

AC Motor Protection

by

Stanley E. Zocholl

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Introduction

All electrical apparatus and systems need protective relays to monitor and initiate tripping in the case of short circuit current caused by faults and insulation failure. Indeed, ac motors are no exception to the rule and need overcurrent protection against short circuits from external faults in connecting cables and from internal faults in the motor windings. In addition, motors are thermally rated and limited, and protective relays must be applied to prevent overheating during operating conditions where no faults are present. In this respect, ac motor protection presents a unique challenge to the protection engineer and requires knowledge of both thermal and mechanical characteristics as well as electrical characteristics familiar to electrical engineers.

IEEE Standard C37.96-2000, *Guide for AC Motor Protection*, recommends the use of overcurrent relays for overload and locked rotor protection. In these applications, setting the overcurrent inverse time-current characteristic to coordinate with the motor thermal limit curves provides protection. Because of the familiar use of overcurrent protection, little attention is paid to the nature of motor thermal limit curves and their relation to winding temperature in an induction motor. Yet, the limit curves are based on thermal models that enable microprocessor relays to continuously calculate and monitor motor temperature in real time. For this reason, it will be helpful to understand the relation between parameters of horsepower, speed, locked rotor torque,

Introduction

full load and locked rotor current, and hot and cold locked rotor limit times in relation to motor thermal protection.

Our approach will be to develop the electrical, mechanical, and thermal models that determine the motor characteristics and lead to optimum thermal and fault protection.

AC Motors

The entities we are dealing with are shown in Figures 1 and 2. Each figure shows the cross section of a two-pole ac motor where three-phase stator windings are distributed so that the energized windings produce an approximate sine wave flux in the air gap.

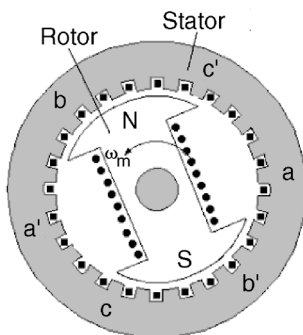


Figure 1 Two-Pole Synchronous Motor Showing DC Field Winding

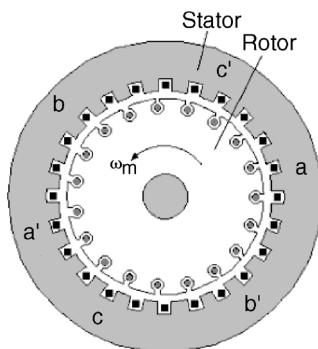


Figure 2 Two-Pole Induction Motor With Squirrel Cage Rotor

AC Motors

Also, the placement of the three-phase windings causes the field to rotate at a speed determined by the frequency of the source and the number of poles according to the relation:

$$rpm = \frac{120}{p}f \quad (1)$$

where:

rpm is the speed in revolutions per minute
 f is the frequency in cycles per second
 p is the number of poles

Synchronous Motors

The rotor of the synchronous motor has a dc field winding. The rotating field causes the motor to run at the synchronous speed indicated in Equation 1, and power output is increased by a momentary advance in the angle of the rotor with respect to the phase of the system voltage. Synchronous motors have limited short-circuited windings similar to an induction motor for the purpose of starting. The dc field is applied when the motor achieves 85-90 percent of synchronous speed and the motor pulls in to synchronism. Synchronous motors require dc field protection and the protection from the instability caused by loss of field.

Induction Motors

The windings in the slots of rotor in an induction motor are bars running parallel to the shaft. Rings connect the bars and are welded or brazed on the rotor ends to form a short-circuited assembly. The rotor bar assembly resembles a squirrel cage, from which the type of motor takes its name. Applying voltage to the stator causes the rotating field to cut the rotor bars and induce voltage in the rotor. The voltage drives a large current through the short-circuited bars. The field of the rotor current opposes the stator field and produces a torque to accelerate the rotor. At synchronous speed there would be no relative motion between the rotor and the stator field, and no induced voltage. Consequently, the rotor attains a speed a few percent short of the synchronous speed at a point where the induced current supplies the load torque and losses. The difference between the synchronous speed and the rotor speed is called the slip frequency.

Motor Characteristics

Induction Motor System

The data needed to analyze a motor problem are presented in the following example. A plant process is shut down for maintenance once every two years. After scheduled maintenance, an 1800-rpm, 2.4 kV, 1200-hp pump motor tripped on startup. With little information available, records show the motor starting time as 20 seconds and the locked rotor time as 14 seconds. The motor bus is fed by a transformer with 5.6 percent impedance that dips the terminal voltage 75 percent of nominal on starting. We need to determine the cause of the trip.

Here is an overview of what needs to be done:

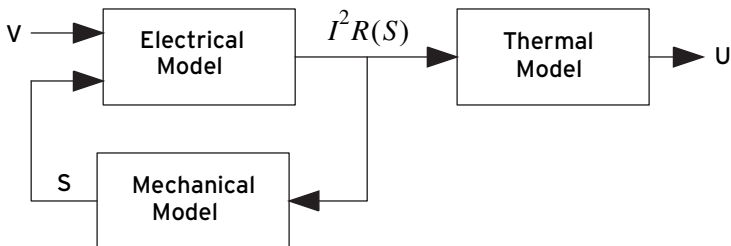


Figure 3 Motor System Block Diagram

Analyzing induction motor starting requires the use of electrical, mechanical, and thermal models that interact as shown in Figure 3. 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 comprises the mechanical model. Here, the load torque and the moment of inertia of all the rotating elements, all of which are slip dependent, resist the driving torque developed by the motor. The thermal model is the equation for heat rise due to current in a conductor determined by the thermal capacity, the thermal resistance, and the slip-dependent I^2R 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 U_0 . We must use a recursive solution since the rotor impedance changes continuously with slip.

As complex as this process may appear, we can add a few standard values and do the complete analysis with the minimum information given. In fact, it can be done in less than a minute using the motor modeling program, SEL-5802.

Estimating Input Data

Figure 4 is the menu of the data, which defines the electrical and the thermal model of the motor.

MOTOR DATA		
Rated Horse Power	HP 1200	Hp
Rated Speed	FLW 1783	rpm
Synchronous Speed	SynW 1800	rpm
Locked Rotor Torque	LRQ 0.8	pu
Full Load Current	FLA 269	amps
Locked Rotor Current	LRA 1614	amps
Hot Stall Limit Time	To 14	sec.
Cold Stall Limit Time	Ta	sec.
OK		

Figure 4 Menu of Essential Motor Data

We have used the voltage and horsepower to calculate the full load current:

$$FLA = \frac{746 \cdot HP}{0.8 \cdot \sqrt{3} \cdot V} = \frac{746 \cdot 1200}{0.8 \cdot \sqrt{3} \cdot 2400} = 269 \tag{2}$$

We assumed the typical value of 6 times FLA as the locked rotor current and calculated the full load speed using one percent slip at full load. Depending on the class and application of the motor, the locked rotor torque can take on values of 0.8, 1.0, or 1.2. The value of 0.8 is the appropriate value for a pump motor.

Defining the Electrical Model

The motor modeling program uses the motor data in Figure 4 to generate the per unit impedances of the Steinmetz equivalent circuit of the motor including the slip-dependent positive- and negative-sequence rotor resistance and reactance (see Figure 5):

Locked rotor current

$$I_L = \frac{LRA}{FLA} = 6.0 \quad (3)$$

Rotor resistance at rated speed

$$R_0 = \frac{SynW - FLW}{SynW} = 0.01 \quad (4)$$

Locked rotor resistance

$$R_1 = \frac{LRQ}{I_L^2} = 0.022 \quad (5)$$

Stator resistance

$$R_S = \frac{R_0}{5} = 0.002 \quad (6)$$

Total series resistance

$$R = R_1 + R_S = 0.024 \quad (7)$$

Motor Characteristics

Total series impedance

$$Z = \frac{1}{I_L} = 0.167 \quad (8)$$

Total series reactance

$$X = \sqrt{Z^2 - R^2} = 0.165 \quad (9)$$

Locked rotor reactance

$$X_1 = \frac{X}{2} = 0.082 \quad (10)$$

Stator reactance

$$X_S = X - X_1 = 0.082 \quad (11)$$

Rotor reactance at rated speed

$$X_0 = (\tan(12.75^\circ))(1 + R_0 + R_S) - X_S = 0.147 \quad (12)$$

Positive-sequence rotor resistance

$$R_{r+} = (R_1 - R_0) \cdot S + R_0 \quad (13)$$

Positive-sequence rotor reactance

$$X_{r+} = (X_1 - X_0) \cdot S + X_0 \quad (14)$$

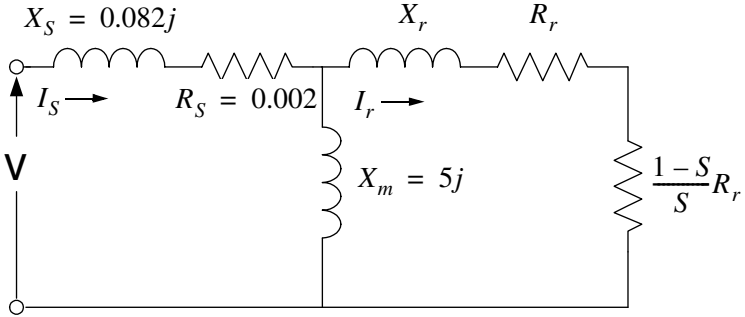
Negative-sequence rotor resistance

$$R_{r-} = (R_1 - R_0) \cdot (2 - S) + R_0 \quad (15)$$

Negative-sequence rotor reactance

$$X_{r-} = (X_1 - X_0) \cdot (2 - S) + X_0 \quad (16)$$

The above calculations result in the equivalent circuit shown in Figure 5.



Positive Sequence

$$R_r = (R_1 - R_0) \cdot S + R_0$$

$$X_r = (X_1 - X_0) \cdot S + X_0$$

Where:

$$R_0 = 0.009$$

$$R_1 = 0.022$$

$$X_1 = 0.082$$

$$X_0 = 0.141$$

Negative Sequence

$$R_r = (R_1 - R_0) \cdot (2 - S) + R_0$$

$$X_r = (X_1 - X_0) \cdot (2 - S) + X_0$$

Motor Torque:

$$Q_m = \frac{I_r^2 R_r}{S}$$

Figure 5 Motor Equivalent Circuit

Motor Characteristics

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 Figure 6, will be useful in defining the input watts of the thermal and mechanical models. The load torque shown is defined in the following section.

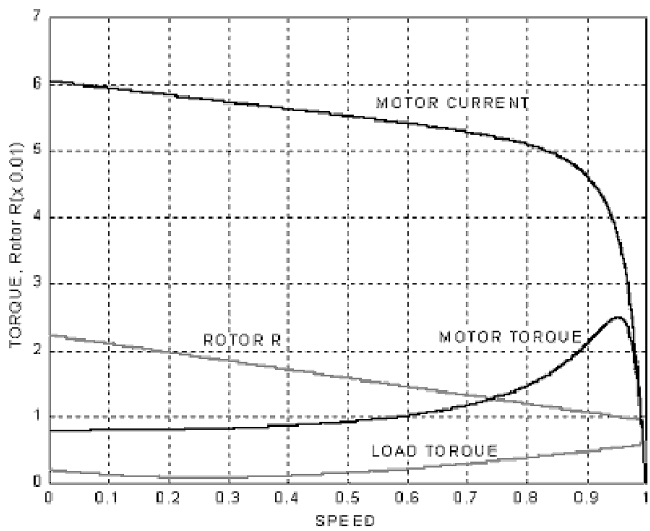


Figure 6 Current and Torque Versus Slip

Defining the Mechanical Model

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

$$(Q_M - Q_L) = M \frac{d\omega}{dt} \quad (17)$$

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
- ω is the velocity

The equation expressed in time-discrete form and solved for slip becomes:

$$(Q_M - Q_L) = M \frac{\omega - \omega_0}{DT} \quad (18)$$

$$\omega = \frac{(Q_M - Q_L)}{M} DT + \omega_0 \quad (19)$$

$$S = (1 - \omega)$$

Motor Characteristics

The electromechanical power developed by the rotor is represented by the losses in the slip-dependent load resistor in Figure 5 on page 11. Consequently, the positive-sequence mechanical power is:

$$P_M = I_{r+}^2 \cdot \frac{1-S}{S} R_{r+} \quad (20)$$

where:

I_{r+}^2 is positive-sequence rotor current

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

$$Q_M = \frac{I_{r+}^2 \cdot R_{r+}}{S} \quad (21)$$

Figure 7 shows the typical contour of the load torque versus speed curve of a pump or fan.

