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Experiences in a Motor Protection Retrofit

Introduction

The initial stage of any project is often the business case development. This article outlines the business case for the motor protection retrofit at a large thermal generation plant. The key protection improvements for this installation are reviewed including the advantages of the thermal model and the application of the slip-dependent thermal model.

Background and Issues

Maintenance Schedule and Spare Parts

The existing electromechanical thermal-replica motor protection and interposing relays are well beyond their service life, obsolete from a manufacturing perspective, and have limited spare parts. The plant requirement for maintenance on this existing equipment is to calibrate and complete functional tests every five years. Historically, the calibration on a single thermal-replica motor protection and interposing relay scheme takes a full day. There are a total of 90 motor protection schemes within the facility.

Digital relays are self-checking and do not require the same extent of calibration and functional testing. Digital relays are capable of recording and storing event reports, sequential event report data, motor start reports, motor start trending, and motor operating statistics, as well as alarming for self-diagnosed failures. Digital relays are continuously self-testing and reporting operating status. Only functional testing is required after the original in-service commissioning is complete. This functional testing takes less than 30 minutes. The cycle for the digital relay functional testing corresponds to the current Northeast Power Coordinating Council requirements for digital relay reverification.

Silver Migration

The existing auxiliary relay cases in the motor protection panels have proven to be susceptible to silver migration. Silver migration is the ionic movement of silver between two potentials. The moisture present in the humid air of the thermal plant acts as an electrolyte. The silver transfers from the contacts of an auxiliary relay onto the terminals of its mounting case. When the silver migrates so that two terminals are bridged, protection failures can occur. The plant has recorded several false trips during the past few years.

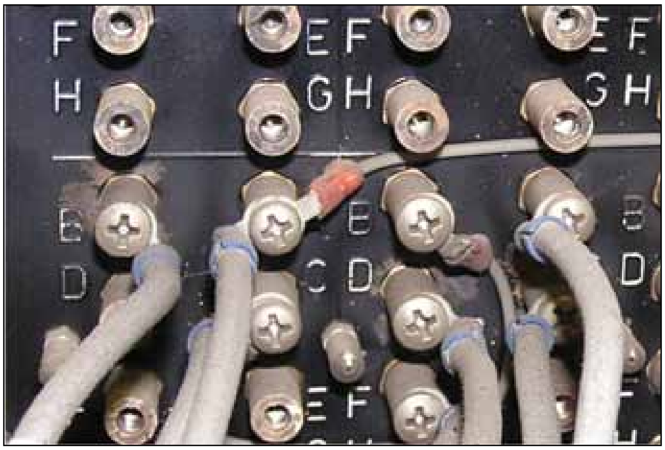


Figure 1 — Auxiliary Relay Case Showing Silver Migration

The new digital relays have internal timers, internal latches, digital inputs, and enough output contacts so that the auxiliary relays and auxiliary relay cases are no longer required.

Digital Recording and Data

The plant currently has no digital fault recording equipment on the 4 kV motors or 4 kV bus. The new digital relays sample and store analog and digital data. This provides the operating data required to quickly determine what caused a trip without completing all the detailed tests that were required previously to troubleshoot any motor protection trips. Following a motor protection trip from existing electromechanical protection, it was a requirement to functional test the protection. With the stored digital data from the new digital relays, this is no longer a requirement. The new digital relays also provide motor operating statistics and motor trend reports. These files can be used to provide an early warning regarding changes in motor start current, thermal capacity used during starting, and motor start time. As an example, these types of detailed data can indicate gradually increasing load torque, which could lead to an unwanted motor trip. Analyzing these types of data can assist with planning motor maintenance schedules and help to avoid unplanned downtime.

Thermal Model and Motor Cooling

The existing motor protection relies on operators and operating procedures to determine the correct time between starts and prevent damage to motors caused by frequent multiple motor starts. The new digital relays provide a lockout feature to prevent motor starting until the thermal element calculates that there is enough available thermal capacity to allow a start without tripping. The protection engineer sets the rotor and stator thermal capacity used during starting, and the relay provides a lockout until the motor has cooled to the defined capacity.

