Enhanced Motor Protection With the Slip-Dependent Thermal Model: A Case Study

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Enhanced Motor Protection With the Slip-Dependent Thermal Model: A Case Study

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Abstract—**Protection of induction motors can be enhanced with today's microprocessor-based protective relays and a slip-dependent thermal model. This paper briefly introduces the concept of the thermal model and explains how to apply a slip-dependent thermal model to better protect motors in retrofit applications, where very little data are available. In such cases, assumptions must be made to estimate safe locked-rotor times based on historical motor starting times and electromechanical relay settings. These assumptions are then checked by reviewing motor start report data collected on the initial starts of the motor. Thermal capacity measured during start is used to validate the improved protection and settings may then be revised without the risk of a trip on normal starts. The motor start reports from multiple motors will be presented, along with the protection settings produced in this manner. The paper describes how microprocessor-based protection is successfully provided for all conditions in this application, replacing the thermal overload protection, which had been blocked for two minutes during starting because of the difficulties in starting high-inertia loads.**

I. INTRODUCTION

Many motors in industrial facilities have been in service for thirty or more years with electromechanical protective relays. These relays are nearing the end of their service life and need to be replaced. Modern microprocessor-based relays are the natural choice for these retrofit applications and offer many improvements over electromechanical overcurrent relays, electromechanical or static thermal-replica relays, or thermal overload relays. These enhancements include improved thermal modeling of the motor heating, event reporting, sequential event reporting, motor start reports, motor start trending, motor operating statistics, additional protection features, and additional control functions.

However, information about the thermal capabilities of these motors is practically non-existent, since the original manufacturer's information (thermal limit curves) is often lost. In addition, older motors may have been rewound, rendering the original motor manufacturer's data suspect. Typically, the only information available to set a new microprocessor-based relay for an existing motor is the motor nameplate information, existing electromechanical protective relay settings, and operator experience of typical starting times.

NEMA MG 1 [1] lists the required information the motor manufacturer must provide on the motor nameplate.

The pertinent nameplate information needed to set a microprocessor relay includes:

- Rated-Load Amperes (FLA)
- Locked-Rotor kVA Code Letter or Locked-Rotor Current in Amperes
- Service Factor (SF)
- Time Rating—typically continuous for a medium voltage motor
- RPM at Rated Load (Rated Speed)

The existing thermal overload or electromechanical (EM) relay may or may not provide adequate thermal protection for the motor. However, one can be fairly certain the curve selected on an existing EM relay allows the motor to start without tripping.

The protection engineer calculates the approximate locked-rotor current using the locked-rotor code letter, and uses this current to determine the trip time on the existing curve. For example, if the code letter is "G", then the locked-rotor current is in the range of 5.6–6.29 kVA/hp.[1] Once the motor horsepower and rated voltage are known, the locked-rotor current can be calculated. The trip time for this current is then determined from the existing EM relay time current curve. This time is used as the initial assumption for the motor safe hot locked-rotor time setting (LRTHOT1).

Operators in an industrial facility typically know how long high inertia loads take to accelerate under varying loading conditions. For instance, a large induced draft fan in a power plant may take anywhere from 10 to 60 seconds to start. The damper positioning in the fan ductwork, or pitch of the fan blades, affects loading during the motor start and thus affects acceleration time to rated speed. An operator may know, based on either experience or control system trend information, that a particular fan takes a maximum of 40 seconds to start. In comparison, the EM relay in this same application may have a trip time of 50 seconds at locked-rotor current. In this case, the operator's experience may override the existing EM relay setting, allowing the protection engineer to use 40 seconds as the motor safe hot locked-rotor time as a starting point for the motor protection.

These data collection methods estimate the motor safe hot locked-rotor time. Although the motor nameplate has most of the information needed to set modern microprocessor relays, an estimate is required because the nameplate does not state how long the motor can withstand locked-rotor current before the rotor bars melt or warp. Safe hot locked-rotor time is required to set the thermal model of the relay. The estimated safe hot locked-rotor time can be used as a starting point for the relay setting.

Given the estimated safe hot locked-rotor time, the motor can be started with reasonable assurance that rotor bar heating during the start will be limited to a safe level. The thermal capacity used during starting can then be examined from one or more motor start reports. Based upon how close the relay measures to 100% thermal capacity (trip level) during starting, the LRTHOT1 setting can be reduced to better protect the motor.

Solutia Inc. manufactures Acrilan® acrylic fiber at their manufacturing facility in Decatur, AL. This facility has had thermal overloads protecting motors in the plant since installation in the 1960s. Plant Power and Control, LLC (in Alabaster, AL) replaced the motor protection on a 600 hp induced draft fan, a 500 hp induced draft fan, and a 350 hp blower motor at this facility within the last year. These motors are the basis for the case study presented in this paper.

Years ago, the initial starts of the large fan motors caused undesired trips during motor inrush. The plant personnel installed a time-delay auxiliary relay that shorted the thermal overload relay contact for two minutes during starting. After the time-delay relay timer expired, the short was removed and the thermal overload was placed back into service. Since the most likely time for a motor to fail is during a start, when currents are highest, new protection with improved reporting of motor operations was requested for these aging motors.

II. SLIP-DEPENDENT THERMAL MODEL

Most microprocessor-based relays available today attempt to calculate the heating in the motor by measuring the current only. The various manufacturers' models calculate the heating in terms of what is commonly called thermal capacity or thermal register, where 0% is completely cooled and 100% is the trip threshold. This thermal capacity is accumulated based upon the measured current, such that during motor starting, the protection is essentially an I2t element, with maximum starting time dictated 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. The protection provided by induction disk overcurrent relays is similar.

The relay chosen for the replacement upgrades described in this paper uses a thermal model that calculates motor slip during the start. The relay calculates the slip based upon measured current and voltage and two settings entered by the user. The required settings are:

- Full-load Slip (in pu of synchronous speed)
- Locked-rotor Torque (in pu of full-load torque, also called rated torque)

The relay uses the calculated slip to compute the positive- and negative-sequence rotor resistance throughout the motor start. Calculation of rotor resistance accurately reflects the heating that takes place in the motor during a start and results in longer allowable acceleration times before tripping than would be allowed by an I2t element. The details of this thermal model are documented in [2].

III. EXAMPLE 1: 600 HP INDUCED DRAFT FAN

The first motor examined was a 600 hp induced draft (ID) fan in the Unit 6 power plant boiler. The only data available for this motor was taken from the motor nameplate, as no thermal limit curves were available. The data used from the nameplate to set the protection was:

- Rated-Load Amperes (FLA) = 149 A
- Locked-rotor kVA Code Letter was not available on the motor nameplate. Based on typical data, 6.5 • FLA was used as a starting point.
- Service Factor (SF) = 1.0
- Time Rating – continuous
- RPM at Rated Load (Rated Speed) = 1189 rpm
- Voltage = 2300 V

We selected most of the required settings from this data. Full-load amps was set directly to the FLA of the motor (149 A). The service factor was set to 1.05 to provide a small margin above rated conditions, since discussions with the operators revealed that the motor might be operated slightly overloaded under some conditions. The SF setting affects the stator overload (motor running) model, but does not affect the rotor model, which is of primary concern during starting. The decision to allow this slight overload does, of course, compromise the running protection of the motor.