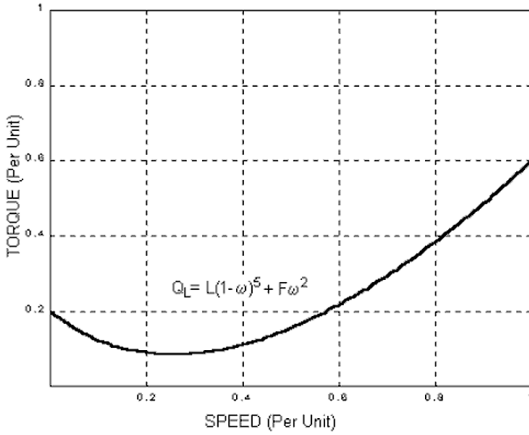


Figure 7 Contour of Load Torque

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:

$$Q_L = L \cdot (1 - \omega)^5 + F \cdot \omega^2 \quad (22)$$

Figure 6 on page 12 shows the load torque relative to the motor torque. The torque difference ($Q_M - Q_L$) is the accelerating torque as expressed by Equation 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.

Motor Characteristics

The mechanical data are entered into the menu shown in Figure 8.

MECHANICAL DATA		
WK ² of motor & drive WK2 5000 lb-ft ²		
Initial load torque	L 0.2	pu
Final load torque	F 0.6	pu
< OK > [] View Load Curve		

Figure 8 Mechanical Data Menu

Typical values for the load are shown with the moment of the inertia specified in units of lb-ft². Since all of the model parameters are specified in per unit of motor base values, the WR^2 is converted to the inertia constant, M , using the following relation:

$$M = \frac{WR^2}{g} \cdot \frac{2\pi}{60} \cdot \frac{SynW}{Q_R} \quad (23)$$

where:

g is the acceleration due to gravity

$SynW$ is the synchronous speed

Q_R is the torque calculated from rated speed and horsepower:

$$Q_R = 5252 \cdot \frac{RHP}{FLW} \quad (24)$$

With this motor and load, the moment of inertia of 5000 lb-ft² produces a 23-second starting time.

Defining the Thermal Model

The differential equation for the temperature rise in a conductor, neglecting heat loss, is:

$$I^2 r = C_T \frac{d\theta}{dt} \quad (25)$$

where:

$I^2 r$ is the input watts (conductor loss)

C_T is the thermal capacity of the conductor in watt-sec./°C

$\frac{d\theta}{dt}$ is the rate of change of temperature in °C/second

The equation can be integrated to find the temperature rise:

$$\theta = \frac{1}{C_T} \int_0^t I^2 r \cdot dt \quad (26)$$

Therefore, for constant input watts:

$$\theta = \frac{I^2 r}{C_T} t \quad (27)$$

Motor Characteristics

where

θ is the temperature in $^{\circ}\text{C}$

The heat equation can be represented as a current generator feeding a capacitor (see Figure 9). In this analogy, the current is numerically equal to the watts, the capacitor equals the thermal capacitance, and the charge accumulated on the capacitor represents the temperature rise over ambient caused by the watts.

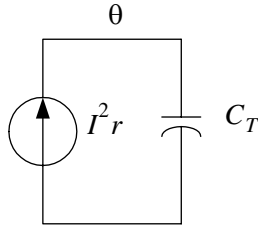


Figure 9 Electrical Analog Circuit

The temperature can be expressed in per unit and be plotted versus per unit current as a time-current characteristic. To do this let:

$$I = m \cdot I_{rated} \quad (28)$$

and substitute for I in Equation 27:

$$\theta = \frac{(m \cdot I_{rated})^2 r}{C_T} t \quad (29)$$

Dividing Equation 27 through by $\frac{(I_{rated})^2 r}{C_T}$ gives:

$$\theta \frac{C_T}{(I_{rated})^2 r} = m^2 t \quad (30)$$

which can be written simply as:

$$U = m^2 t \quad (31)$$

The above equations show that an $I^2 t$ curve can represent a thermal limit. In Equation 31, U represents a specific temperature expressed in seconds. U can be determined from the locked rotor thermal time limit. If, at locked rotor current m_L , the thermal time limit is T_a seconds, then U_L in Equation 32 represents the temperature rise over ambient:

$$U_L = m_L^2 \cdot T_a \quad (32)$$

Using the derived constant, U_L , Equation 31 can be rewritten to solve for time, t , in terms of per unit current, m .

$$t = \frac{U_L}{m^2} \quad (33)$$

Using Equation 33, a plot of time, t , versus per unit current, m , on a log-log grid is a straight line with a slope of 2.

Motor Characteristics

If, at the per unit locked rotor current, m_L , the time to reach the thermal time limit is T_o with the rotor initially at operating temperature, U_o , then Equation 34 relates T_a , T_o , and U_o .

$$\begin{aligned} m_L^2 \cdot T_a &= m_L^2 \cdot T_o + U_o \\ U_o &= m_L^2 \cdot (T_a - T_o) \end{aligned} \tag{34}$$

Equation 31 is the familiar I^2t characteristic, which plots as a straight line of slope 2 on log-log paper. The plot shown in Figure 10 represents a specific limiting temperature.

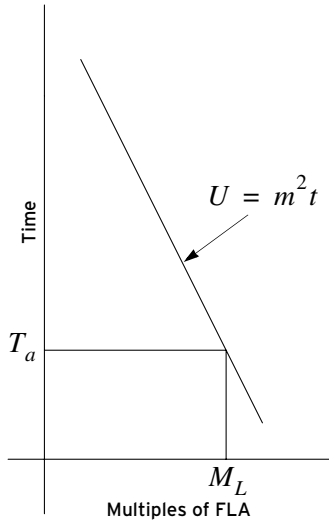


Figure 10 Time-Current Characteristic

The operating temperature, U_o , is caused by one per unit current flowing in the thermal resistance of the conductor. Consequently, Equation 34 is the thermal resistance as shown in the electrical analog in Figure 11.

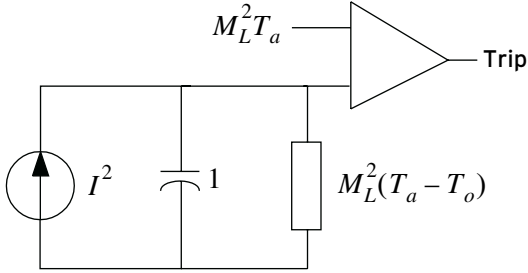


Figure 11 Electrical Analog With Thermal Resistance

Figure 12 shows the rotor thermal model where the input watts are a function of the slip-dependent positive- and negative-sequence resistance, and the current is in per unit of rated motor full load current.

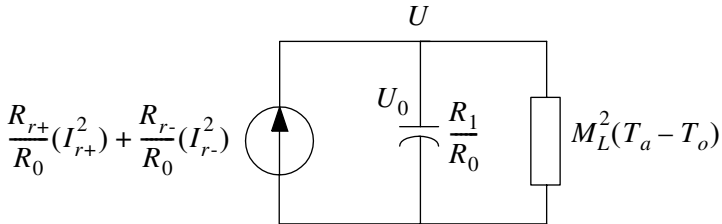


Figure 12 Motor Thermal Model

The Motor Analysis

With the interactive electrical, mechanical, and thermal models defined by the input data, we can now relate the motor current, voltage, and rotor hot spot temperature to time during the start. The plots are calculated by the program and displayed after specifying the parameters in the case menu shown in Figure 13.

CASE CONDITIONS		
Source Voltage	U 1.0	pu
Source Reactance	Xs .056	pu
Initial Temperature	Uo 1.0	pu
Plot Time	Tmax 30	Sec
PLOT MENU		
☒ Volts	☒ Temperature	
☒ Current	☐ Speed	
☐ Log Plot	☒ Relay Response	
☐ Curr, Torq, Rot Res. vs Speed		
☐ Write ASCII Files to Disk B:		
OK		

Figure 13 Case Menu

The plots are shown in Figure 14.

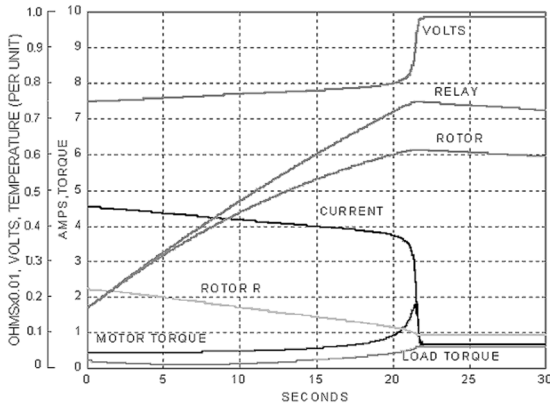


Figure 14 Plot of Motor Voltage, Current, and Rotor Hot Spot Temperature

The plot is essentially an oscillogram of the starting condition. Analyzing the plot, we can see that assigned WR^2 gives the approximate starting time and that temperature, U , reaches only 0.615 per unit of the thermal limit. The relay response indicates an adequate relay coordination margin.

A program option displays a log-log plot of the SEL-501 characteristics shown in Figure 15 and automatically calculates the settings as shown in Figure 16.

Motor Characteristics

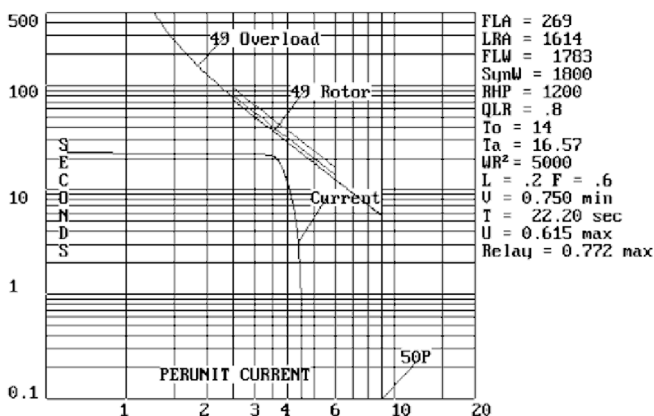


Figure 15 Log-Log Plot of Current and SEL-501 or SEL-701 Characteristic

SEL-501 Motor Setting Example		
Motor Relay Application	APP	MOT units
CT Ratio	CTR	100
Motor Full Load Amps	FLA	2.6 amps
Motor Locked Rotor Amps	LRA	16 amps
Motor Locked Rotor Time	LRT	14 sec.
Rotor Thermal Time Dial	TD	.9 pu
Motor Service Factor	SF	1.0
Phase Definite-Time OC	50PP	24 amps
Phase Definite-Time Delay	50PD	6 cycles
Phase Instantaneous OC	50H	32 amps
Res. Definite-Time OC	50NP	1.5 amps
Res. Definite-Time Delay	50ND	10 cycles
Residual Instantaneous OC	50NH	5 amps
Optional Negative Sequence Settings:		
Neg. Seq. Definite-Time OC	50QP	1.5 amps
Phase Definite-Time Delay	50QD	240 cycles
Continue		

Figure 16 Motor Relay Settings

The parameters chosen to supplement the motor nameplate data allowed us to verify the known motor voltage and accelerating time. The study determined an adequate relay coordination time when the proper relay thermal protection characteristic is applied. The trace of the starting current verified that the existing moderately inverse relay, set for 14 seconds at locked rotor current, lacked the coordination time for the long duration reduced voltage start.

Epilogue

What caused the 1200-hp motor to trip during startup? The time-current plots in Figure 15 on page 24 show no problem in coordinating relays that have an I^2t characteristic with the thermal limit curves of the motor. However, the shape of the induction characteristics available at the time of installation cause conflicts in coordination. As shown in Figure 15, no coordination problem is found in coordinating an I^2t relay characteristic with the locked rotor limit. However, as shown in Figures 17 and 18, a coordination problem can be attributed to the shape of the long-time induction characteristics used at the time of installation. The relay must be set at least 0.03 seconds less than the locked rotor limit of 14 seconds. Consequently, the starting current encroaches the curve at lower multiples of current. Figure 17 shows that a higher voltage and lower load or moment of inertia could allow the normal motor start. However, Figure 18 shows the miscoordination with reduced voltage and nominal load.