High-Inertia Loads

The standby boiler feed pump (SBFP) and the forced draft (FD) fan motors each have starting times considerably longer than their safe stall times. The existing electromechanical thermal-replica protection relays have been desensitized to accommodate the long starting times. The plant had used speed switches in the past, but over time the speed switches proved to be too unreliable and were retired. The probability of a motor stall is low, but the consequence of a failure is higher. The failure of an FD fan motor would cause a forced derating to half load until the motor was repaired. Repair for this 2,300 hp motor could take one week to three months, depending on the severity of the motor damage. If both SBFP motors are unavailable, the generator will be on forced outage until the motor is repaired or a spare unit is made available. Repair or replacement of this 5,500 hp motor could take from one week to three months.

Alternatives and Economic Analysis

The base case considered for this business case is status quo. This plan could lead to the failure of a critical motor that could leave a main unit unavailable or derated for one day to three months, depending on the severity of the failure.

This option will still cost $104,000 (Canadian) over the next five years while the auxiliary relay cases are replaced per an existing program. Because it is not practical or possible to replace all the auxiliary cases at once, nuisance motor tripping may be an issue because of the silver migration. All costs associated with this alternative are avoided by upgrading all of the 4 kV motor protection schemes.

Alternative 1: Upgrade 4 kV Motor Protection on Critical Motors Only

This option addresses the spare parts availability, system reliability problems, and the silver migration issue on half of the motor protection schemes. The auxiliary relay cases on the motor protection schemes that are not changed will still have to be replaced as scheduled. As the original 35-year-old motor protection schemes left on the noncritical motors age, more failures will occur. Although these failures will not affect the availability of a generator unit, motor protection failures could cause costly motor damage and will eventually require upgrading the relays.

Alternative 2: Delay Work One Year

Delaying the project will not immediately address the spare parts availability and system reliability. The frequency of motor protection calibration and troubleshooting to verify proper operation will only increase as the equipment continues to age. Similar to the base case, delaying the project will increase the probability of a forced outage or equipment damage.

Alternative 3: Upgrade 4 kV Motor Protection

The recommended and accepted proposal is to replace all existing 4 kV motor protection relays and the auxiliary relay cases with new digital relays that meet the motor protection requirements.

The new protective relays provide the following:

- Protection for motors with start times longer than their safe stall time.
- Thermal lockout for multiple start protection.
- Improved protection for motors previously protected with 51 elements.
- Data acquisition and troubleshooting using the digital data stored in the relay.

The photos in Fig. 2 show the installation of the digital relays. Installation costs were kept to a minimum by taking advantage of existing wiring. The photos show that generally only internal panel wiring required modification.

Figure 2 — Motor Protection Retrofit

Motor Starting and Calculating Motor Slip

Most digital motor protection relays calculate the heating in the motor by measuring the current. The relay calculates the heating in terms of thermal capacity. The thermal capacity is defined where zero percent is completely cooled and 100 percent is the limit threshold. The thermal capacity is accumulated based on measured current so that during motor starting, the protection is essentially an I^2t element, with the maximum starting time limited by the hot motor safe stall time. Problems arise when starting motors with high-inertia loads, as the time required to start the motor may approach or even exceed the hot safe stall time [1].

The relay used for this retrofit uses a thermal model that calculates motor slip during start. During the start of an induction motor, the rotor resistance changes from a high locked rotor value to a low running value. This motor protection relay uses voltage and current to calculate the slip-dependent rotor resistance that enables the calculation of rotor temperature while it varies during a motor start. The details of this thermal model can be reviewed in [2].

In summary, four quantities are required by the slip-dependent thermal model in order to calculate the locked rotor resistance and rotor resistance at rated speed. These four quantities are the locked rotor torque (LRQ), the locked rotor current in per unit (I_L), the full-load speed (FLω), and the synchronous speed (Synω).

The locked rotor resistance R_M is calculated directly from LRQ in per unit of rated torque and the locked rotor current in per-unit current.

Locked Rotor Resistance

$$R_M = \frac{LRQ}{I_L^2} \tag{1}$$

The rotor resistance at rated speed R_N is calculated directly from FLω and Synω. The rotor resistance at rated speed is the motor full-load slip (FLS).

Rotor Resistance at Rated Speed

$$R_N = 1 - \frac{FL\omega}{Syn\omega} \tag{2}$$

At the instant of motor starting, the relay calculates the motor resistance by sampling the positive-sequence voltage $V_1(cyc)$ and the positive-sequence current $I_1(cyc)$ at a selected initial cycle. The real part of this impedance is the initial motor resistance R_P.

Initial Motor Resistance

$$R_P = \mathrm{real}\left(\frac{V_1(cyc)}{I_1(cyc)}\right) \tag{3}$$

Now, with a sampled value for R_P and the locked rotor resistance R_M, the stator resistance can be calculated, where A = 1.2, a constant shown in [2].

