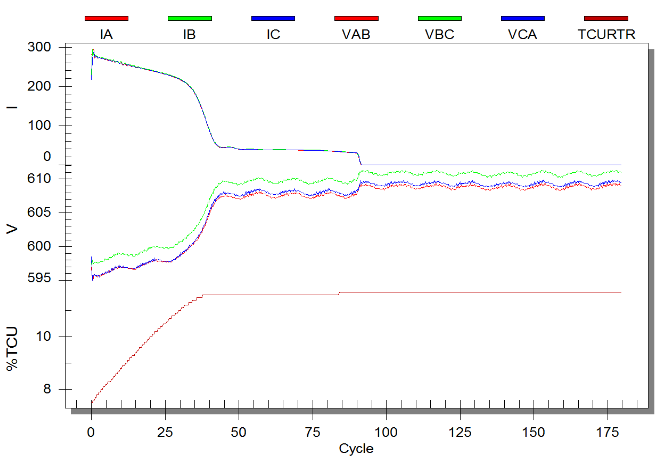

Fig. 7. Event report showing voltage phase unbalance.

Excessive voltage drop results in reduced motor starting torque. Voltage monitoring is typically also used to ensure that all three phases are present before starting, protecting the motor from single-phase operation and damage.

IX. Thermal Capacity Used

AC induction motors are rated for use based on the amount of horsepower they can deliver to the load. Electromechanical protective relays use the same overcurrent protection techniques developed to protect conductors for motor protection. The concept is to evaluate the amount of overcurrent passing through the motor and limit the amount of time based on the magnitude of the overcurrent. Higher amounts of overcurrent result in a shorter time to trip. This protection is typically referred to as I^2t protection, accordingly. Two problems result from this approach. First, it assumes that the resistance side of the heat equation is constant, which, as has been demonstrated, is not correct during the start cycle of the motor. Second, designers of ac motors rate the motor on its ability to operate at specified temperatures. If that temperature is exceeded, then damage to the motor results. These design points are specified on the motor nameplate with parameters such as insulation class and service factor. Because the temperature is dependent not only on the overcurrent the motor may experience but also on the temperature of the motor before the overload occurs, the I^2t model does not make the best motor protection device. Resistance temperature devices (RTDs) were added to the protection to help compensate for the ambient and preoverload motor temperature, improving the model but still falling short of correctly matching the damage curve of the motor.

Modern digital protective relays include the processing and memory not only to track the motor parameters and heating, but to use the preoverload conditions to properly predict and protect the motor from crossing the damage curve. Tracking the amount of heat in a motor compared with the maximum allowed heat is referred to as the thermal capacity used (TCU). TCU is a much more accurate model of the heat in a motor. TCU is graphed with other motor parameters, as shown in Fig. 8. Matched with an appropriate motor thermal model, the motor can be properly protected while maximizing the available horsepower.

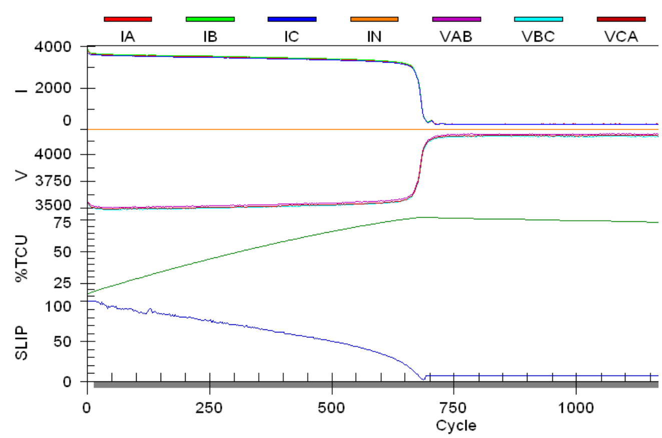

Fig. 8. Motor start report, including TCU.

A. *Thermal Model*

Accurate motor protection using a thermal model for heat buildup can increase allowable motor start times, which is important in high-inertia load applications, and provide better tracking, avoiding false trips during cyclic loading. When optimizing the process operating times, it is important to minimize unscheduled downtime. Incorrect motor protection trips can be a major impact on process efficiency. Appropriate motor protection can protect the motor, have a positive influence on operation, and provide a valuable control variable that can be used for process optimization.

B. Application of TCU

Applying the TCU variable to process control provides a great way to increase throughput without risking process interruptions from motor protection trips. Many process control schemes seek to optimize the process by monitoring the load on the motor. Typically, this has been accomplished using the motor amperes as a control feedback. The variation, noise, and proper application of amperes make the motor amperes a challenging process control variable. Additionally, separating the process control calculation from the protection scheme does not allow the process control to know exactly how close the motor is to tripping. TCU is a composite signal made up of many motor parameters, including amperes, current unbalance, service factor, motor heating time constant, and other parameters.