Motor Characteristics

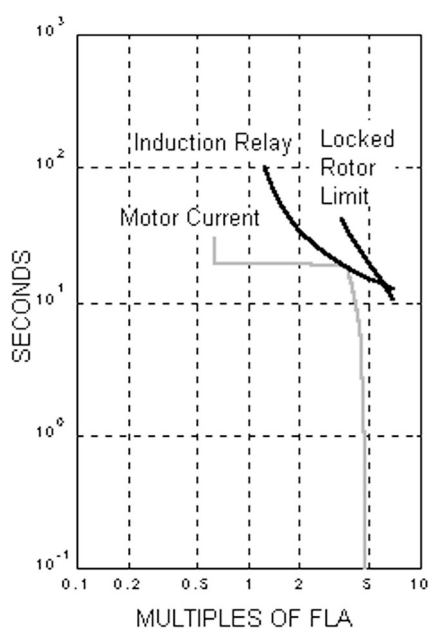


Figure 17 Coordination With Higher Voltage

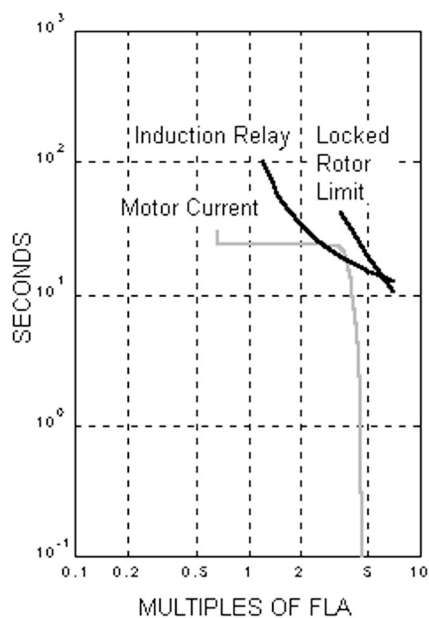


Figure 18 Miscoordination With Reduced Voltage

Protection Using Thermal Model

Thermal Protection

Manufacturers of motor relays have used RTDs to try to protect motors from thermal damage. Unfortunately, the slow response of RTDs reduces their value. Users must instead rely on inverse time-phase overcurrent elements and a separate negative-sequence overcurrent element to detect currents that could lead to overheating. Neither time-overcurrent protection nor RTDs account for thermal history or accurately track the excursions of conductor temperatures.

An element should be used that accounts for the slip-dependent I^2r heating of both positive- and negative-sequence current. The element is a thermal model, defined by motor nameplate and thermal limit data. This mathematical model calculates the motor temperature in real time. The temperature is then compared to thermal limit trip and alarm thresholds to prevent overheating from overload, locked rotor, too frequent or prolonged starts, or unbalanced current.

What data defines the thermal model? Full load speed, the locked rotor current and torque, and the thermal limit time define it. What does torque have to do with the thermal model?

The I^2r heat source and two trip thresholds are identified by the motor torque, current, and rotor resistance versus slip shown in Figure 19. It shows the distinctive characteristic of the induction motor to draw excessively high current until the peak torque develops near full speed. Also, the skin effect of the slip frequency causes the rotor resistance to exhibit a high locked rotor value labeled R_1 , which decreases to a low running value at rated slip labeled R_0 .

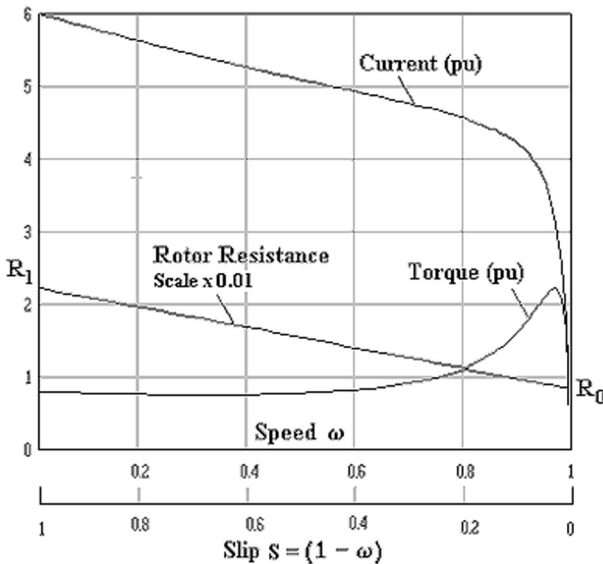


Figure 19 Current, Torque, and Rotor Resistance of an Induction Motor Versus Speed

Protection Using Thermal Model

A typical starting current of six times the rated current and a locked rotor resistance, R_1 , of three times the value of R_0 causes the $I^2 r$ heating to be $6^2 \times 3$ or 108 times normal. Consequently, an extreme temperature must be tolerated for a limited time to start the motor. A high emergency $I^2 t$ threshold is specified by the locked rotor limit during a start, and a second lower threshold for the normal running condition is specified by the service factor. Therefore, the thermal model requires a trip threshold when starting, indicated by the locked rotor thermal limit, and a trip threshold when running, indicated by the service factor.

How is the heating effect of the positive- and negative-sequence current determined? The positive-sequence rotor resistance is plotted in Figure 19 and is calculated using current I , torque Q_M , and slip S in the following equation:

$$R_r = \frac{Q_M}{I^2} S \quad (35)$$

It is represented by the linear function of slip shown in Figure 19. The positive-sequence resistance R_{r+} is a function of the slip S :

$$R_{r+} = (R_1 - R_0) S + R_0 \quad (36)$$

The negative-sequence resistance R_{r-} is obtained when S is replaced with the negative-sequence slip $(2 - S)$:

$$R_{r-} = (R_1 - R_0) (2 - S) + R_0 \quad (37)$$

Factors expressing the heating effect of positive- and negative-sequence current are obtained by dividing Equations 36 and 37 by the running resistance R_0 . Consequently, for the locked rotor case, and where R_1 is typically three times R_0 , the heating effect for both positive- and negative-sequence current is three times that caused by the normal running current.

$$\left. \frac{R_{r+}}{R_0} \right|_{S=1} = \left. \frac{R_{r-}}{R_0} \right|_{S=1} = \frac{R_1}{R_0} = 3 \quad (38)$$

For the running case, the positive-sequence heating factor returns to one, and the negative-sequence heating factor increases to 5:

$$\left. \frac{R_{r+}}{R_0} \right|_{S=0} = 1 \quad \left. \frac{R_{r-}}{R_0} \right|_{S=0} = 2\left(\frac{R_1}{R_0}\right) - 1 = 5 \quad (39)$$

These factors are the coefficients of the positive and negative currents of the heat source in the thermal model.

Starting and Running States of the Thermal Model

Because of its torque characteristic, the motor must operate in either a high current starting state or be driven to a low current running state by the peak torque occurring at about 2.5 per unit current. The thermal model protects the motor in either state by using the trip threshold and heating factors indicated by the

Protection Using Thermal Model

current magnitude. The two states of the thermal model are shown in Figure 20.

The thermal model is actually a difference equation executed by the microprocessor. However, the electrical analog circuit shown in Figure 20 can represent it.

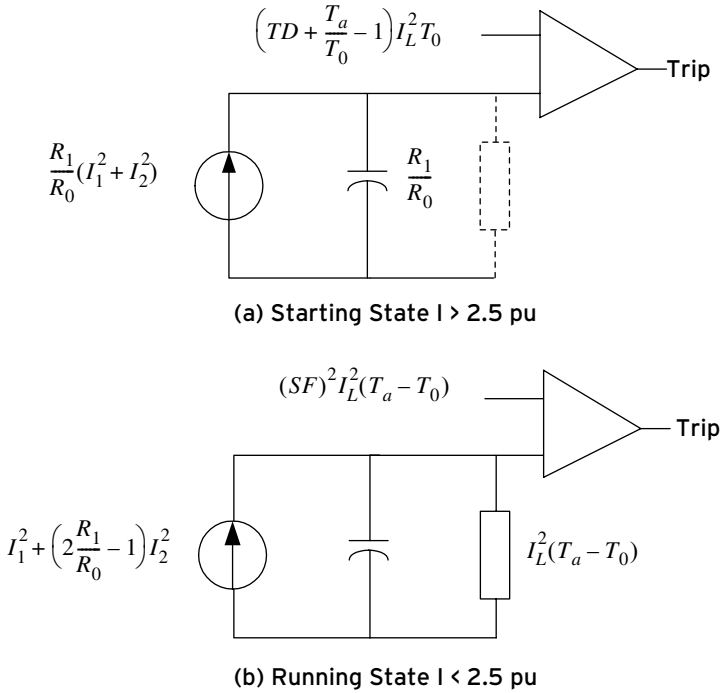


Figure 20 States of the Thermal Model

In this analogy, a current generator represents the heat source, the temperature is represented by voltage, and electrical resistance and capacitance represent thermal resistance and capacitance.

The parameters of the thermal model are defined as follows:

R_1 = Locked rotor electrical resistance (per unit ohms)

R_0 = Running rotor electrical resistance also rated slip
(per unit ohms)

I_L = Locked rotor current in per unit of full load current

T_a = Locked rotor time with motor initial at ambient

T_o = Locked rotor time with motor initially at operating
temperature

The starting state is shown in Figure 20(a) and is declared whenever the current exceeds 2.5 per unit of the rated full load current and uses the threshold and heating factors derived for the locked rotor case. Thermal resistance is not shown because the start calculation assumes adiabatic heating. The running state, shown in Figure 20(b), is declared when the current falls below 2.5 per unit current and uses the heating factors derived for the running condition. In this state, the trip threshold “cools” exponentially from a locked rotor threshold to the appropriate threshold for the running condition using the motor thermal time constant. This emulates the motor temperature that cools to the steady state running condition.

Protection Using Thermal Model

In the model, the thermal limit, $I_L^2 T_a$, represents the locked rotor hot spot limit temperature, and $I_L^2(T_a - T_o)$ represents the operating temperature with full load current. The locked rotor time T_a is not usually specified but may be calculated by using a hot spot temperature of six times the operating temperature in the following relation:

$$\frac{I_L^2 T_a}{I_L^2(T_a - T_o)} = 6 \quad (40)$$
$$\frac{T_a}{T_o} = 1.2$$

There are two reasons for using the rotor model in the running state. The first is that the rotor model accounts for the heating of both the positive- and the negative-sequence current and conserves the thermal history at all times throughout the starting and running cycle. The second is that it is an industry practice to publish the overload and locked rotor thermal limits as one continuous curve as illustrated in Figure 21.

Figure 21 is the time-current characteristic of the thermal model plotted with the motor initially at ambient temperature. Despite the difference in input watts and thresholds, the characteristics of the running and starting states plot as a continuous curve. This condition occurs when the locked rotor threshold is set at 0.8 of $I_L^2 \cdot T_a$, and the motor service factor is 1.2.

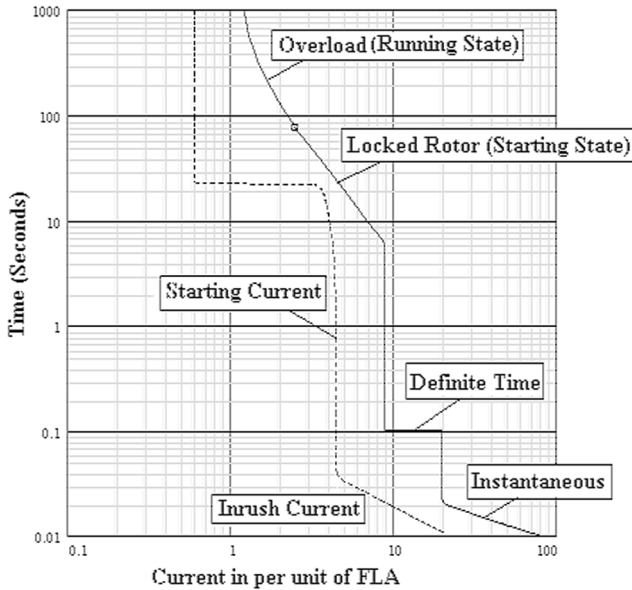


Figure 21 Motor Characteristic and Starting Current

As a final refinement, assigning standard values of 3 and 1.2 to the ratios R_1/R_0 and T_a/T_o , respectively, allows the model parameters to be determined from five fundamental settings:

FLA	Rated full load motor current in secondary amps
LRA	Rated locked rotor current in secondary amps
LRT	Thermal limit time at rated locked rotor current
TD	Time dial to trip temperature in per unit of LRT
SF	Motor rated service factor

U.S. Patent No. 5,436,784 covers the thermal circuit derived in this paper and shown in Figure 20 on page 32.

Fault Protection

In addition to the thermal element described above, definite-time and instantaneous phase and ground elements provide protection for faults in the motor leads and internal faults in the motor itself. The characteristics of these elements are plotted in Figure 21 on page 35. A definite-time setting of about 6 cycles allows the pickup to be set to 1.2 to 1.5 times locked rotor current to avoid tripping on the initial X_d'' inrush current (shown magnified). The instantaneous element is set at twice the locked rotor current for fast clearing of high-current faults. Similar definite-time and instantaneous elements provide for ground fault protection

Motor Thermal Limit Curves

The operation of an induction motor is limited by its thermal capacity and winding temperature. The manufacturer specifies motor thermal capabilities using thermal limit curves. A thermal limit curve is a plot of the maximum possible safe time versus line current in the windings of the machine for conditions other than normal operation. Three situations are represented:

- a) Locked Rotor
- b) Starting and Accelerating
- c) Running Overload

The curves are presented in accordance with guidelines in IEEE Std 620-1996 *Guide for the Presentation of Thermal Limit Curves for Squirrel Cage Induction Motors* [2]. The document states that the curves shall represent two initial conditions: the machine initially at ambient temperature and the machine initially at operating temperature. Plots of time versus the magnitude of the starting current at 100 percent and 80 percent of rated voltage are also included.