Full-load slip is easily calculated as:

$$\mathrm{FLS} = 1 - \mathrm{nr} / \mathrm{ns}$$

$$\mathrm{FLS} = 1 - 1189 / 1200$$

$$\mathrm{FLS} = 0.0092$$

The locked-rotor torque was unavailable for this motor, so we estimated that the locked-rotor torque was likely in the range of 1.10–1.30, based on large fan motor data available from similar facilities. An LRQ setting of 1.25 was selected. The LRQ setting affects the rotor resistance the relay uses for the locked-rotor condition with a higher LRQ setting increasing the calculated rotor resistance. Thus, a higher LRQ setting is conservative and will result in slightly higher thermal capacity used over the course of the motor start.

The final setting to be made in the starting portion of the thermal model of the relay was the safe hot locked-rotor time. Since the existing protection was thermal overloads, a reasonable locked-rotor time from existing settings was indeterminate, and no motor thermal capability curves were available. The remaining piece of viable information came from operator experience. The expected acceleration time, according to the operators, was in the 30-second range. Based on this, the hot locked-rotor time (LRTHOT1) was set to 25 seconds for the initial start attempt. The initial thermal model settings for the relay are summarized in Table 1.

TABLE 1
600 HP BOILER ID FAN INITIAL RELAY SETTINGS

Setting Name	**Initial Value**
FLA	149 A
FLS	0.0092
LRQ	1.25
LRA	6.5 • FLA
SF	1.05
LRTHOT1	25 seconds

Fig. 1 contains plots of motor current, voltage measured at the relay, measured slip, and calculated thermal capacity for the initial start. This plot was produced with available software using motor start report data recorded by the relay. As shown in Fig. 1, the initial start attempt showed the actual motor acceleration time to be about 1000 cycles, or just under 17 seconds. Furthermore, the thermal capacity used was extremely low, only reaching 38.5% of thermal capacity. The slip calculated by the relay during the motor start is shown, and as expected it trends down from 100% at locked-rotor to rated slip when the current drops to full-load amps.

It should be noted that this start attempt was done with the inlet dampers to the fan closed, which resulted in the load starting much faster than if the start were attempted with the dampers open. When the dampers are open on starting, the fan must move air through all of the ductwork and boiler. The plant operators stated that the fan is typically started with the dampers closed.

A simulation of the motor start was performed in MATLAB software to see how closely the actual quantities measured by the relay tracked with the simulated data based on the known motor parameters. This simulation is discussed in detail in the Appendix. The simulated motor currents, voltages, and thermal capacity matched the measured data very well, as shown in Fig. 2.

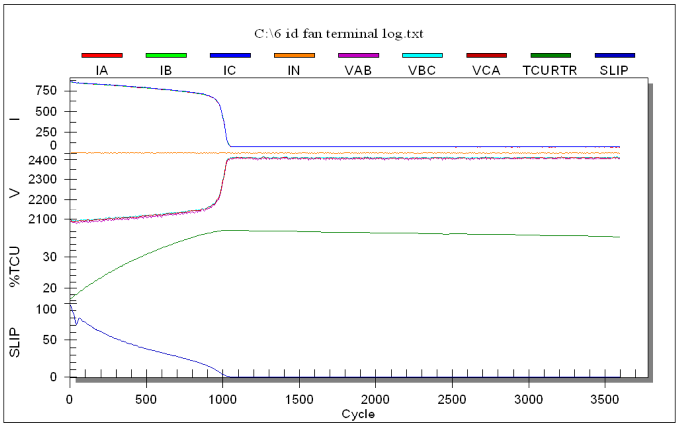


Fig. 1. Motor Start Report for Unit 6 ID Fan (600 hp)

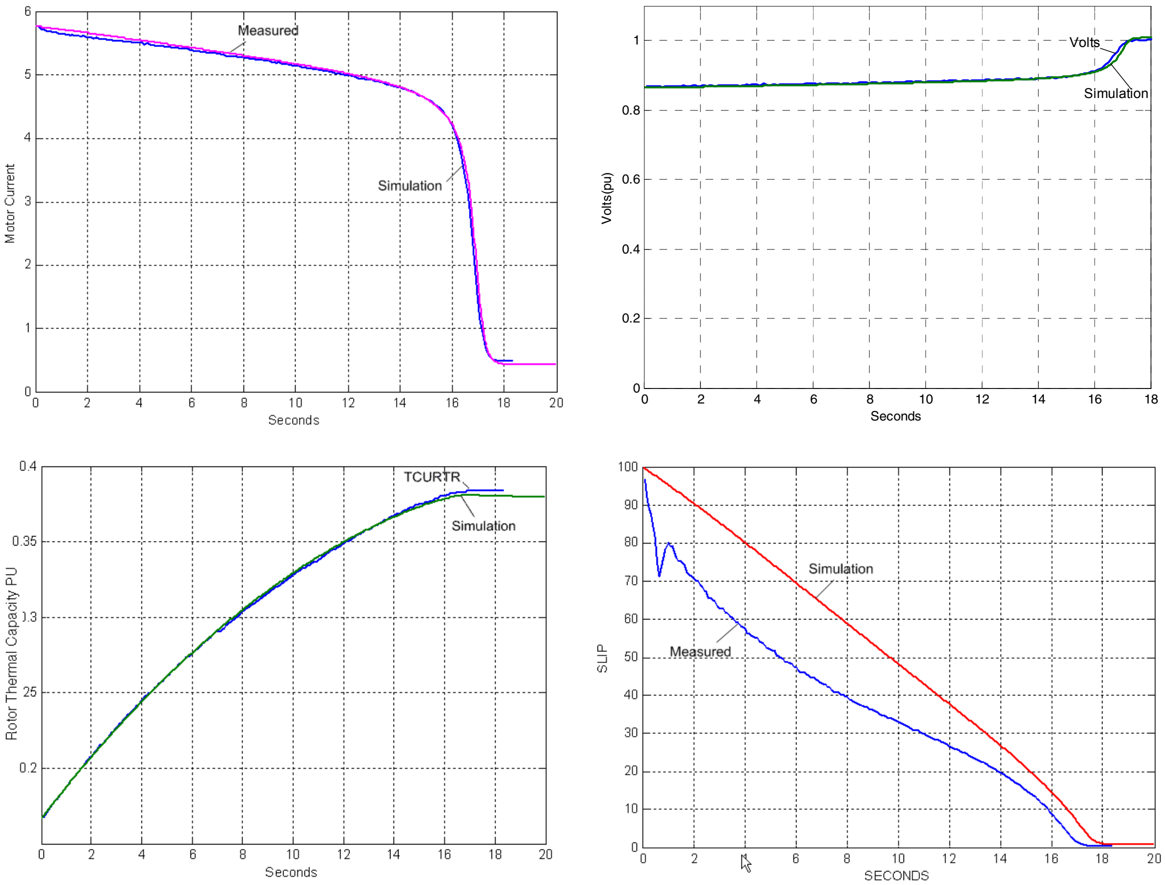


Fig. 2. Comparison of MATLAB Simulation for Unit 6 ID Fan (600 hp): Current, Voltage, Thermal Capacity (U), and Slip

IV. EXAMPLE 2: 500 HP INDUCED DRAFT FAN

The second motor examined was a 500 hp induced draft (ID) fan in the Unit 5 power plant boiler. Again, the only data available for this motor was taken from the motor nameplate, as no thermal limit curves were available. The data from the nameplate used to set the protection was:

- Rated-Load Amperes (FLA) = 107 A
- Locked-rotor kVA Code Letter was not available on the motor nameplate. Based on typical data, 6.5 • FLA was used as a starting point.
- Service Factor (SF) = 1.0
- Time Rating—continuous
- RPM at Rated Load (Rated Speed) = 1189 rpm
- Voltage = 2300 V

Since the majority of the data was similar to the 600 hp ID fan, the settings were nearly identical. Full-load amps was set directly to the FLA of the motor (107 A). The service factor was set to 1.05 to provide a small margin above rated conditions. Full-load slip was set to 0.0092 as in the 600 hp motor and locked-rotor torque was set to 1.25 as well. Safe hot locked-rotor time was set to 25 seconds since the thermal overloads had been blocked during starts of this motor also.