1) Process Control:

Because TCU is a composite signal, no additional filtering is needed. The summation of heat sources is scaled to the maximum heat allowed and presented as a percent of the maximum. As a process control feedback, it provides important motor information and critical protection information as well. Using the feedback TCU on a motor allows the process flow to increase until the TCU set point is reached. The TCU set point is assigned based on the response of the process control to tuning. The closer the TCU set point is to 100 percent, the smaller the margin is for control error. Setting the TCU set point too low operates the process at less than optimal throughput.

As an example, consider the control system for a simple conveyor belt feeding a crusher. Throughput is typically limited by the heating of the motor driving the crusher. Monitoring the motor amperes presents a noisy signal with varying spikes of current as each chunk is crushed. Additionally, without recording the previous motor heating, the process control is unaware of the protection trip point. By implementing the feedback TCU, the control system is aware of the heat in the motor and the proximity of the current operating condition to the maximum.

In our example, as a large chunk moves into the crusher, the motor current spikes momentarily and then drops down. The TCU variable accurately tracks the exact heat going into the motor and provides feedback on heat as a percent of the trip level. This signal provides proper filtering of the amperes through the thermal model of the motor and accounts for previous heating, heating time constant, and cooling time constant. Additional process control value can be gained by the direction and rate of change of TCU. Using TCU as a speed signal to the feed conveyor can optimize the throughput of the system by operating the crusher at its safe load maximum. When the crusher TCU is above the set point, the feed conveyor slows down. When the crusher TCU is below the set point, the conveyor can speed up. The system is thus optimized, and a safe set point is selected below the trip point of 100 percent TCU.

2) Controlling Cyclic Loads:

Many processes contain loading that is not smooth or constant. For electromechanical motor protection, this cyclic loading poses a particular problem. Based on the protection using the I^2t model, the relay overcompensates for short-term overloads and fails to accurately track the heat in the motor (see Fig. 9). The result is the I^2t relay prematurely trips the motor protection, causing unneeded process downtime.

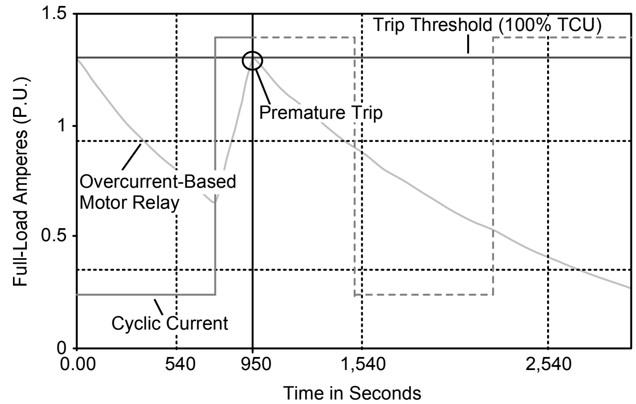

Fig. 9. Overcurrent-based relay false trip.

A digital relay with a properly executed thermal model accounts for the heating from cyclic loading and only trips when the maximum heat level is reached (see Fig. 10).

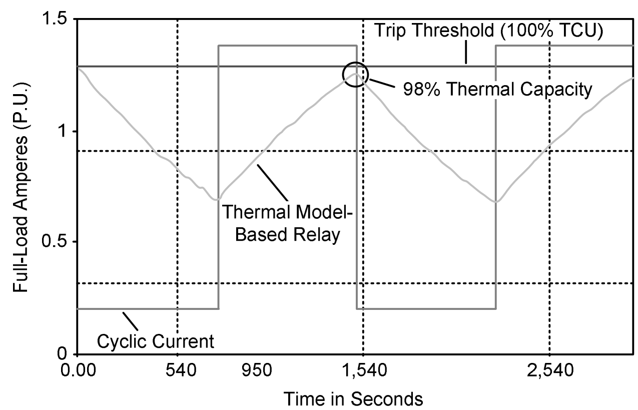

Fig. 10. Thermal model-based relay showing proper operation.

Selecting information from a properly configured motor protection relay can provide more high-quality data than simply monitoring current alone.

X. PATTERNS AND TRENDS

Every application of a motor protection and control scheme is unique in some manner. The challenge for engineers is to be able to account for the variations in motors and processes and still make the best use of the information provided. This presents the challenge of recognizing motor or process problems without absolute settings. There are several ways to recognize possible problems by monitoring the information available in the protective relay.

A. Normal Start Patterns

Modern relays monitor and store important information about the operation of the motor. Each time a motor is started, the protective relay stores all the relay data collected during the start. Because the relay stores information from every start, trending information is also stored in the relay and is available for use from the maintenance or control system.