Figure 22 is a plot of the thermal limit curves of a 440-V, 400-hp, 3600-rpm motor showing the stator overload curve and the locked rotor characteristic. Figure 23 is a plot of the thermal limit curves for a 4160-V, 1170-hp, 1200-rpm motor and shows the accelerating thermal limit of the rotor.

Motor Thermal Limit Curves

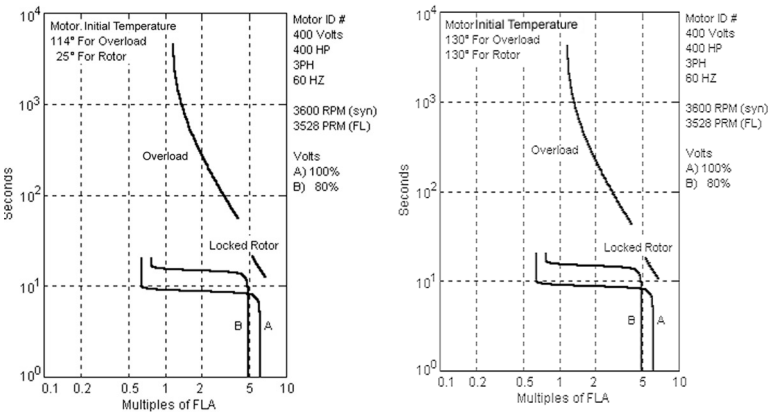


Figure 22 400-HP Motor Overload and Locked Rotor Thermal Limit Curves

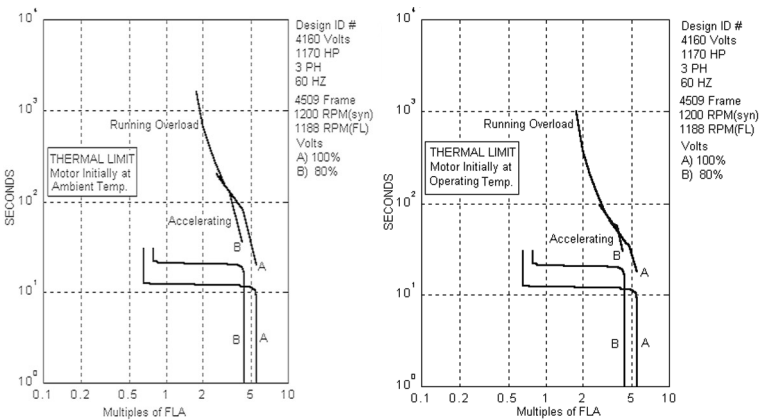


Figure 23 1170-HP Motor Overload and Accelerating Thermal Limit Curves

Rotor Thermal Limit

Figures 22 and 23 show that the rotor characteristic can be either an I^2t curve or an accelerating characteristic at selected voltage. The latter, shown in greater detail in Figure 24, shows the additional time available for starting if the rotor is accelerating.

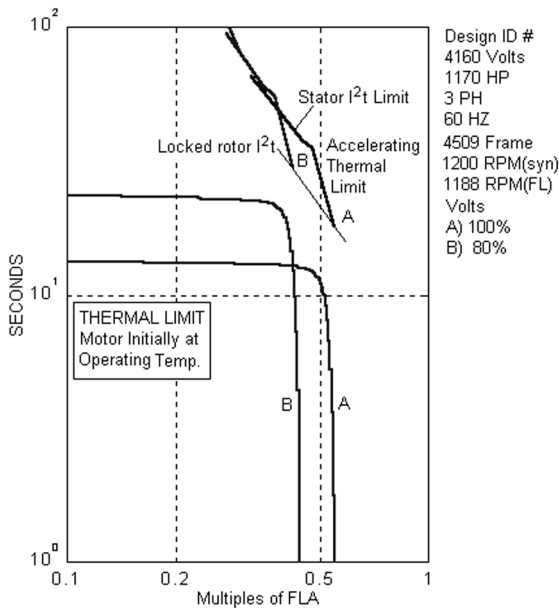


Figure 24 1170-HP Motor Accelerating Thermal Limit Curve

We have seen that the rotor resistance is a function of slip and decreases from a high locked rotor value to a low running value as the motor accelerates (see Figure 5 on page 11 and Figure 6 on page 12). Although the current remains at a high value during the

Motor Thermal Limit Curves

start, the decreasing resistance accounts for the additional thermal limit time at each value of current during acceleration. The I^2t locked rotor characteristic occurs at zero speed (slip =1) and is the line connecting minimum time points of Curves A and B. This results in a slight change in current and an increase in the time to reach the thermal limit. The locus of the time versus current with changing speed produces the steep ATL characteristic. As the rotor time increases, the stator becomes the limit. Curves A and B terminate at the stator I^2t characteristic.

Stator Thermal Limit

We were able to use motor data including locked rotor torque, locked rotor time, full load speed, and hot and cold locked rotor time to define a rotor thermal model that is used to calculate the rotor temperature for any operating condition. The thermal model was then used to explain the locked rotor and the accelerating thermal limit characteristic. Other than the thermal curve, there is no supporting motor data required of the manufacturer that defines the stator thermal model. In addition, the shape of overload characteristics differs depending on the manufacturer. Figures 22 and 23 on page 38 are examples of the variation in shape.

It so happens that the overload characteristic in Figure 22 has the form of a first order thermal model and fits the thermal characteristic equation defined in Clause 3.1.2 of Reference [4]:

$$t = \tau \cdot \ln \left(\frac{I^2 - I_p^2}{I^2 - (k \cdot I_B)^2} \right) \quad (41)$$

where:

- t is the operating time
- τ is the time constant
- I_B is the basic current
- k is the constant
- I is the relay current

Figure 22 also lists the initial temperature for which the hot and cold characteristics are plotted and allows us to determine the initial currents I_H and I_C in the following equations:

$$\begin{aligned} t_{H-CURVE} &= \tau_{th} \ln \left(\frac{I^2 - I_H^2}{I^2 - I_{SF}^2} \right) \\ t_{C-CURVE} &= \tau_{th} \ln \left(\frac{I^2 - I_C^2}{I^2 - I_{SF}^2} \right) \end{aligned} \quad (42)$$

Motor Thermal Limit Curves

where:

τ_{th} is the thermal time constant.

I is the motor current in per unit of full load.

I_{SF} is the current at the service factor.

I_H is the current that raised the temperature to 130°C

I_C is the current that raised the temperature to 114°C

The curves obey the first order process, and we are able to choose τ_{th} , I_H , and I_C so that the equations fit the curves. The ratio of the initial currents squared is related to the rise of the initial temperature over ambient as follows:

$$\frac{I_H^2}{I_C^2} = \left(\frac{130 - 25}{114 - 25} \right) = 1.179 \quad (43)$$

$$I_C^2 = \frac{I_H^2}{1.179} \quad (44)$$

The following solution of Equation 42 will be satisfied when $\tau_{th} = 1370$ and $I_H = 0.92$:

$$I^2 \left(1 - e^{-\frac{t_{H-CURVE}}{RC}} \right) + I_H^2 \cdot e^{-\frac{t_{H-CURVE}}{\tau_{th}}} = 1.15^2 \quad (45)$$

$$I^2 \left(1 - e^{-\frac{t_{C-CURVE}}{RC}} \right) + \frac{I_H^2}{1.179} \cdot e^{-\frac{t_{C-CURVE}}{\tau_{th}}} = 1.15^2$$

Figure 25 shows the first order stator model that can be used to calculate the stator temperature under any operating condition of the 400-hp motor shown in Figure 22. However, the overload curves in Figure 23 are of a different shape and do not list the temperature in the initial temperature data. Consequently, no stator thermal model can be derived.

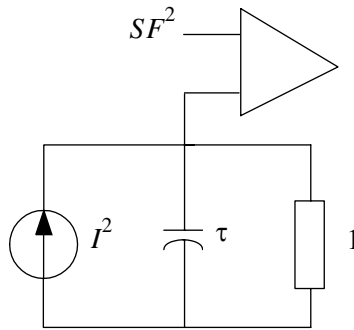


Figure 25 First Order Stator Thermal Models

Motor Protection Requirements

Pullout or Stall Protection

Induction motors will stall when the load torque exceeds the breakdown torque and forces the speed to zero or to some operating point well below rated speed. This occurs when the shaft load torque exceeds the motor developed torque given in Equation 21. In this condition, caused by reduced voltage or excess mechanical load, the motor draws excessive current approaching that of the locked rotor condition. Figures 26 and 27 compare the normal and load stall cases. In the normal case, the motor and load torque reach equilibrium at 99 percent of synchronous speed where the torque is 0.6 per unit of full load. In the stall case, the load torque exceeds the breakdown torque that causes the motor to stabilize at 50 percent speed and a current of 90 percent of the locked rotor current.

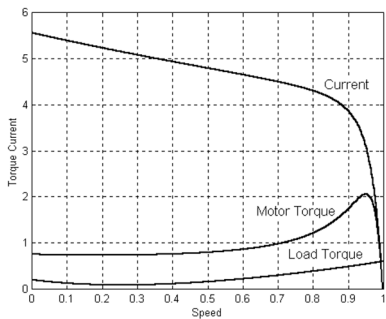


Figure 26 Normal Load

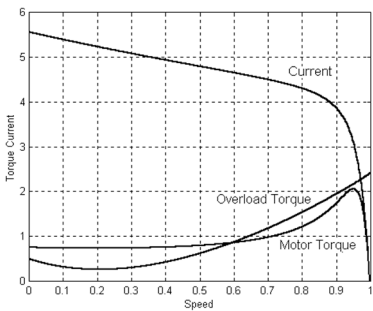


Figure 27 Load Causing Stall

Stall is caused by two conditions:

- a) Load torque exceeds the locked rotor prior to startup
- b) Sudden increase in the shaft load during normal operation

Failure to open a pump discharge gate is the cause of the locked rotor case. Failed bearings are a common cause of stall during a normal running condition.

Normal Starting

An overcurrent relay with an inverse characteristic set to trip for current above the breakdown torque level provides protection for the stall or locked rotor condition. To allow the motor to start and at the same time detect the locked rotor or stall condition, the protection must be set above the motor starting time and below the running overload and accelerating thermal limit or locked rotor thermal limit.

The coordination of the locked rotor protection applied to the 1170-hp motor is shown in Figures 28 and 29. The SEL-701 provides a family of generic extremely inverse curves covering the locked rotor time range from 2.5 to 112.5 at 6 multiples of FLA. The curves are labeled 1 through 45, each curve yielding an increase of 2.5 seconds at 6 multiples of FLA. Curve 5 is selected

Motor Protection Requirements

because it has the time closest to, but less than the locked rotor time of 14.9 seconds at 6 multiples of FLA.

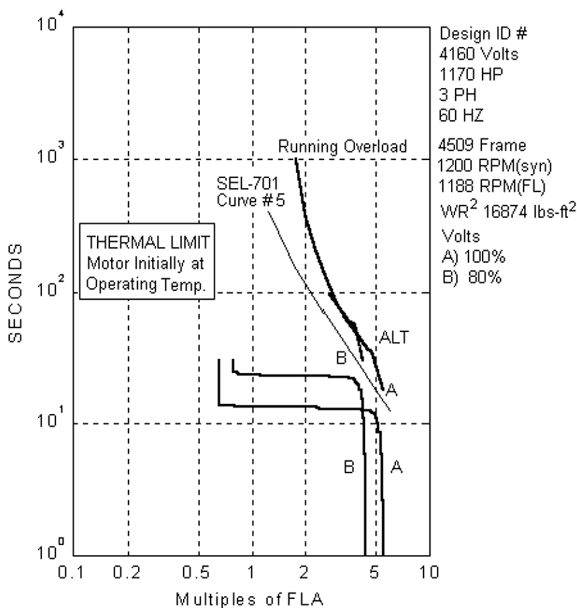


Figure 28 Locked Rotor Protection Using a Generic Curve

Motor Protection Requirements

The thermal model curve shown in Figure 29 was set using the rating method by entering the following motor data using a 300:5 CT:

FLA	Rated full load motor current in secondary amps	2.60
LRA	Rated locked rotor current in secondary amps	14.00
LRT	Thermal limit time at rated locked rotor current	15.00
TD	Time dial to trip temperature in per unit of LRT	0.90
SF	Motor rated service factor	1.15

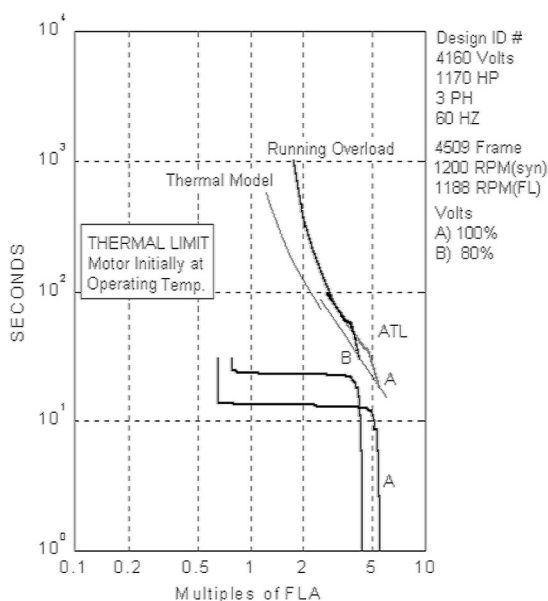


Figure 29 Locked Rotor Protection Using Thermal Model

High-Inertia Starting

Figures 28 and 29 show the normal load case where the starting timer is shorter than the locked rotor time. The normal load allows the relay trip time to be long enough to let the motor start yet short enough to prevent the current from exceeding the locked rotor limit. Figure 30 shows the start of the same motor where the moment of inertia of the load has been increased from the 16874 lb-ft² in the original case to 26000 lb-ft².