Stator Resistance

$$R_S = R_P - \frac{R_M}{A} \tag{4}$$

he slip, shown in (6), is a function of the changing motor input resistance, shown in (5), the previously calculated locked rotor resistance R_M, the rotor resistance at rated speed R_N, and the stator resistance R_S. The motor input resistance is measured and updated every processing interval. The motor slip is calculated every two cycles.

Motor Resistance

$$R = \mathrm{real}\left(\frac{V_1}{I_1}\right) \tag{5}$$

Motor Slip

$$S = \frac{R_N}{A(R - R_S) - (R_M - R_N)} \tag{6}$$

Positive-Sequence Rotor Resistance

$$R_1 = (R_M - R_N)S + R_N \tag{7}$$

A comparison of the standard I^2t starting element, which assumes a constant rotor resistance, with the slip-dependent starting element shows that the slip-dependent model simply includes the slip-dependent rotor resistance in the heat source of the thermal model [2] [3].

Settings and Testing for 5,500 hp Standby Boiler Feed Pump

The available motor data provided most of the information required to calculate the settings for the digital relay. Full-load amperes (FLA) was set to 685 A. The setting for locked rotor current was increased from 4.82 • FLA to 5.5 • FLA (an increase of roughly 300 A) as suggested by the company that rebarred the rotor to a larger style rotor bar. The stator was not modified. Service factor (SF) was set to 1.05 as per the motor ratings. FLS was calculated as: (FLS = 1 – nr/ns) (FLS = 1 – 3565/3600 = 0.0097). The hot safe stall time was set at 9.0 seconds.

The following settings were applied to the relay:

```
RID       := UNIT 4 SBFP2
TID       := 4-532-CB-A5
CTR1      := 800     FLA1  := 685.0   E2SPEED := N      CTRN    := 100
PTR       := 35.00   VNOM  := 4160    DELTA_Y := WYE    SINGLEV := N
E49MOTOR:= Y         FLS   := 0.0097  LRQ     := 0.96   49RSTP  := 91
SF        := 1.05    LRA1  := 5.5     LRTHOT1 := 9.0    RTC1    := AUTO
```

Fig. 3 is the motor start report for this 5,500 hp SBFP. The traces show the motor current, terminal voltage, rotor temperature in per unit of the trip value or thermal capacity, and slip.

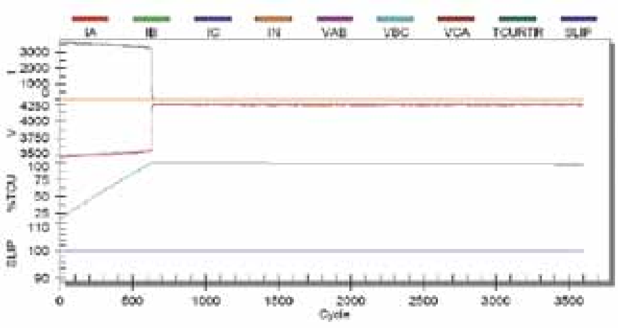


Figure 3 — SBFP Motor Start Report, LRQ = 0.96

Fig. 3 shows that the slip remained at 1.0 for the entire start. Because of the high-inertia load, the motor start time is longer than the hot safe stall time, and the thermal capacity reaches 100 percent. When the calculated slip exceeds 1.0, the relay assigns a slip of 1.0 and calculates the temperature rise using the high locked rotor resistance. Following a review of the motor start data, the motor manufacturer suggested a revised LRQ of 0.7 per unit of rated torque and a hot safe stall time of 6.5 seconds.

The following settings were applied to the relay:

```
RID       := UNIT 4 SBFP2
TID       := 4-532-CB-A5
CTR1      := 800     FLA1  := 685.0   E2SPEED := N      CTRN    := 100
PTR       := 35.00   VNOM  := 4160    DELTA_Y := WYE    SINGLEV := N
E49MOTOR:= Y         FLS   := 0.0097  LRQ     := 0.70   49RSTP  := 91
SF        := 1.05    LRA1  := 5.5     LRTHOT1 := 8.0    RTC1    := AUTO
```

The applied settings used a hot safe stall time that was less conservative than suggested at 8.0 seconds. Fig. 4 is the start report for the revised settings. During the 11-second start, the rotor temperature reaches 75 percent of the maximum allowed temperature. The revised LRQ quantity results in a new stored constant for locked rotor resistance R_M (1) and also results in a revised calculated value for R_S (4). The stator resistance R_S is dependent on R_M and R_P, as per (3). The relay measures and calculates R_S during every start.