B. Deviation From Normal Start Patterns

The starting patterns for most ac motors are very repeatable. Knowing this repeatable pattern provides information for diagnosing problems or, better yet, for predicting problems before they cause downtime. For example, if a motor typically takes 6 seconds to start, when it exhibits start times significantly longer or shorter, the motor is providing a hint as to changes in the system. Deviations of 20 percent or more are worth investigating. One of the great values of monitoring the start times is that the information is important and actionable even though the motor started and appears to be running correctly.

Fig. 11 shows a motor summary report with historical data that can be used to set normal deviation limits. Many systems monitor that a motor started when the command was issued, but there is more information available in the relay for those interested in optimizing the system.

```
Unit 3 FD FAN 2
3-532-CB-B10

Record  Began      Number    Start  Start  Max      Min
Number  on         of        Time   %TCU   Start I  Start
V       Date       Starts    (s)           (A)      (V)
1      07/20/2009    0       ---    ---    ---      ---
2      06/20/2009    2       12.8   81     1980     3884
3      05/21/2009   21       12.7   81     1975     3861
4      04/21/2009   20       13.0   82     1980     3864
```

Fig. 11. Motor start trend report.

C. Trending

Trending the parameters of the motor over the normal range of operation can also provide insight to potential problems or issues with the process or other control equipment. Matching the trended phase current with known flow rates can indicate line blockage or pump suction issues.

Modern distributed control systems (DCSs) have the ability to compare many variables. Matching flow rates with valve position, temperature, and viscosity to motor load provides a cross-comparison on each feedback loop. Calibration checks and adjustments can be triggered from these types of crosschecks in process equipment control and feedback loops.

XI. Predictive Analysis

Information from the protective relay can also provide a predictive tool for operator information or to implement an automatic control strategy. Because the information is constantly supplied, advanced evaluation techniques, such as rate of change, can easily be implemented. These advanced techniques can be used to predict the behavior of the system and take actions before a failure occurs.

A. Time to Trip

One forecasting variable built into the protective relay is the estimated time to trip. Because the relay knows the TCU, current contribution to heating, and rate of change of the thermal capacity, the relay can accurately predict the time until a trip occurs. Knowing the predicted trip time allows the operator to make changes needed to avoid a trip and outage. This functionality can also be programmed into the DCS for automatic process adjustments based on time-to-trip warnings. The time-to-trip forecast is constantly updated and accurately reflects the changes as they relate to motor overload.

B. Process Changes

Monitoring TCU for rapid (faster than normal) changes can also be used for predictive control. When the DCS tracks a rapid rate of change of TCU, warnings can be issued even before an alarm level and time-to-trip indication is triggered from the relay. Process changes made by the operator can be correlated and system warnings or set point boundaries established using motor trending information in conjunction with a strong DCS monitoring plan.

XII. Event Analysis

In addition to monitoring and recording every motor start, protective relays also record all data based on an event trigger. This trigger is typically tied to a motor trip condition, but simple programming allows event reports to be triggered for any input change to the relay. For example, the relay can be set to capture a full event report each time an adjacent motor is started or each time a valve is opened or closed. The trigger in the relay can be a level measured by the relay, such as a voltage drop, or an input to the relay I/O from a limit switch.

A. Sequence of Events

The protective relay maintains a time-stamped sequence of events (SOE). This sequence clearly shows the order and timing of each event associated with the relay. Time stamps for these events are maintained at 4 milliseconds or faster. When troubleshooting process issues, this fast detection and recording system provides much finer time resolution than typical DCS reports do (see the SOE report in Fig. 12).

```
=>>SER 5 <Enter>
MOTOR RELAY

#     DATE          TIME         ELEMENT    STATE
5   11/16/2005  04:24:05.785   RUNNING    Asserted
4   11/16/2005  04:24:07.497   50P1T      Asserted
3   11/16/2005  04:24:09.486   50P1T      Deasserted
2   11/16/2005  04:24:09.807   RUNNING    Deasserted
1   11/16/2005  04:24:09.807   STOPPED    Asserted
```

Fig. 12. SOE report.

B. Oscillography

Event reports include a full oscillography for the voltages and currents the relay is monitoring both before and after the event trigger. It includes all the internal monitoring variables and the pickup levels of the protection elements. All this information is provided in a time-stamped report available for review or download to a separate database (see Fig. 13).