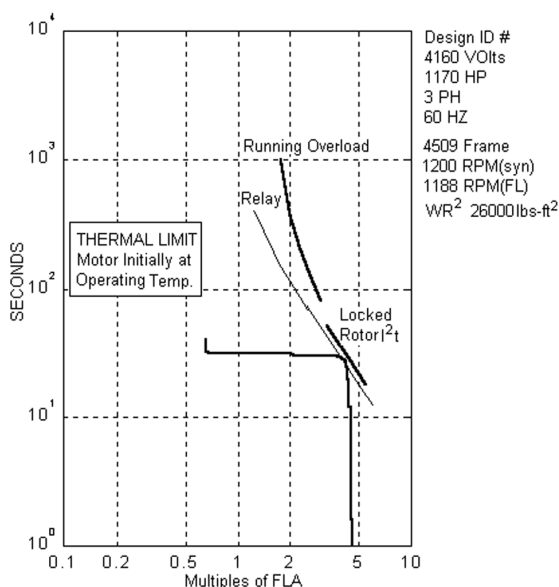


Figure 30 High-Inertia Starting Current

The increase extends the starting time, and the current encroaches on the locked rotor limit. This is the classic high-inertia case

where the motor appears to overheat and the relay cannot be set to avoid a trip. However, as discussed above, the skin effect of the slip frequency causes the rotor resistance to decrease from a high locked rotor value, R_1 , to a low running value, R_o , at rated speed. Although the starting current remains high, the I^2R watts decrease and allow more starting time during acceleration.

Figure 31 shows a plot of the starting current, the rotor resistance, the relay response, and the rotor temperature during the high inertia start. The plot shows clearly that the I^2t relay responds only to current and asserts a trip. The rotor temperature is caused by the reduced I^2R watts and reaches a maximum only 80% of the limiting value.

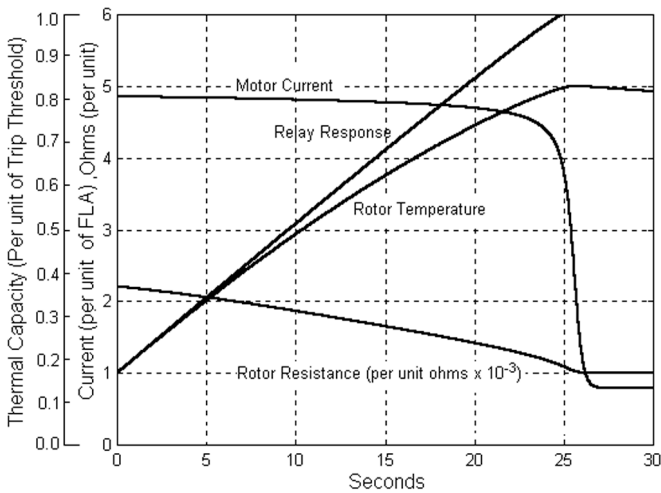


Figure 31 Relay and Rotor Response During High-Inertia Start

Speed Switch Supervision

Even though the relay will trip during a normal start, it is still necessary to set the relay to trip in less than the locked rotor limit in case the motor fails to accelerate. A speed switch should then be used to detect acceleration and block the trip. Speed detection can be in the form of a centrifugal switch or contact-making tachometer.

Impedance Relay Supervision

The speed of a motor is indicated by the apparent impedance magnitude and phase angle measured at the terminals. We can see how the motor impedance changes with speed in the motor equivalent circuit of Figure 5 on page 11. At zero speed, the resistor representing the mechanical power loss is zero, and the motor takes on the locked rotor impedance with a high inductive phase angle. As the speed increases (slip decreases) the motor impedance increases, and its phase angle decreases with the insertion of the load resistor.

Figure 32 shows the trajectory of the motor impedance during a start. If the motor terminal voltage is available, the mho characteristic of an impedance relay can be used to supervise locked rotor protection as shown in the figure. The impedance is that produced by the high inertia start shown in Figures 30 and

31. The impedance relay is set to open its contacts at 50 percent speed.

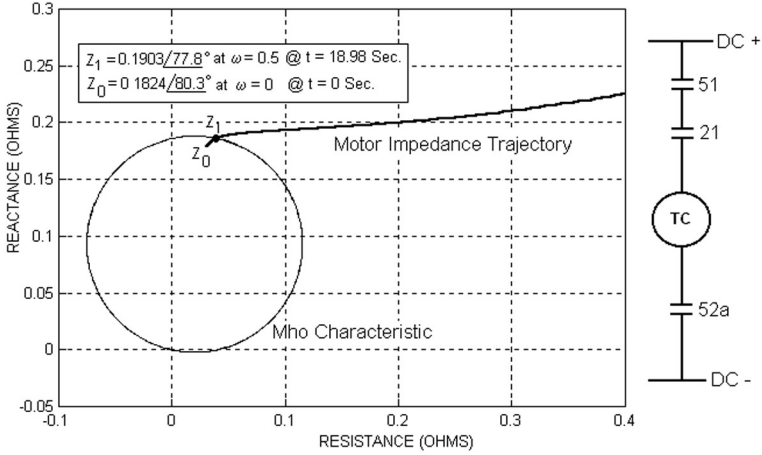


Figure 32 Trajectory of Motor Impedance During Starting

The full load current of the 4160-V, 1170-hp motor is FLA = 159 amps. Using 300:5 CTs and 4200:120 VTs, the phase-distance relay element setting Z_M at characteristic angle of 77.8 degrees is calculated as follows:

$$\begin{aligned}
 Z_{BASE} &= \frac{4160}{159 \cdot \sqrt{3}} = 15.1 \text{ ohms} \\
 Z_M &= .1903 \cdot Z_{BASE} = 2.87 \text{ ohms} \\
 Z_{MHO} &= \frac{CTR}{PTR} \cdot Z_M = \frac{300}{5} \cdot \frac{120}{4200} \cdot Z_M = 4.93 \text{ ohms}
 \end{aligned} \tag{46}$$

Phase and Ground Protection

Phase and ground overcurrent protection are needed to limit the damage caused by faults internal to the motor windings and in the leads in the motor zone of protection. Phase overcurrent also provides a measure of ground fault protection. However, ground faults occur most frequently and can be cleared with greater sensitivity by residual ground overcurrent relays. The application of phase and ground definite-time overcurrent relays is shown in Figure 33.

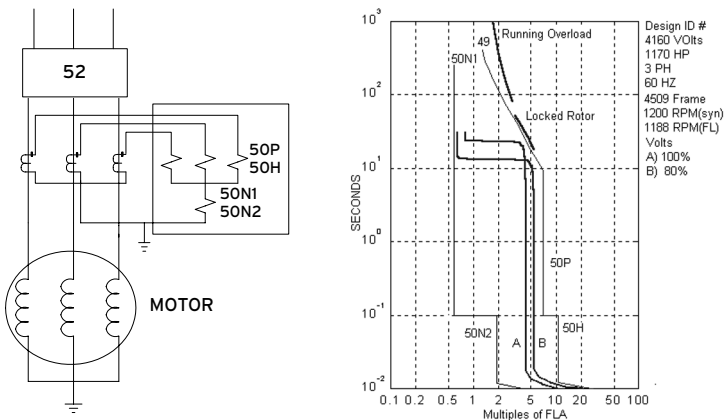


Figure 33 Application of Phase and Ground Definite-Time Overcurrent Elements

The phase definite-time overcurrent element 50P is set at 120 percent of the rated locked rotor current with a 10-cycle time delay to override the subtransient inrush during starting. The

high-set definite-time overcurrent element is set to two times the rated locked rotor current for high-speed clearing of high-fault current.

The definite-time elements 50N and 50NH provide sensitive ground fault protection. The 50N element is set with a pickup of 1.5 amps or 0.56 multiples of FLA with a time delay of 10 cycles. The time delay is set to override false residual current caused by saturation due to asymmetry in the high starting current.

Figure 34 shows offset three-phase starting current with the minimum distortion that produces the false residual current.

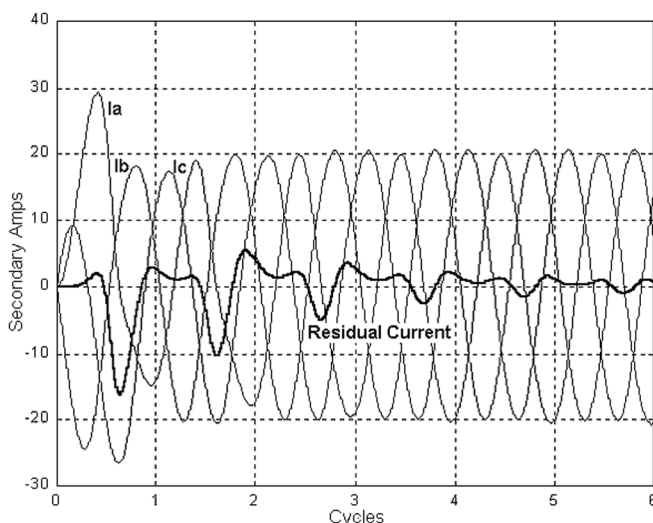


Figure 34 Three-Phase Starting Current With False Residual

Motor Protection Requirements

Figure 35 shows the false residual current and the magnitude of the filtered fundamental that would cause the 50NH element set at 1.5 amps to trip without the appropriate overriding time delay.

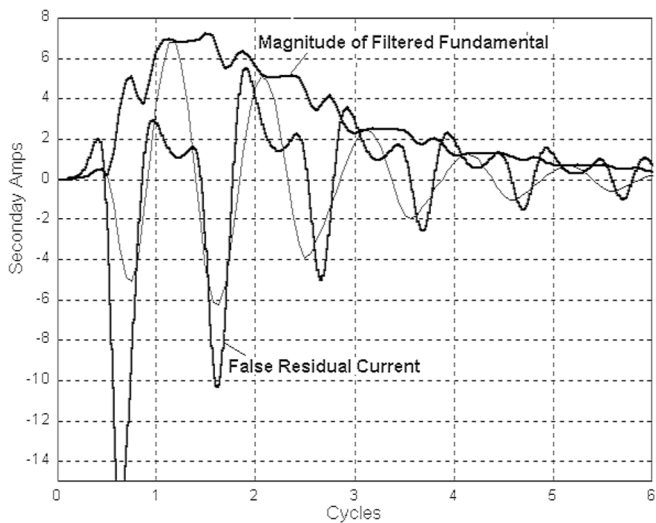


Figure 35 False Residual Current Overridden by Time Delay

For maximum sensitivity, ground fault relays can be connected to toroidal current transformers encircling the lead conductors as shown in Figure 36.