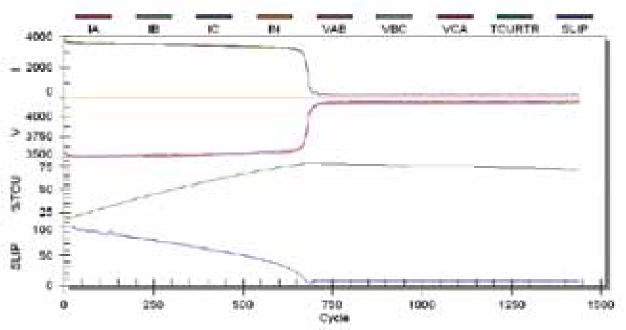


Figure 4 — SBFP Motor Start Report, LRQ = 0.7, Start 1

The motor was started twice more with LRQ at 0.7 and the hot safe stall time at 8.0 seconds. Fig. 5 is a motor start report for Start 3 of the 5,500 hp SBFP with the revised settings. Note that on this repeated start, the traces show the normal motor current and relay terminal voltage. However, in this case, the calculated slip remains at 1.0 for an extended time. The rotor resistance remains at R_M for this time, and the thermal capacity reaches 100 percent.

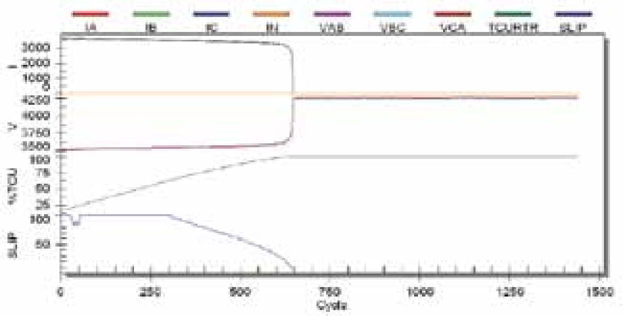


Figure 5 — SBFP Motor Start Report, LRQ = 0.7, Start 3

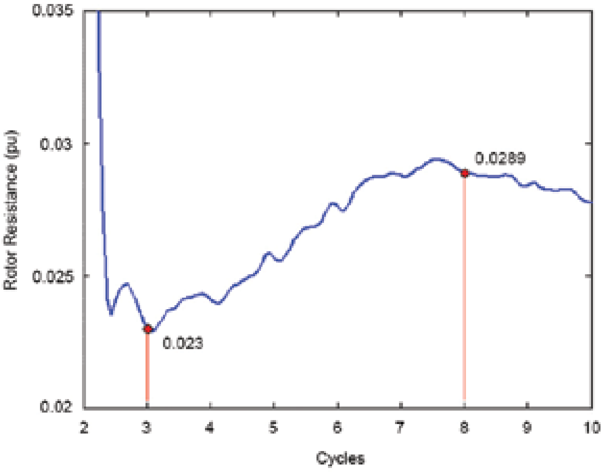


Figure 6 — Varying Starting Resistance During Start 3

A detailed examination of the digital data provided by the relay shows that although the current and voltages are as expected for motor starting, there is a variation in the positive-sequence voltage V_1(cyc) and the positive-sequence current I_1(cyc). Fig. 6 shows a plot of the resulting varying starting resistance over the first eight cycles of the motor start.

During the first few cycles of starting, the rotor resistance is at its initial value R_M, and the slip S is 1.0. Thus, the stator resistance R_S can be determined using the initial measured resistance R_P in (4). The initial cycle at which R_P is measured is not critical when the initial resistance remains constant after a 1- or 2-cycle settling time. This is not the case for this 5,500 hp SBFP, as seen in Fig. 6. To account for this varying starting resistance, the relay software was modified to select the minimum value of R_P over the first few cycles.

Fig. 7 shows a motor start report for this 5,500 hp SBFP with no new settings changes and relay software that is selecting the minimum value of R_P over the first few cycles. The traces show the motor current, relay terminal voltage, rotor temperature in per unit of the trip value or thermal capacity, and slip. This motor start report shows that as the slip decreases, the calculated rotor resistance is decreasing as the motor accelerates. During the 11-second start, the rotor temperature reaches 89.5 percent of the maximum allowed temperature, while the motor takes a full three seconds more than the hot safe stall time of eight seconds to successfully start.