The initial thermal model settings for the relay are summarized in Table 2.

TABLE 2
500 HP BOILER ID FAN INITIAL RELAY SETTINGS

Setting Name	Initial Value
FLA	107 A
FLS	0.0092
LRQ	1.25
LRA	6.5 • FLA
SF	1.05
LRTHOT1	25 seconds

The motor start report in Fig. 3 was collected on 6/6/07, approximately three months after the initial installation. The actual motor acceleration time was approximately 10 seconds, significantly lower than the 17-second acceleration time of the 600 hp motor. As expected, with a programmed 25-second safe hot locked-rotor time and an acceleration time of 10 seconds, the thermal capacity used was low, only reaching 40%. The slip calculated by the relay during the motor start is shown and, as expected, it trends down from 100% at locked-rotor to rated slip when the current drops to full-load amps.

Since this motor had been in service approximately three months when this start report was collected, additional report data was collected from the relay to verify the consistency of recorded starting data across multiple starts. Fig. 4 shows the Motor Operating Statistics Report for this motor. This report accumulates the data shown until an operator manually clears the report.

From this report we can see that 12 motor starts have occurred since 2/1/2007 and that the average Thermal Capacity Used (TCU) is 40.7%, with a peak of 46.0%. The relay was also able to learn the required starting capacity by recording the thermal capacity used for the last 5 successful motor starts and multiplying the largest of these 5 thermal capacities by 115%. This data is shown as Learn Parameters: Start TC (%). The learned starting thermal capacity is used by the relay to prohibit a subsequent motor start until the rotor has adequately cooled. Since the motor accelerates to full speed in less than the programmed safe locked-rotor time, the time required for the motor to remain stopped before another start attempt is very short, allowing a fast restart time.

An additional report was captured to get refined start data across one-month intervals. The Motor Start Trend Report shown in Fig. 5 captures up to eighteen 30-day averages of the motor start information. From this report we can see that the motor starts were consistent in terms of average starting time and thermal capacity used. From this data we also surmised that the starting conditions (i.e., fan damper position) were the same; else we would have seen an excursion in the Start %TCU. Note that there were only 10 starts recorded in this trend report versus 12 starts in the operating statistics report. The Motor Start Trend Report was cleared on 3/7/2007, whereas the operating statistics report was reset on 2/1/2007. The two additional starts evidently occurred between these dates.

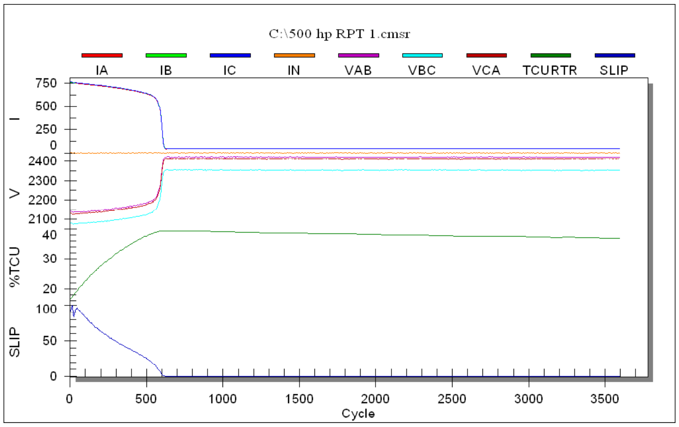
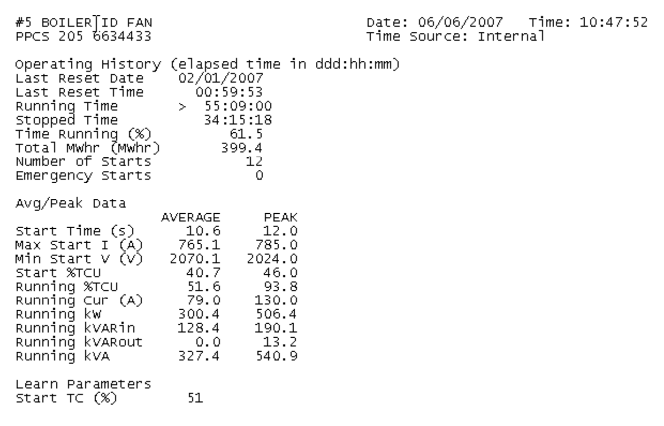


Fig. 3. Motor Start Report for Unit 5 ID Fan (500 hp)



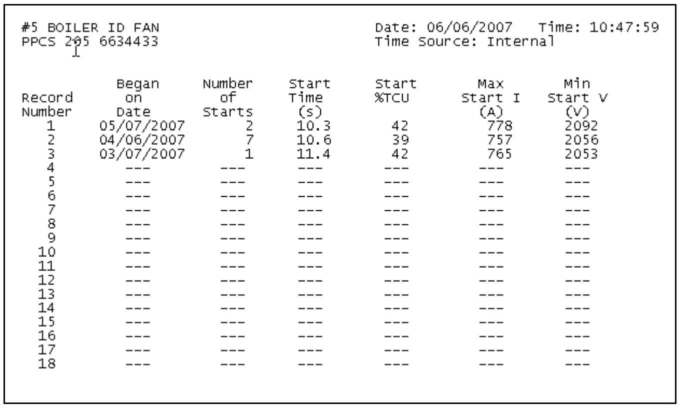
```
#5 BOILER ID FAN                                     Date: 06/06/2007   Time: 10:47:52
PPCS 205 6634433                                     Time Source: Internal

Operating History (elapsed time in ddd:hh:mm)
Last Reset Date     02/01/2007
Last Reset Time       00:59:53
Running Time       >   55:09:00
Stopped Time           34:15:18
Time Running (%)          61.5
Total MWhr (MWhr)        399.4
Number of Starts            12
Emergency Starts             0

Avg/Peak Data
                    AVERAGE      PEAK
Start Time (s)         10.6      12.0
Max Start I (A)       765.1     785.0
Min Start V (V)      2070.1    2024.0
Start %TCU             40.7      46.0
Running %TCU           51.6      93.8
Running Cur (A)        79.0     130.0
Running kW            300.4     506.4
Running kVARin        128.4     190.1
Running kVARout         0.0      13.2
Running kVA           327.4     540.9

Learn Parameters
Start TC (%)             51
```