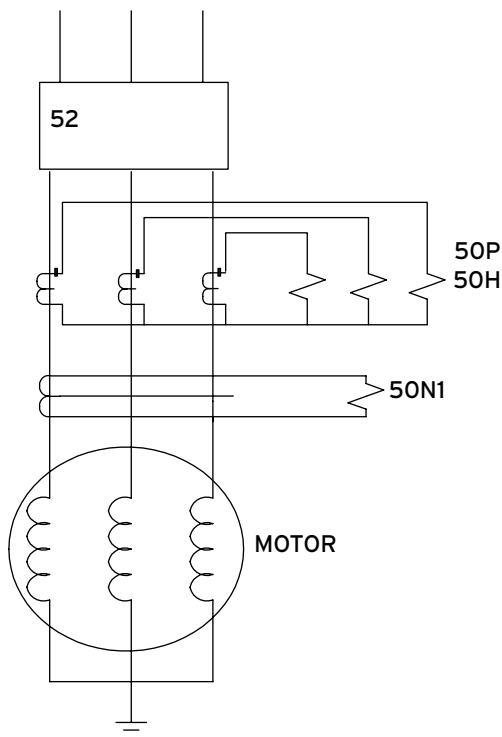


Figure 36 Sensitive Ground Protection Using a Zero-Sequence Ground Sensor

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A 50N1 overcurrent relay set with a pickup of 1.0 amps gives a pickup of 10 amps primary when a 50:5 zero-sequence sensor is used. Saturation is avoided since the sensor responds only to the flux caused by unbalance in the sum of the three-phase currents.

Differential Protection

Differential relays provide fault protection by operating only on the difference of the current entering and leaving the motor windings. Differential relays provide sensitive protection and detect faults well below normal load current and do not trip for high fault current external faults. They also protect motor cables included in the differential zone, but do not detect turn-to-turn faults. Figures 37 and 38 show the connections for differential protection of wye- and delta-connected motors.

Since the percentage differential relay compares the incoming with the outgoing current, the current transformers should be of one ratio, type, and manufacturer. The current transformers should not be used for any other purpose without carefully checking the effect added burden has on performance. Three current transformers are usually located in the switchgear in order to include the motor cables on the zone of protection. The remaining three current transformers are located in the neutral connection of the motor. Six leads must be brought out from the motor as specified at the time of purchase.

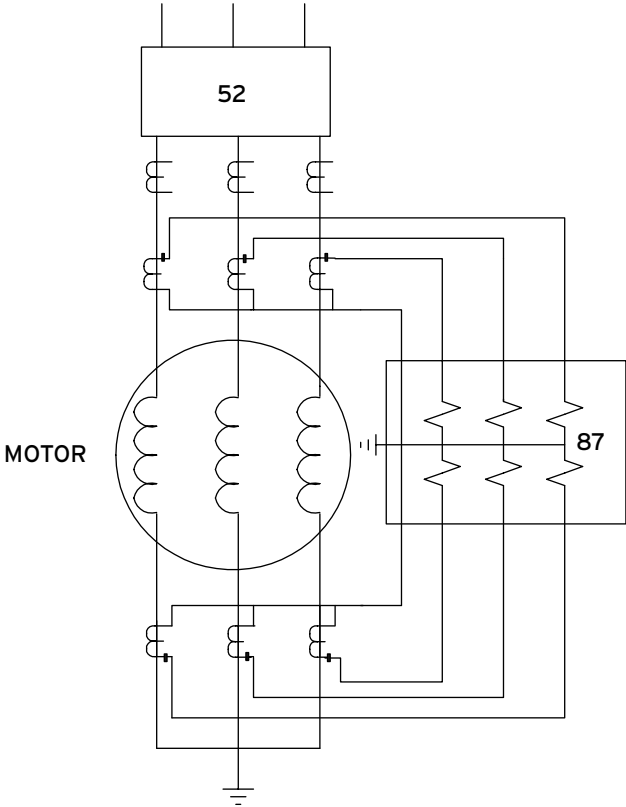


Figure 37 Wye-Connected Differential

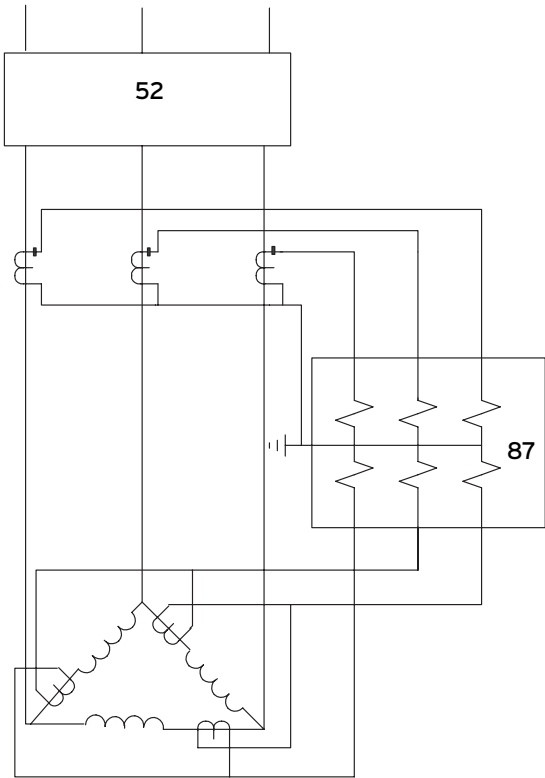


Figure 38 Delta-Connected Differential

The motor leads shown in Figure 39 are arranged so that both ends of each motor winding form the primary winding of the current transformer. The differential relay operates on the difference or internal fault current. This flux-balancing scheme provides extremely sensitive phase and ground protection by using an overcurrent relay.

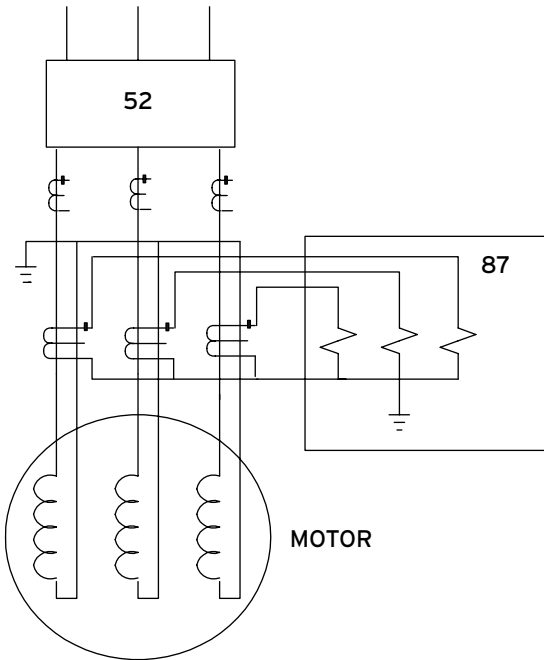


Figure 39 Flux-Balance Differential Protection

In the usual motor configuration, the motor feeder cables cannot be included in the differential zone and must be protected by

Motor Protection Requirements

other devices. Figure 40 shows the application of the SEL-501 Dual Relay to provide motor protection with self-balance differential.

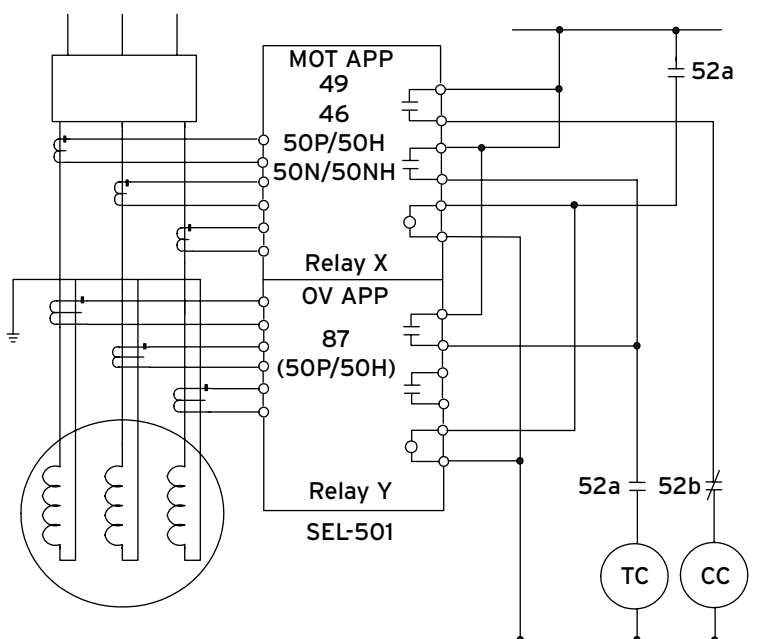


Figure 40 SEL-502 Dual Relay Provides Motor and Differential Protection

Running Overload Protection

Insulation systems, over time, lose their physical and dielectric integrity, and excessive temperature accelerates the process. The length of time at a given temperature determines the insulation

life. The effect of elevated temperature is to reduce the ability of the insulation to withstand electrical or mechanical abuse. The temperature level at which the insulation should be protected is a matter of judgment with some guidance in standards (see NEMA MG1-1998, 20.40, 21.40).

Locked rotor current causes such a high rate-of-rise of rotor temperature that there is little time for heat lost before reaching the limiting temperature. However, induction motors have a large heat storage capacity, and slight overloads for short periods of time do not produce damaging temperature excursions. Motor manufacturers indicate maximum temperature with thermal limit curves that we have discussed above and shown in Figures 22 and Figure 23 on page 38. The equation of the thermal limit curves in Figure 22 is the solution of the first order equation:

$$I^2 R_T = R_T C_T \cdot \frac{d\theta}{dt} + \theta \quad (47)$$

where:

$R_T C_T$ is the thermal time constant = 228 seconds

θ is the temperature at $t = 0$

R_T is equal to 1

The time-discrete form of Equation 47 can be written as:

$$I^2 R_T = R_T C_T \cdot \frac{\theta_n - \theta_{n-1}}{\Delta t} + \theta_{n-1} \quad (48)$$

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Solving for θ_n provides the following iterative equation for temperature:

For $n = 1 \dots$

$$\begin{aligned}\theta_n &= \frac{I_2}{C_T} \Delta t + \left(1 - \frac{\Delta t}{R_T C_T}\right) \cdot \theta_{n-1} \\ \theta_{n-1} &= \theta_n\end{aligned}\tag{49}$$

Next n

Equation 49 is the basis of the algorithm that enables a microprocessor relay to continuously calculate the temperature of a thermal process. The algorithm also monitors the temperature and asserts a trip or an alarm signal when it exceeds predetermined thresholds. All that needs to be identified is the thermal time constant and the trip threshold equal to the square of the service factor.

Figure 41 shows the dynamic response of the algorithm to a high pulse of current followed by a lower constant current. The

temperature shows an exponential rise to a peak followed by an exponential decay to the final value.

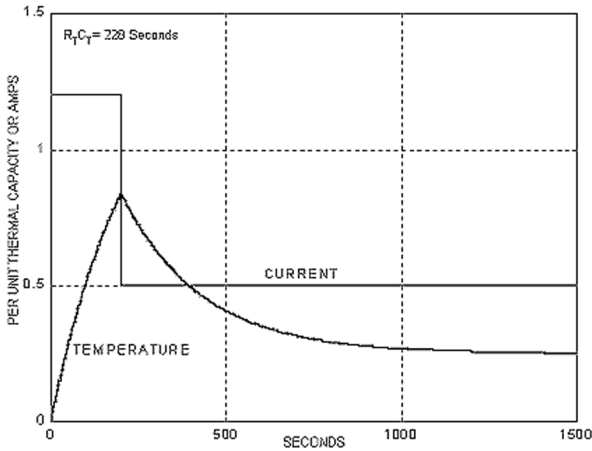


Figure 41 Dynamic Response of the First Order Thermal Model

Thermal Versus Overcurrent Model

Thermal limit curves have the appearance of inverse time-current overcurrent characteristics. Indeed, overcurrent relays are applied for overload protection. It is instructive to compare the response of the thermal model with the response of an overcurrent model of a thermal limit curve. The thermal model given by Equation 49

Motor Protection Requirements

is derived from the first order differential equation. Rather than using the differential equation, the overcurrent model is derived by integrating the reciprocal of the hot curve specified in Equation 3 of the IEEE Standard C37.112-1996. The incremental process is as follows where the $I_0 = 0.92$ and $kI_b = 1.15$:

$$t_H = 1370 \cdot \ln \left(\frac{I^2 - (0.92)^2}{I^2 - (1.15)^2} \right) \quad (50)$$

For $I > 1.15$:

$$\theta_n = \theta_{n-1} + \frac{\Delta t}{t_H} \quad (51)$$

For $I \leq 1.15$:

$$\theta_n = \left(1 - \frac{\Delta t}{1370} \right) \cdot \theta_{n-1} \quad (52)$$

Equation 50 is the time-current characteristic. Equation 51 is used to calculate the response of the overcurrent relay above the pickup current. θ_n and θ_{n-1} are consecutive samples displaced by one time increment. Below pickup, the overcurrent model yields no value and must be reset. Consequently, exponential reset is used with the thermal time constant to emulate the cooling.

Figure 42 shows the response of both models to a current below pickup. Whereas the overcurrent model has no response, the thermal model calculates the temperature that rises exponentially toward the steady state temperature $\theta = 0.846$.