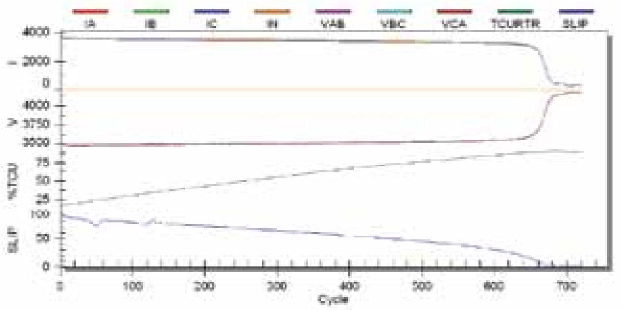
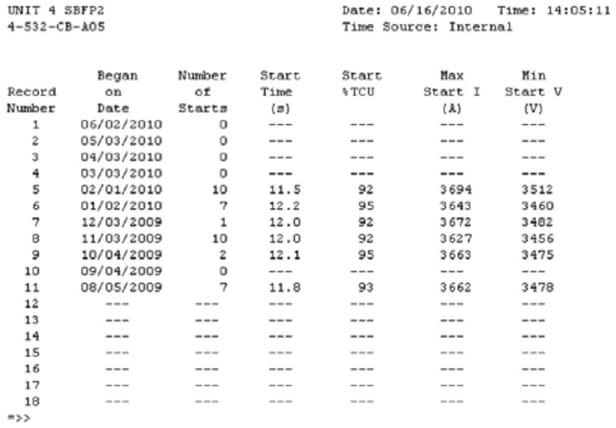


Figure 7 — SBFP Motor Start Report, August 2009

The Unit 4 SBFP motor protection relay has been in service since August 2009. The motor start trend report in Fig. 8 shows consistent start data in terms of average starting time and thermal capacity used for the motor. The starting conditions are clearly very consistent for this Unit 4 SBFP; otherwise, there would have been more variation in the percent thermal capacity. An increase in percent thermal capacity over time could indicate a gradually increasing load torque.



```
UNIT 4 SBFP2                                  Date: 06/16/2010    Time: 14:05:11
4-532-CB-A05                                  Time Source: Internal

              Began     Number     Start      Start       Max        Min
Record          on        of        Time      %TCU      Start I    Start V
Number         Date     Starts      (s)                   (A)        (V)
   1       06/02/2010       0       ---        ---        ---        ---
   2       05/03/2010       0       ---        ---        ---        ---
   3       04/03/2010       0       ---        ---        ---        ---
   4       03/03/2010       0       ---        ---        ---        ---
   5       02/01/2010      10       11.5        92       3694       3512
   6       01/02/2010       7       12.2        95       3643       3460
   7       12/03/2009       1       12.0        92       3672       3482
   8       11/03/2009      10       12.0        92       3627       3456
   9       10/04/2009       2       12.1        95       3663       3475
  10       09/04/2009       0       ---        ---        ---        ---
  11       08/05/2009       7       11.8        93       3662       3478
  12          ---        ---        ---        ---        ---        ---
  13          ---        ---        ---        ---        ---        ---
  14          ---        ---        ---        ---        ---        ---
  15          ---        ---        ---        ---        ---        ---
  16          ---        ---        ---        ---        ---        ---
  17          ---        ---        ---        ---        ---        ---
  18          ---        ---        ---        ---        ---        ---
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Figure 8 — Motor Start Trend Report for Unit 4 SBFP

Conclusions

Motor protection at this plant has been enhanced with the use of digital relays. The slip-dependent thermal model protects the motors while allowing for long acceleration times. The digital relay provides supervision to prevent motor starting until the motor thermal capacity has enough available starting capacity and to prevent damage to motors caused by frequent multiple motor starts. The motor start reports and monthly trend data in the relays can be used to monitor changing starting conditions. The event reports and motor start reports provide data that can be used to enhance the settings and improve the motor protection, as well as confirm a valid protection operation without the need to complete a full protection reverification.

Replacement of the existing 4 kV motor protection relays and the auxiliary relay cases with new digital relays provides the following benefits:

- Ensures reliable protection for the motors.
- Removes the safety hazard associated with a catastrophic failure of a large piece of rotating equipment.
- Reduces the risk associated with equipment failure and silver migration-induced trips.
- Eliminates the maintenance time spent calibrating each relay.
- Removes the need to replace auxiliary relay cases.

References

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