Fig. 4. Motor Operating Statistics Report for Unit 5 ID Fan (500 hp)



```
#5 BOILER ID FAN                                    Date: 06/06/2007   Time: 10:47:59
PPCS 205 6634433                                    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    05/07/2007        2     10.3         42         778      2092
   2    04/06/2007        7     10.6         39         757      2056
   3    03/07/2007        1     11.4         42         765      2053
   4       ---         ---       ---        ---         ---       ---
   5       ---         ---       ---        ---         ---       ---
   6       ---         ---       ---        ---         ---       ---
   7       ---         ---       ---        ---         ---       ---
   8       ---         ---       ---        ---         ---       ---
   9       ---         ---       ---        ---         ---       ---
  10       ---         ---       ---        ---         ---       ---
  11       ---         ---       ---        ---         ---       ---
  12       ---         ---       ---        ---         ---       ---
  13       ---         ---       ---        ---         ---       ---
  14       ---         ---       ---        ---         ---       ---
  15       ---         ---       ---        ---         ---       ---
  16       ---         ---       ---        ---         ---       ---
  17       ---         ---       ---        ---         ---       ---
  18       ---         ---       ---        ---         ---       ---
```

Fig. 5. Motor Start Trend Report for Unit 5 ID Fan (500 hp)

V. EXAMPLE 3: 350 HP BLOWER MOTOR

The third motor examined was a 350 hp blower in the power plant boiler. Although this was a new motor installation, the motor manufacturer did not provide motor thermal limit curves so the only data available for this motor was taken from the motor nameplate. The data from the nameplate needed to set the protection was:

- Rated-Load Amperes (FLA) = 82 A
- Locked-rotor kVA Code Letter = G
- Service Factor (SF) = 1.0
- Time Rating—continuous
- RPM at Rated Load (Rated Speed) = 1189 rpm
- Voltage = 2300 V

Since the majority of the data was similar to the 600 hp ID fan, the settings were nearly identical. Full-load amps was set directly to the FLA of the motor (82 A). The service factor was set to 1.05 to provide a small margin above rated conditions. Full-load slip was set to 0.0092 as in the 600 hp motor and locked-rotor torque was set to 1.25 as well. Safe hot locked-rotor time was set to 25 seconds.

The initial thermal model settings for the relay are summarized in Table 3.

TABLE 3
350 HP BLOWER INITIAL RELAY SETTINGS

Setting Name	Initial Value
FLA	82 A
FLS	0.0092
LRQ	1.25
LRA	6.5 • FLA
SF	1.05
LRTHOT1	25 seconds

The motor start report in Fig. 6 was also collected on 6/6/07, approximately three months after the initial installation. The actual motor acceleration time was approximately 10.5 seconds, and, as expected with a programmed 25-second safe hot locked-rotor time, the thermal capacity used was low, only reaching 33%. The slip calculated by the relay during the motor start is shown and, as expected, it trended down from 100% at locked-rotor to rated slip when the current dropped to full-load amps

Additional reports were collected from this motor as well, since the relay had been in service for approximately three months. From the Motor Operating Statistics Report in Fig. 7 we can see that there were 16 motor starts since 1/30/2007 and that the average Thermal Capacity Used (TCU) was 34.0% with a peak of 35.9%. The learned starting thermal capacity of 38% was very much in line with the average starting thermal capacity and should allow restarts of the motor in a short amount of time.

The Motor Start Trend Report shown in Fig. 8 shows that the motor starts were very consistent in terms of average starting time and thermal capacity used. Note that there were only 15 starts recorded in this trend report versus 16 starts in the operating statistics report. The Motor Start Trend Report was cleared on 4/4/2007, whereas the Motor Operating Statistics Report was reset on 1/30/2007; therefore, the additional start occurred between these dates.

A simulation of the Motor Start Report in Fig. 6 was also performed in MATLAB software to see how closely the actual quantities measured by the relay tracked with the simulated data based on the known motor parameters. The simulated motor currents and thermal capacity matched the measured data very well as shown in the appendix.

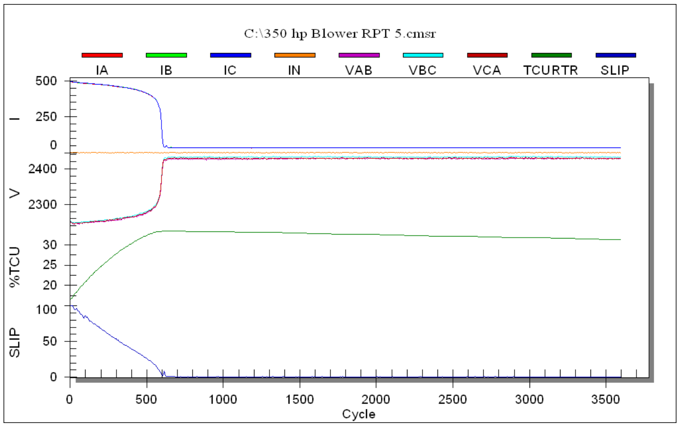
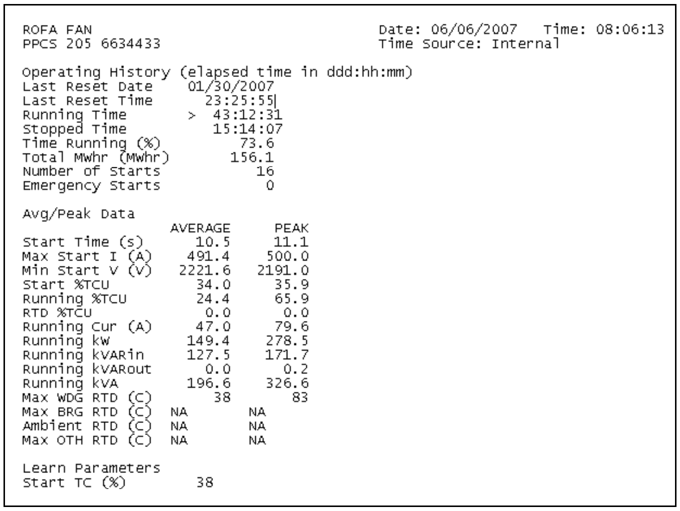


Fig. 6. Motor Start Report for Blower Motor (350 hp)



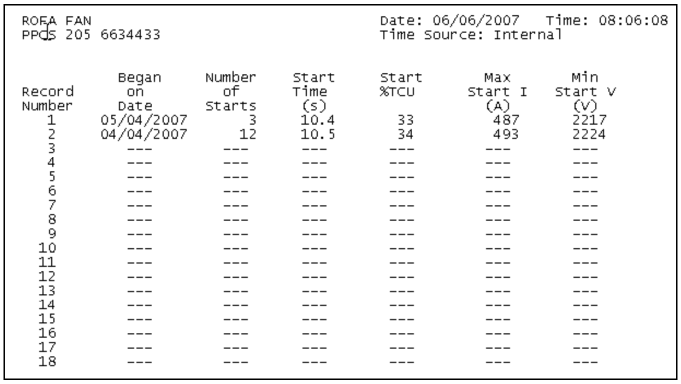
```
ROFA FAN                                     Date: 06/06/2007   Time: 08:06:13
PPCS 205 6634433                             Time Source: Internal

Operating History (elapsed time in ddd:hh:mm)
Last Reset Date     01/30/2007
Last Reset Time       23:25:55
Running Time       >   43:12:31
Stopped Time           15:14:07
Time Running (%)          73.6
Total MWhr (MWhr)        156.1
Number of Starts            16
Emergency Starts             0

Avg/Peak Data
                   AVERAGE      PEAK
Start Time (s)       10.5       11.1
Max Start I (A)     491.4      500.0
Min Start V (V)    2221.6     2191.0
Start %TCU           34.0       35.9
Running %TCU         24.4       65.9
RTD %TCU              0.0        0.0
Running Cur (A)      47.0       79.6
Running kW          149.4      278.5
Running kVARin      127.5      171.7
Running kVARout       0.0        0.2
Running kVA         196.6      326.6
Max WDG RTD (C)        38         83
Max BRG RTD (C)    NA         NA
Ambient RTD (C)    NA         NA
Max OTH RTD (C)    NA         NA

Learn Parameters
Start TC (%)         38
```