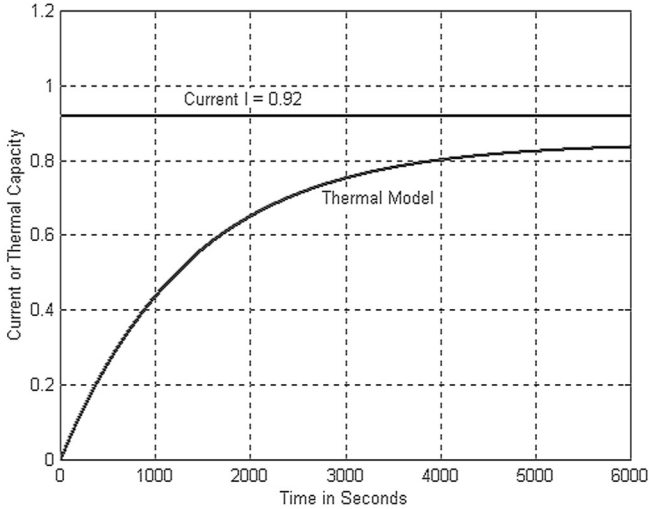


Figure 42 Responses of Models to a Current Less Than the Service Factor

Motor Protection Requirements

Figure 43 shows that the overcurrent and the thermal model produce the same trip time when the protected process is initially at the temperature specified for the hot thermal limit curve.

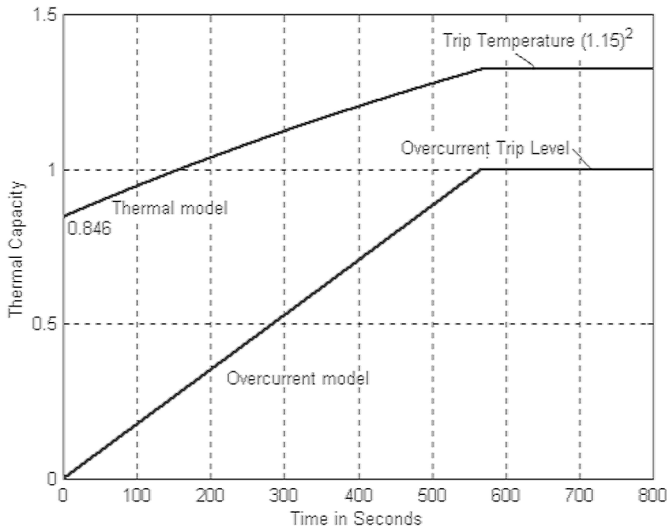


Figure 43 Thermal and Overcurrent Response With Initial Temperature at 0.846

Figure 44 shows the trip times with a lower initial temperature. The thermal model asserts a trip signal at the limiting

temperature, while the overcurrent trips at the hot curve time, independent of the initial temperature of the protected process.

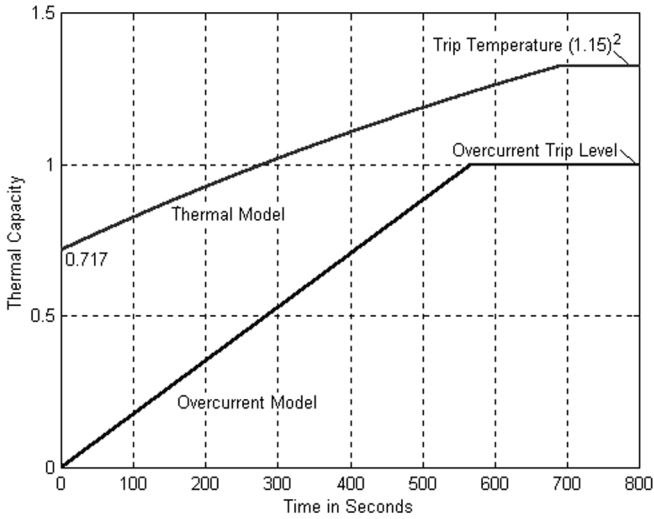


Figure 44 Thermal and Overcurrent Response With Initial Temperature at 0.717

In Figures 45 and 46, the thermal model and the overcurrent model are subjected to a cyclic overload with the protected thermal process initially at 0.846 per unit of thermal capacity. The cyclic current alternates between 1.4- and 0.4-per-unit current every 10 minutes. Note that the average of the currents squared and the rms currents are:

Motor Protection Requirements

$$I_{2aver}^2 = \frac{I_{high}^2 + I_{low}^2}{2} = \frac{1.4^2 + 0.4^2}{2} = 1.06 \quad (53)$$

$$I_{RMS} = \sqrt{1.06} = 1.03$$

The cyclic current is not an overload that raises the temperature to the trip value of $(1.15)^2$. Figure 45 shows that the cyclic temperature response of the thermal model reaches a 1.06 average, 80 percent of the trip value.

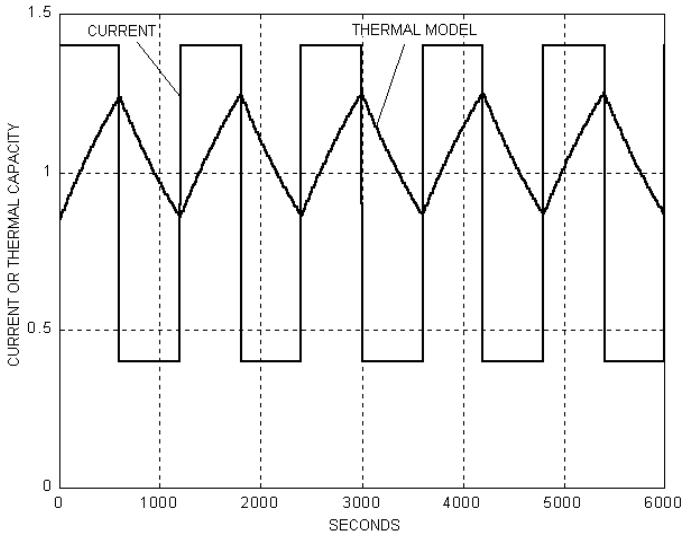


Figure 45 Thermal Model Responds to the RMS Current of the Cyclic Overload

The overcurrent relay model does not measure temperature, and its signal rises too quickly and falls too slowly to avoid issuing a premature trip signal as shown in Figure 46.

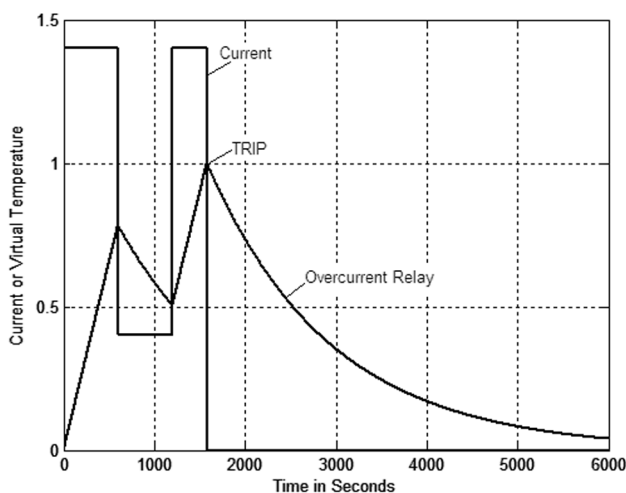


Figure 46 Overcurrent Model Trips Prematurely With Cyclic Overload

RTD Temperature Sensors

Stator temperature can be obtained directly from resistance temperature devices embedded in the insulation near the winding conductors. The sensors, known as RTDs, are placed during construction of the motor. RTDs have a linear positive temperature coefficient of resistance. Consequently, a direct measurement of the RTD resistance including its leads is measured in a bridge circuit and converted directly to temperature. Motors of 1500 hp and above usually are equipped with three RTDs per phase winding, two RTDs to measure bearing temperature, and an additional RTD to indicate temperature. Available types of RTDs are 100-ohm platinum, 100-ohm nickel, 120-nickel, and 10-ohm copper. The extra phase RTDs provide for redundancy.

Microprocessor relays accommodate for the measurement of up to 12 RTDs and provide trip and alarm temperature threshold to supplement the thermal overload protection. However, they respond too slowly to be used as the primary overload protection. RTDs are particularly useful in detecting overheating caused by clogged ventilation. The RTDs provide the direct temperature measurement when the winding temperature rises faster than indicated by current.

Current Balance Protection

Unbalanced current in the stator winding causes an adverse distribution current in the rotor, resulting in excess heating. The current distribution occurs as follows. A balanced current in the energized three-phase stator windings creates a field that rotates at synchronous speed. With the motor at rest, the field induces a voltage that drives short circuit current in rotor bars. The current in turn reacts with the stator field to produce torque that accelerates the rotor. At the same time, the flux forces the current to flow in a third of the cross section of the rotor bars at the outer periphery of the rotor when the rotor is at rest. With the current in one-third the area, the rotor resistance is three times the running resistance as shown on Figure 6 on page 12. As the motor accelerates, the rotor catches up with the rotating flux. As the slip frequency decays, the current occupies more and more of the rotor cross-sectional area. This 60-hertz skin effect is called the deep bar effect. It is an important phenomenon used by motor designers to increase the starting torque by increasing the initial resistance.

Motor Protection Requirements

Therefore, rated speed causes the current to be uniformly distributed. However, with unbalanced stator current, the negative-sequence current causes a field that rotates in a direction opposite to that of the rotor. This means that the field rotates at twice the frequency, less a few percent slip, and causes the current to occupy a sixth of the area of the rotor bars. This concentration of current causes excess heating that can quickly overheat and damage the rotor. The distribution is shown in Figure 47.

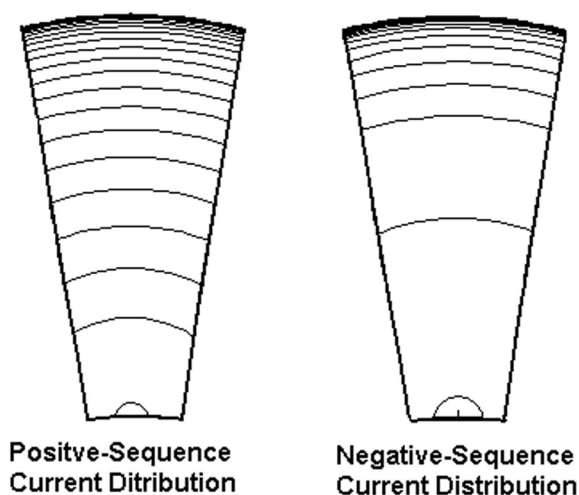


Figure 47 Distribution of Rotor Bar Current

In the previous discussion of thermal models (see Equation 39), we found that the negative-sequence heating factor depends on the ratio of the locked rotor resistance, R_l , and the running resistance, R_o , and that the locked rotor torque and the rated

speed determine the ratio. Consequently, for a typical ratio of 3, the heating factor of negative-sequence current is five that of the positive-sequence current. We can then see that any unbalance causes excessive heating and that an open phase in a running motor is the most severe case. When single phasing occurs, the negative-sequence current equals the positive-sequence current. At full load, the heating effect is that of a locked rotor case:

$$I_1^2 + 5 \cdot I_2^2 = (1 + 5) \cdot I_{FLA}^2 = 6 \cdot I_{FLA}^2 \quad (54)$$

The running thermal model shown in Figure 20 on page 32 accounts for the negative-sequence heating and provides unbalance protection under all operating conditions. The unbalanced current condition can be considered to be an abnormal running condition that can be cleared immediately using a negative-sequence overcurrent element. A pickup setting of $3I_2 = 1.5$ amps with a time delay up to 4 seconds is a usual setting.

Abnormal Voltage

Motors in general are capable of operating at rated load with a ± 10 percent variation from normal voltage. However, overvoltage increases magnetizing current and eddy current losses and decreases power factor. Since motors are in general constant kVA loads, current increases with decreasing voltage. In addition, torque decreases as the square of the voltage. Consequently, low

Motor Protection Requirements

voltage causes increased temperature and the possibility of stalling, in the worst case. In the case of a synchronous motor, the motor may not reach sufficient speed to enable it to pull into synchronism when the field is applied.

Both under- and overvoltage elements are provided in microprocessor motor protection relays. However, whether or not these protective elements are required depends upon the service that the protected motor is providing. Essential motors should not be removed from service by relays that do not protect the system from the effect of a fault on the motor or its associated circuit. In particular, power plant auxiliary fans and pumps are essential to keeping a generator from shutting down during critical system disturbances. Voltage elements are applied with an appropriate time delay to allow for the depressed voltage during starting and to override short duration disturbances.