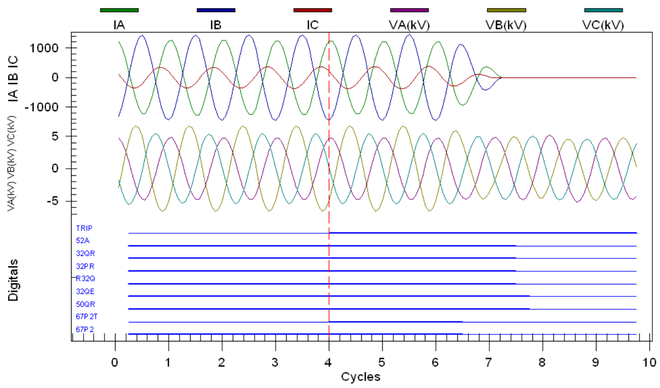

Fig. 13. Oscillographic event report.

C. Almost-Tripped Events

Because event reports are so valuable and easy to trigger, the concept of triggering an event based on a trip can be expanded to include issues that almost tripped. In most cases, trip commands from the relay include some delay to allow for coordination, noisy signals, and security. This information can be used to indicate conditions that triggered a pickup of the protection element, but because the time delay did not time out, no trip was issued. This almost-tripped event can have great value when planning to avoid future issues. The issuance of an almost-tripped event should compel the engineer to dig into the cause and possible avoidance of the situation causing the event. This action can include reviewing the relay settings or reviewing the process or electrical system for changes that were not accounted for in the power system study. A common example is the addition of load to a feeder without coordinating the changes with other equipment on the feeder or adjacent feeders.

Look at almost-tripped events as a warning: this time the motor kept running, but next time it may not.

XIII. Real-Time Operator Information

Modern protective relays include multiple communications alternatives to get information out of the relay and into the hands of the operators in real time.

A. Direct Display on Distributed Control

Motor load, horsepower, TCU, and status can all be easily transferred from the relay to the DCS. Operators can take advantage of key process information as seen through the protective relays in real time. A typical DCS screen showing motor information is shown in Fig. 14.

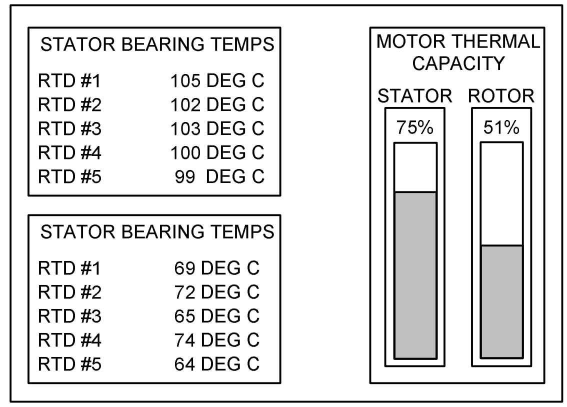

Fig. 14. DCS screen view of real-time motor data.

Relay trends and predictive warnings, such as time to trip and almost tripped, can be sent to the operator and logged for maintenance. Knowing that a motor tripped is important, but knowing that a motor may trip if changes are not made in a set time frame can prevent the trip and save valuable process continuity.

B. Maintenance Notification

Communication and automation in protective relays allow the relay to send an alarm to a maintenance system or maintenance planner. These notifications can be triggered from run-time limits, number of starts, changes in trends, alarms, or almost any combination of the information in the relay. Broken rotor bar detection is a good example of information that is important to the maintenance planner. Although knowing a potential issue with the motor rotor bars may keep operators from stopping the motor, there is little they can do to remedy the defect. From a maintenance perspective, scheduling testing and/or replacement during the next available outage can save thousands of dollars in both maintenance costs and process losses. Communications protocols and connections are specifically designed in the protective relay separate from the protection functions. Adding communications links to a protective relay will not compromise the speed or security of the protection.

XIV. Conclusion

Protective relays can provide important operational data that can be used to save time, money, and lost production. Because protective relays are vital to the safe operation of equipment and are a key part of a system, extracting information from a relay is almost cost-free. A big part of taking advantage of this low-cost information is knowing and understanding what data are available and how to effectively use these data. As protective relays continue to evolve, more reliability-based information will be available for use to the process control and operation engineers. The limits of how to use the data to improve the process and save costs are expanding with each innovative application implemented. This information is available in protective relays today at little or no cost.

XV. References

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XVI. Biography

Mark Zeller received his BS from the University of Idaho in 1985. He has broad experience in industrial power system maintenance, operations, and protection. He worked over 15 years in the paper industry, working in engineering and maintenance with responsibility for power system protection and engineering. Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2003, he was employed by Fluor to provide engineering and consulting services. Since joining SEL, Mark has held positions in research and development, marketing, business development, and sales and customer service. Mark has authored numerous technical papers and has patents pending through SEL. He has been a member of IEEE since 1985.

Previously presented at the 2014 IEEE Rural Electric Power Conference, Fort Worth, TX, May 2014.

20131205 • TP6593