Fig. 7. Motor Operating Statistics Report for Blower Motor (350 hp)



```
ROFA FAN                                                Date: 06/06/2007   Time: 08:06:08
PPCS 205 6634433                                        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      05/04/2007       3       10.4        33         487      2217
   2      04/04/2007      12       10.5        34         493      2224
   3         ---         ---        ---        ---        ---       ---
   4         ---         ---        ---        ---        ---       ---
   5         ---         ---        ---        ---        ---       ---
   6         ---         ---        ---        ---        ---       ---
   7         ---         ---        ---        ---        ---       ---
   8         ---         ---        ---        ---        ---       ---
   9         ---         ---        ---        ---        ---       ---
  10         ---         ---        ---        ---        ---       ---
  11         ---         ---        ---        ---        ---       ---
  12         ---         ---        ---        ---        ---       ---
  13         ---         ---        ---        ---        ---       ---
  14         ---         ---        ---        ---        ---       ---
  15         ---         ---        ---        ---        ---       ---
  16         ---         ---        ---        ---        ---       ---
  17         ---         ---        ---        ---        ---       ---
  18         ---         ---        ---        ---        ---       ---
```

Fig. 8. Motor Start Trend Report for Blower Motor (350 hp)

VI. ANALYSIS AND SETTING RECOMMENDATIONS

Since the new microprocessor-based relays are able to provide protection during all phases of motor operation, all three of the motors in this facility have better protection than originally provided by the thermal overloads; and, as can be seen from the various reports, the operators obtain much better information on the motor starting characteristics. However, the question remains: how much can we improve the protection and still allow the motor to safely start?

The easiest relay setting to change to provide faster tripping for a true locked-rotor condition is the safe hot locked-rotor time setting. We might reduce the applied time of 25 seconds to a time slightly longer than the measured acceleration time of the motors and still be reasonably certain that the motor will not trip on normal starts. The simulation can be used to evaluate how much of a reduction might be appropriate.

Observation of the start data for the three motors shows that the thermal capacity used is fairly low for all starts. There are several possible reasons for this:

1. Actual starting time is less than the relay setting LRTHOT1.
2. Actual starting current is less than the LRA1 setting, because of reduced voltage during the start as well as the lack of certainty in the actual locked-rotor current value when the setting was selected.
3. Function of the slip-dependent thermal model, which, by calculating rotor resistance, tracks actual motor heating during a start more accurately than a relay with an I2t characteristic.

In order to assess the impact of Item 3, the effect of Items 1 and 2 can be effectively removed by using the simulation to start the motors with 1 pu voltage at the motor terminals, and by reducing the safe locked-rotor time setting in the thermal model simulation.

Based upon the motor start data collected and previously presented, adjustments for hot locked-rotor time (LRTHOT1) might be:

- 600 hp ID Fan LRTHOT1 = 18 seconds
- 500 hp ID Fan LRTHOT1 = 12 seconds
- 350 hp ID Fan LRTHOT1 = 12 seconds

Simulations were performed for the 350 hp motor with the proposed setting revisions for two cases:

1. Motor terminal voltage applied at 1.0 pu motor voltage.
2. Motor terminal voltage applied at 0.80 pu motor voltage.

The results of these cases are shown in Fig. 9 and Fig. 10.

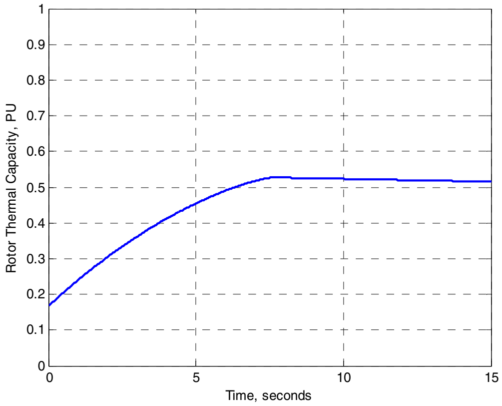


Fig. 9. 350 hp Motor, LRTHOT1 = 12 sec, V = 1.0 pu

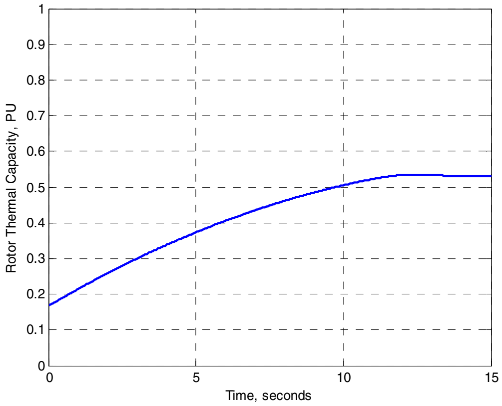


Fig. 10. 350 hp Motor, LRTHOT1 = 12 sec, V = 0.8 pu

Note that although the starting time was longer, the thermal capacity used with 0.80 pu voltage was not significantly higher than the thermal capacity used with 1.0 pu voltage, and there was no concern for the relay reaching the thermal trip threshold (Rotor Thermal Capacity = 1) for either case. This result was somewhat expected, since reduced voltage results in reduced starting current (resulting in less rotor heating) and reduced motor torque results in proportionally longer starting time (resulting in greater rotor heating).

A final simulation was performed at 0.80 pu voltage and LRTHOT1 = 8 seconds, which was LESS than the total acceleration time for these conditions. Fig. 11 shows that the thermal element would not operate during a normal start. Fig. 12 illustrates how long the thermal element would require to trip the motor should the rotor remain locked under these same conditions. While an EM relay or microprocessor I2t thermal element would have to be set longer than 12 seconds at 80% of locked-rotor current to ensure that the motor would start, the slip-dependent model tripped faster than the acceleration time of 12 seconds for true locked-rotor conditions yet still allowed normal starts.

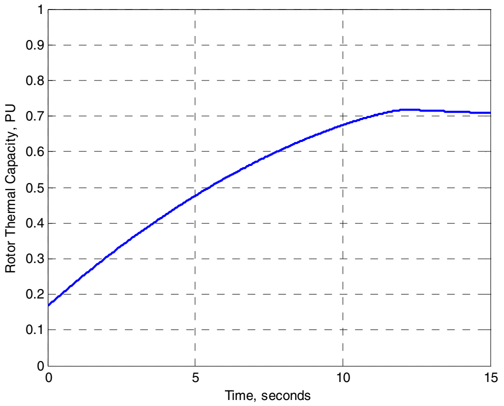


Fig. 11. 350 hp Motor, LRTHOT1 = 8 sec, V = 0.8 pu

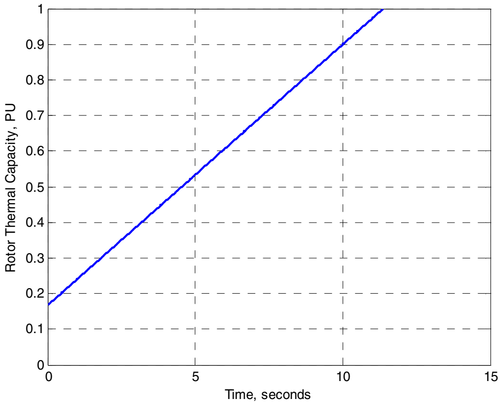


Fig. 12. 350 hp Motor, LRTHOT1 = 8 sec, V = 0.8 pu, Rotor Locked

These simulations show that, with the slip-dependent model, setting the relay hot locked-rotor time based on observed acceleration time (or perhaps even less than the observed acceleration time) does not compromise the ability of the motor to start with voltage conditions ranging from 80%–100% of the motor rated voltage.

However, calculating the lowest setting possible that will still ensure the ability to start the motor requires analysis tools that are typically unavailable to protection engineers. An acceptable compromise was to set the thermal model hot safe stall time equal to or slightly greater than the observed acceleration time. With the slip-dependent thermal element, we were assured that the motor would not trip under normal starting conditions. Yet, assuming that the motor was properly sized during the original facility design effort to accelerate the load without damage, we were also assured that the motor was adequately protected.

Consequently, the hot locked-rotor time settings for the three example motors could have been reduced significantly, as proposed. However, the operators at this facility elected to forego the adjustments to ensure that the motors would successfully start should they ever have to be started under other operating scenarios (such as dampers open). The recommended protection is still superior to the original protection, which had to be blocked during starting to prevent nuisance trips.

VII. CONCLUSIONS

Motor protection can be greatly enhanced today with microprocessor-based relays, even with very little motor data available. The slip-dependent thermal model protects the motor and allows for long acceleration times, as compared to traditional microprocessor I2t elements and electromechanical relays. Settings can be applied and if desired, refined over the course of operation of the load and varying operating characteristics. The motor start reports and trend information in modern relays are valuable tools for improving protection over time. Simulations of motor starts under reduced voltage conditions indicate that the calculated thermal capacity used does not increase significantly; therefore, inappropriate tripping is unlikely to occur when the motor is started under minimum expected voltage conditions.

VIII. APPENDIX: MOTOR STARTING COMPUTER SIMULATION

Analyzing induction motor starting requires the use of electrical, mechanical, and thermal models that interact as shown in Fig. 13. In the electrical model, the voltage, V, and the slip, S, determine the rotor current. The summation of all torques acting on the motor shaft defines the mechanical model. Here, the slip-dependent load torque and the moment of inertia resist the driving torque developed by the motor. The thermal model is the differential equation for heat rise due to current in a conductor and is defined by the thermal capacity, the thermal resistance, and the slip-dependent I2R watts. As the ultimate protection criteria, the thermal model is used to estimate the rotor temperature, U, resulting from the starting condition with initial temperature U0. A recursive solution is used since the rotor impedance changes continuously with slip.[3]

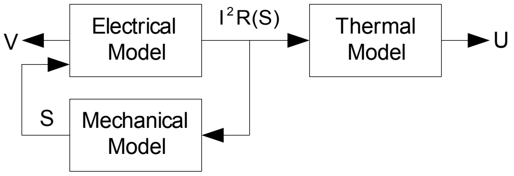


Fig. 13. Motor System Block Diagram

As complex as this process may appear, we can add a few standard values and do the complete analysis with the minimum information given. The electrical and mechanical models for the motor and load combination are determined using an iterative process, which involves adjusting the model parameters until the simulation results match the measured currents and voltages. The source voltage and impedance are used to adjust the motor current at locked-rotor to the measured value, and a portion of the source impedance so determined is applied between the relay and the motor to ensure that the simulated relay voltage matches the measured relay voltage.

A. Estimating Input Data for the 350 HP 1200 RPM Blower Fan Motor

The voltage and horsepower are used to calculate the full-load current.

$$\mathrm{FLA} = \frac{746\,\mathrm{hp}}{0.8 \cdot \sqrt{3} \cdot \mathrm{V}} = \frac{746 \cdot 350}{0.8 \cdot \sqrt{3} \cdot 2300} = 82 \qquad (1)$$

This information may also be available from the motor nameplate.

The locked-rotor current of 6.7 • FLA was determined from the relay motor start report and the rated speed was determined from the nameplate. The locked-rotor torque was taken to be 1.25. The motor data items that define the electrical and the thermal model are:

Rated Horsepower	HP	350 hp
Rated Speed	FLW	1188 rpm
Synchronous Speed	SynW	1200 rpm
Locked-rotor Torque	LRQ	1.25 pu
Full-load Current	FLA	82 A
Locked-rotor Current	LRA	550 A
Hot Stall time Limit	T_O	25 sec
Cold Stall Time Limit	T_A	30 sec

B. Defining the Electrical Model

The motor modeling program uses the motor menu data to generate the pu impedances of the Steinmetz equivalent circuit of the motor including the slip-dependent positive- and negative-sequence rotor resistance and reactance (see Fig. 14).

Locked-rotor current:

$$I_L = \frac{\mathrm{LRA}}{\mathrm{FLA}} = 6.7 \qquad (2)$$

Rotor resistance at rated speed:

$$R_N = \frac{\mathrm{SynW} - \mathrm{FLW}}{\mathrm{SynW}} = 0.001 \qquad (3)$$

Locked-rotor resistance:

$$R_L = \frac{\mathrm{LRQ}}{I_L^2} = 0.0278 \qquad (4)$$

Stator resistance:

$$R_S = 3 \cdot R_N = 0.003 \qquad (5)$$

Total series resistance:

$$R = R_L + R_S = 0.0308 \qquad (6)$$

Total series impedance:

$$Z = \frac{1}{I_L} = 0.149 \qquad (7)$$

Total series reactance:

$$X = \sqrt{Z^2 - R^2} = 0.1458 \qquad (8)$$

Locked-rotor reactance:

$$X_L = \frac{X}{2} = 0.0729 \qquad (9)$$

Stator reactance

$$X_S = X - X_L = 0.0729 \qquad (10)$$

Rotor reactance at rated speed

$$X_0 = (\tan(9.2°))(1 + R_S) - X_S = 0.0896 \qquad (11)$$

Positive-sequence rotor resistance:

$$R_1 = (R_L - R_N) \cdot S + R_N \qquad (12)$$

Positive-sequence rotor reactance:

$$X_1 = (X_L - X_N) \cdot S + X_N \qquad (13)$$

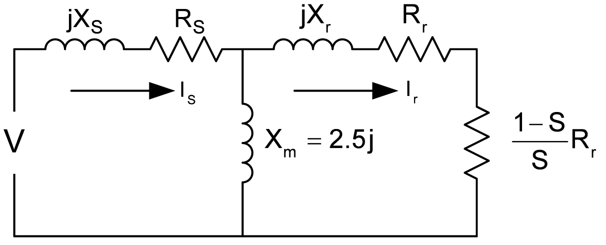
Negative-sequence rotor resistance:

$$R_2 = (R_L - R_N) \cdot (2 - S) + R_N \qquad (14)$$

Negative-sequence rotor reactance:

$$X_2 = (X_L - X_N) \cdot (2 - S) + X_N \qquad (15)$$

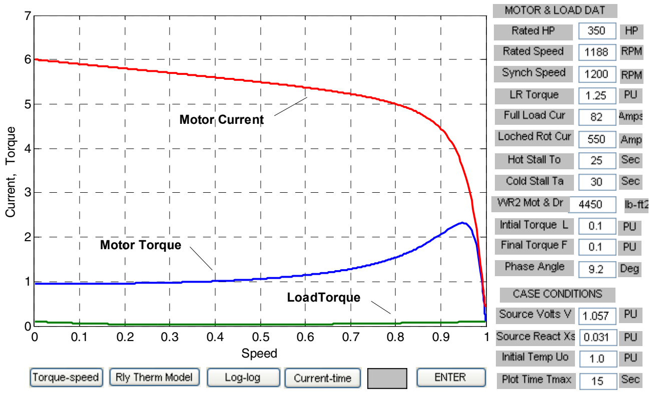
The above calculations result in the equivalent circuit shown in Fig. 14.



Positive Sequence	Negative Sequence
$R_r = R_1 = (R_L - R_N)S + R_N$	$R_r = R_2 = (R_L - R_N)(2 - S) + R_N$
$X_r = X_1 = (X_L - X_N)S + X_N$	$X_r = X_2 = (X_L - X_N)(2 - S) + X_N$

Fig. 14. Steinmetz Model

We can now use the program to calculate the characteristic of rotor torque and current versus slip at rated volts by varying the slip from 1 to 0. This characteristic, shown in Fig. 15, will be useful in defining the input watts of the thermal and mechanical models. The load torque shown is defined in the following section.



MOTOR & LOAD DAT
Rated HP 350 HP
Rated Speed 1188 RPM
Synch Speed 1200 RPM
LR Torque 1.25 PU
Full Load Cur 82 Amps
Loched Rot Cur 550 Amp
Hot Stall To 25 Sec
Cold Stall Ta 30 Sec
WR2 Mot & Dr 4450 lb-ft2
Intial Torque L 0.1 PU
Final Torque F 0.1 PU
Phase Angle 9.2 Deg

CASE CONDITIONS
Source Volts V 1.057 PU
Source React Xs 0.031 PU
Initial Temp Uo 1.0 PU
Plot Time Tmax 15 Sec

Fig. 15. Current and Torque with Motor Model Parameters

C. *Defining the Mechanical Model*

The mechanical model is the equation expressing the summation of torques acting on the shaft:

$$(Q_M - Q_L) = M\frac{d\omega}{dt} \tag{16}$$

where Q_M is the motor torque, Q_L is the load torque, M is the combined moment of inertia of the motor and the drive, and ω is the velocity. The equation, expressed in time discrete form and when solved for slip, becomes:

$$(Q_M - Q_L) = M\frac{\omega - \omega_0}{DT} \tag{17}$$

$$\begin{aligned} \omega &= \frac{(Q_M - Q_L)}{M}DT + \omega_0 \\ S &= (1-\omega) \end{aligned} \tag{18}$$

The electromechanical power developed by the rotor is represented by the losses in the slip-dependent load resistor in Fig. 14. Consequently, the positive-sequence mechanical power is:

$$P_M = I_1^2 \cdot \frac{1-S}{S} R_1 \tag{19}$$

where I_1^2 is the positive-sequence rotor current.

Dividing the power P_M by the velocity, (1 - S), gives the motor torque:

$$Q_M = \frac{I_1^2 \cdot R_1}{S} \tag{20}$$

Fig. 16 shows the typical contour of the load torque versus speed curve of a pump or fan. The load torque is characterized by an initial breakaway torque value, L, and momentary decrease followed by the increase to its final value, F. The program uses the empirical equation:

$$Q_L = L \cdot (1-\omega)^5 + F \cdot \omega^2 \tag{21}$$

Fig. 15 shows the load torque relative to the motor torque. The torque difference (Q_M - Q_L) is the accelerating torque as expressed by (17). The accelerating power and the moment of inertia determine the time it takes the motor to reach the peak torque and attain rated speed.

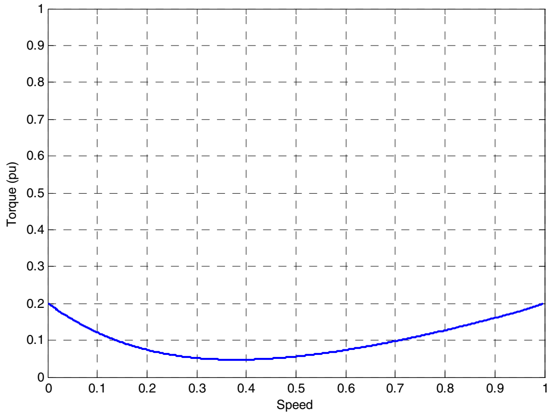


Fig. 16. Contour of Load Torque

Typical values for the load are shown with the moment of the inertia specified in units of lb-ft^2. Since all the model parameters are specified in pu of motor base values, the WR^2 is converted to the inertia constant, M, using the following relation:

$$M = \frac{WR^2}{g} \cdot \frac{2\pi}{60} \cdot \frac{SynW}{Q_R} \tag{22}$$

where g is the acceleration due to gravity, SynW is the synchronous speed, and Q_R is the torque calculated from rated speed and horsepower:

$$Q_R = 5252 \cdot \frac{RHP}{FLW} \tag{23}$$

With this motor and load, the moment of inertia of 4450 lb-ft^2 produces an approximate 10-second starting time to match the measured starting time.

D. *Defining the Thermal Model*

Fig. 17 shows the first order thermal model that incorporates the I2t properties of the rotor thermal limit curves as well as the effect of the slip-dependent positive- and negative-sequence rotor resistance on the input watts. The I2t value of the operating temperature is used as the thermal resistance to ensure that one pu input produces the operating temperature.

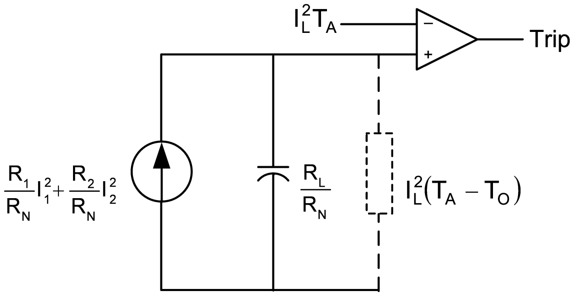


Fig. 17. Rotor Thermal Model

The following discrete form of the differential equation of the rotor thermal model is processed each sample period to calculate the temperature U:

For I > 2.5

$$U_n = \left(\frac{R_1}{R_N}I_1^2 + \frac{R_2}{R_N}I_2^2\right)\frac{\Delta t}{C_{Th}} + U_{n-1} \tag{24}$$

For I ≤ 2.5

$$U_n = \left(\frac{R_1}{R_N}I_1^2 + \frac{R_2}{R_N}I_2^2\right)\frac{\Delta t}{C_{Th}} + \left(1 - \frac{\Delta t}{R_{Th}C_{Th}}\right)\cdot U_{n-1} \tag{25}$$

where the thermal capacitance $C_{Th} = R_L/R_N$ and the thermal resistance $R_{Th} = (I_L)^2(T_A - T_O)$. I_1 and I_2 are the positive- and negative-sequence currents, respectively. Note that the thermal resistance is only considered when the current drops below 2.5 pu, so that the calculation of temperature is adiabatic for starting current. At each sample, U_n is compared to the trip threshold and asserts the trip signal if the limiting temperature is exceeded.

Slip (S) must be determined in order to calculate the slip-dependent rotor resistance. The speed algorithm applied to the 350 hp motor is as follows:

$$R = \text{real}\left(\frac{V_1}{I_1}\right) \tag{26}$$

where V_1 and I_1 are the positive-sequence motor voltage and current measured at each sample.

$$A = 1.2 \tag{27}$$

R_L and R(1), which is the initial value of R measured during start, are used to determine the stator resistance Rs which includes the source resistance:

$$Rs = R(1) - \frac{R_L}{A} \tag{28}$$

then

$$S = \frac{R_N}{\left(A(R - R_S) - (R_L - R_N)\right)} \tag{29}$$

and

$$R_r = (R_L - R_N)S + R_N \tag{30}$$

The comparison plots shown in Fig. 18 through Fig. 21 validate the accuracy of the simulation and its use as a tool for determining optimum motor protection setting.

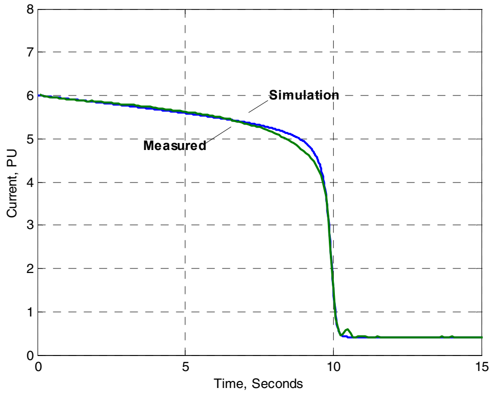


Fig. 18. Simulated and Measured Current for 350 hp Blower Motor

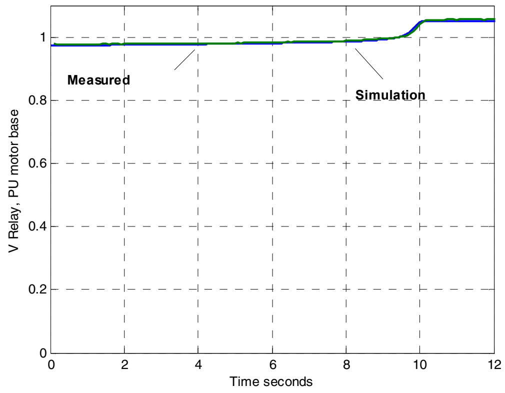


Fig. 19. Simulated and Measured Voltage at the Relay in PU Motor Base Voltage for 350 hp Blower Motor

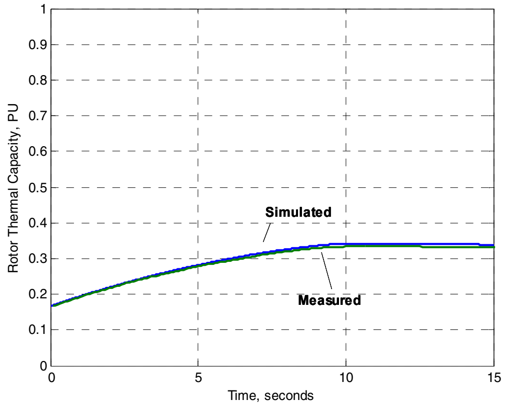


Fig. 20. Simulated and Measured Rotor Thermal Capacity, TCURTR, for 350 hp Blower Motor

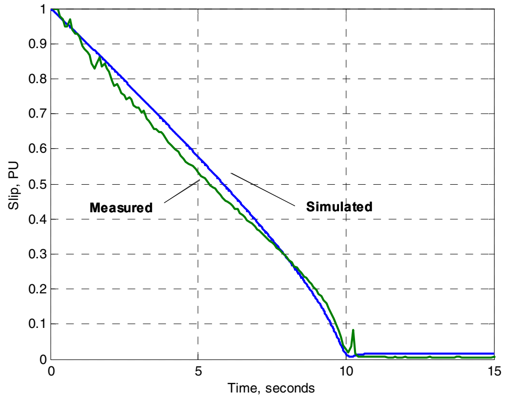


Fig. 21. Simulated and Measured Slip for 350 hp Blower Motor

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[2] S. E. Zocholl, "Tutorial: From the Steinmetz Model to the Protection of Inertia Drive Motors," presented at the 34th Western Protective Relay Conference, Spokane, WA, October 2001.

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X. ADDITIONAL READINGS

S. E. Zocholl, E. O. Schweitzer, and A. Aliaga-Zegarra, "Thermal Protection of Induction Motors Enhanced by Interactive Electrical and Thermal Models," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-103, No. 7, July 1983.

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XI. BIOGRAPHIES

Patrick Whatley, P.E., holds a B.S. in Electrical Engineering from Auburn University and an M.S. in Power Engineering from the University of South Florida. After several years in the industrial division of General Electric, he joined Florida Power & Light (FPL), working in the Protection and Control, Substation, and Transmission departments. Since 1997, he has been employed with Plant Power & Control Systems (PP&CS), an engineering, consulting, and OEM equipment manufacturing company where he oversees all technical issues and reviews equipment design. Mr. Whatley is a registered professional engineer in Alabama, Florida, Georgia, and Mississippi.

Mark E. Lanier, P.E., received his B.S. in Electrical Engineering from the University of South Carolina in 1989. He joined Duke/Fluor Daniel, a subsidiary of Duke Energy, upon graduation as an electrical power systems engineer where he worked for fourteen years designing coal- and gas-fired power plant electrical systems. In 2003 he left Duke Energy and joined Schweitzer Engineering Laboratories, Inc. as a field application engineer. He is a registered professional engineer in the State of South Carolina. Mr. Lanier also received his M.B.A. from the University of South Carolina in 2007.

Lee Underwood, P.E., received a B.S. in Electrical Engineering from the University of Virginia in Charlottesville in 1990. From 1990 to 1996, Lee worked as a Design and Systems Engineer for Duke Power Oconee Nuclear Station, with emphasis on dc power systems, medium and low voltage switchgear, and protective relaying. In 1996, he joined Duke/Fluor Daniel, and participated in the design and construction of electrical systems for coal-fired power plants. Mr. Underwood joined Schweitzer Engineering Laboratories, Inc. as a field application engineer in 2004. He is a member of the IEEE Power Engineering Society and a registered professional engineer.

Stanley (Stan) Zocholl has a B.S. and an M.S. in Electrical Engineering from Drexel University. He is an IEEE Life Fellow and a member of the Power Engineering Society and the Industrial Application Society. He is also a member of the Power System Relaying Committee. He joined Schweitzer Engineering Laboratories in 1991 in the position of Distinguished Engineer. He was with ABB Power T&D Company Allentown (formerly ITE, Gould BBC) since 1947 where he held various engineering positions, including Director of Protection Technology.

His biography appears in Who's Who in America. He holds over a dozen patents associated with power system protection using solid state and microprocessor technology and is the author of numerous IEEE and Protective Relay Conference papers. He received the Power System Relaying Committee Distinguished Service Award in 1991. He was the Chairman of PSRCW G J2 that completed the AC Motor Protection Tutorial. Mr. Zocholl is the author of two books, *AC Motor Protection*, second edition, ISBN 0-9725026-1-0 and *Analyzing and Applying Current Transformers*, ISBN 0-9725026-2-9.

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Conference for Protective Relay Engineers.
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