Synchronous Motor Protection

Synchronous motors are started as unloaded induction motors with starting torque provided by limited rotor bars called amortisseur or damping windings. The starting interval is short and requires a short duration locked rotor protection if it is applied at all. Thermal overload is applied for the stator winding. The dc field current is applied to the synchronous motor as it nears synchronous speed. Loss-of-field excitation occurs when the dc current to the synchronous motor field is removed, either

by opening the dc supply breaker or contactor, degradation of the contact of the brushes to the slip rings, or control or rectifier failure of a brushless system. The reduction or absence of excitation, which results in excessive VARs into the motor, causes end iron heating and stray load losses. The ultimate result is a loss of synchronism.

Microprocessor motor protection relays provide a VAR element for loss-of-field protection of large synchronous motors. Figure 48 is a diagram of the equivalent circuit used in a loss-of-field power swing study. The diagram shows the typical time increment and the motor inertia constants that are used and where f is the system frequency.

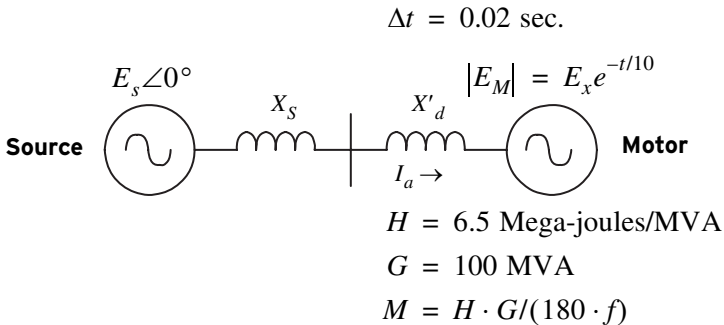


Figure 48 Motor Equivalent for Loss-of-Field Study

The incremental change of the motor velocity is obtained by assuming input power P_{IN} and using the parameters listed in Figure 48 in the following power transfer equations:

Motor Protection Requirements

$$P_{OUT} = \frac{E_S E_M}{X_S X_d'} \sin(\alpha) \quad (55)$$

$$P_{ACC} = P_{IN} - P_{OUT} \quad (56)$$

$$\omega = \frac{\Delta t}{M} P_{ACC} + \omega_0 \quad (57)$$

$$\alpha = \omega \cdot \Delta t + \alpha_0 \quad (58)$$

Note that the disturbance causing the incremental change in the velocity ω and the phase angle α is the exponential decay of the magnitude of the motor internal voltage due to the loss of field.

Figure 49 shows the VAR trajectory during a loss-of-field event. The trace starts with the normal condition of lagging VARs and progresses toward leading VARs as the field flux decays.

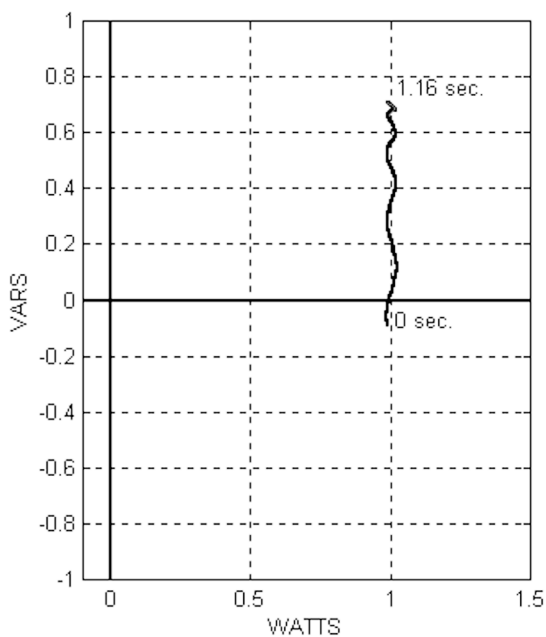


Figure 49 VAR Trajectory During Loss-of-Field

Drive Protection

Motor drives are subject to load jams that can stall the motor after a period of normal operation and also to load loss caused by a broken conveyor belt. These abnormal drive conditions can be detected using the motor current. Load jam increases the motor current to near the locked rotor level. The load jam element operates by sensing starting current and is enabled after a time delay that is longer than the motor starting time. Load jam pickup is set greater than any expected load current and less than the locked rotor. The load loss element trips and/or alarms after an appropriate time delay.

The load loss element is armed after the motor starts following a settable load loss starting time delay. The delay allows pumps or compressors to reach normal load. The trip and/or alarm occur when the current drops below a load loss current setting for a predetermined time delay. When the relay is equipped with voltage inputs, the load loss can be operated with a three-phase power measurement element. As before, starting current arms the load loss element. Trip and/or alarm occur when the input power falls below the load loss minimum power setting after an appropriate time delay.

Guidelines for Calculating Settings for Motor Protection Relays

Required Motor Data

Following are the data for a 1170-hp induction motor. The list is the complete set of data required to calculate the motor starting time and the motor protection element settings:

- | | | |
|-----|----------------------------|------------------------------------|
| 1. | Rated Voltage | 4160 volts |
| 2. | Source Impedance | 0.04 per unit of motor base |
| 3. | Rated Horse Power | 1170 hp |
| 4. | Rated Speed | 1188 rpm |
| 5. | Synchronous Speed | 1200 rpm |
| 6. | Locked Rotor Torque | 0.89 per unit of full load torque |
| 7. | Rated Service Factor (SF) | 1.15 per unit of full load current |
| 8. | Full Load Current (FLA) | 159 amps |
| 9. | Locked Rotor Current (LRA) | 869 amps |
| 10. | Hot Locked Rotor Time | 18.0 seconds |
| 11. | Cold Locked Rotor Time | 21.6 seconds |
| 12. | Motor With Drive WR^2 | 16,874 lb-ft ² |

Guidelines for Calculating Settings for Motor Protection Relays

Estimating Motor Data

The reasonable estimate of full load current can be calculated using the rated voltage and horsepower in the following equation:

$$I_{FLA} = \frac{746 \cdot hp}{0.8 \cdot V_{rated} \cdot \sqrt{3}} = \frac{746 \cdot 1170}{0.8 \cdot 4160 \cdot \sqrt{3}} = 151 \quad (59)$$

The calculation is within 5 percent of listed value. The reasonable estimate is obtained by assuming that the locked rotor current is six times the full load current:

$$I_{LR} = 6 \cdot I_{FLA} = 6 \cdot 151 = 906 \quad (60)$$

The estimate is within 10 percent of the listed locked rotor current. In addition, the rated speed can be estimated by assuming a rated slip of 1 percent. The listed speed in this case is 0.9 per unit of the 1200-rpm synchronous speed. The WR^2 may also be estimated using a motor starting study when the motor starting time is known from experience. However, the locked rotor time cannot be estimated and must be obtained from the manufacturer.

Selecting CTs Used for Motor Protection Relaying

CT Ratio

Motor protection relays provide full-load settings from 1-8 amps to accommodate a range of existing current transformers when

Guidelines for Calculating Settings for Motor Protection Relays

upgrading motor protection. For new installations, select the current transformers using the nearest standard ratio that places the motor full load current nearest two-thirds of the CT primary rating. Using the FLA of the 1170-hp motor data:

$$CT_{RATING} = \frac{3}{2} \cdot I_{FLA} = \frac{3}{2} \cdot 159 = 238.5 \quad (61)$$

Select 300:5 as the next highest standard CT ratio.

CT ANSI Rating

The criterion to avoid saturation is:

$$20 \geq V_S = \left(\frac{X}{R} + 1 \right) \cdot I_b \cdot Z_b \quad (62)$$

where:

- I_b is the maximum fault current in per unit of CT rating
- Z_b is the CT burden in per unit of standard burden
- X/R is the X/R ratio of the primary fault circuit
- V_S is the saturation voltage to be limited to 20 or less

For motor applications, the CT should not saturate when subjected to the asymmetrical portion of the motor starting or locked rotor current. If locked rotor current for the 1170-hp motor

Guidelines for Calculating Settings for Motor Protection Relays

is 869 amps and the total CT burden including leads and winding resistance is 0.5 ohms:

$$I_b = \frac{I_{LRA}}{CT_{RATING}} = \frac{869}{300} = 2.9 \quad (63)$$

The X/R ratio is taken as the tangent of the locked rotor impedance angle. Eighty degrees can be taken as the motor impedance phase angle.

$$\frac{X}{R} = \tan(80^\circ) = 5.67 \quad (64)$$

The standard burden for a C50 CT is 0.5. Therefore the Z_b is one per unit of the standard burden. Consequently, 300:5 C50 CTs meet the criteria and avoid saturation during a motor start:

$$20 \geq V_s = \left(\frac{X}{R} + 1 \right) \cdot I_b \cdot Z_b = (5.67 + 1) \cdot 2.9 \cdot 0.5 = 19.3 \quad (65)$$

The CT rating assures that there will be no false residual current during a start that would trip a sensitive ground overcurrent relay.

Note that the maximum phase-to-phase fault current on power plant auxiliary buses can be as high as 40,000 amps with an X/R ratio of 40. Dedicated overcurrent relays with high ratio and adequate ANSI ratings are required to trip and clear faults of this severity.

Setting Guidelines

Phase and Residual O/C Settings

The criteria for setting the phase and ground definite-time overcurrent elements are as follows:

Level 1 Phase O/C Pickup 50P1P	= 1.2 Times Locked Rotor Current (LRA)
Level 1 Phase O/C Time Delay 50P1D	= 0.10 seconds
Level 2 Phase O/C Pickup 50P2P	= 1.5 Times Locked Rotor Current
Level 2 Phase O/C Time Delay 50P2D	= 0.0 seconds
Level 1 Residual O/C Pickup 50N1P	= 1.5 amps
Level 1 Residual O/C Time Delay 50N1D	= 0.1667 seconds
Level 2 Residual O/C Pickup 50N2P	= 5.0 amps
Level 2 Residual O/C Time Delay 50N2D	= 0.0 seconds
Negative-Sequence O/C Pickup 50QP*	= 1.5 amps
Negative-Sequence O/C Time Delay 50QD	= 4.0 seconds

*Note that 50QP responds to $3I_2$

Overload and Locked Rotor Settings

The SEL-701 Motor Protection Relay provides three distinct methods for setting the thermal protection of the rotor and stator. The method used depends on the preference of the application engineers. The methods are:

RATING METHOD: In this method, you enter motor rating and nameplate data. The relay uses the data to determine the parameters of the start and running thermal models.

When using the RATING METHOD, enter the following data:

FLA	Rated full load motor current in secondary amps	2.90
LRA	Rated locked rotor current in secondary amps	14.00
LRT	Thermal limit time at rated locked rotor current	18.00
TD	Time dial to trip temperature in per unit of LRT	0.90
SF	Motor rated service factor	1.15

Guidelines for Calculating Settings for Motor Protection Relays

The data are for the 1170-hp, 4160-V motor using 300:5 CT and are entered in secondary amps. The characteristic of the resulting thermal model is shown in Figure 50.

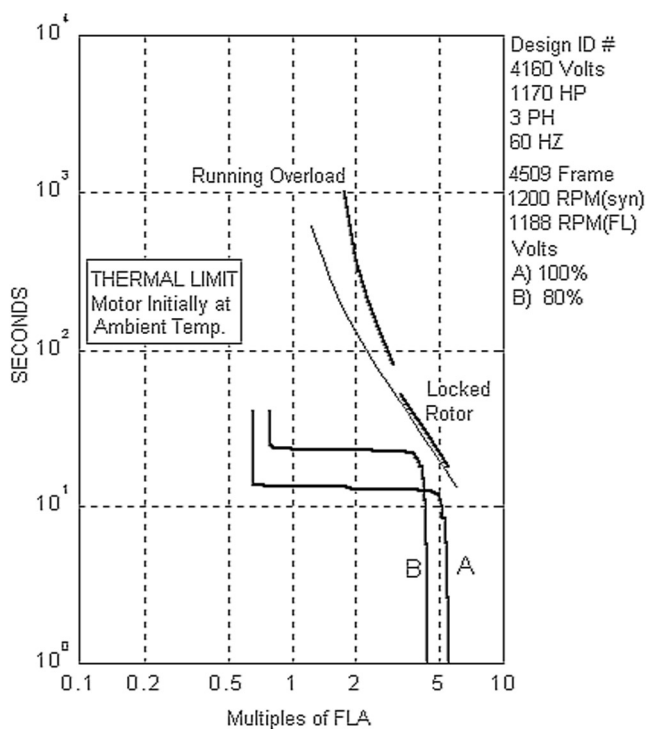


Figure 50 Thermal Model Characteristics Set by Rating Method

**Guidelines for Calculating Settings for
Motor Protection Relays**

GENERIC METHOD: In this method, you select one of a family of 45 thermal characteristic curves to coordinate with a locked rotor characteristic. Select the nearest curve without exceeding the hot locked rotor time. The selected characteristic is the same thermal model as the rating method. Figure 51 shows the selection of Generic Curve #5.

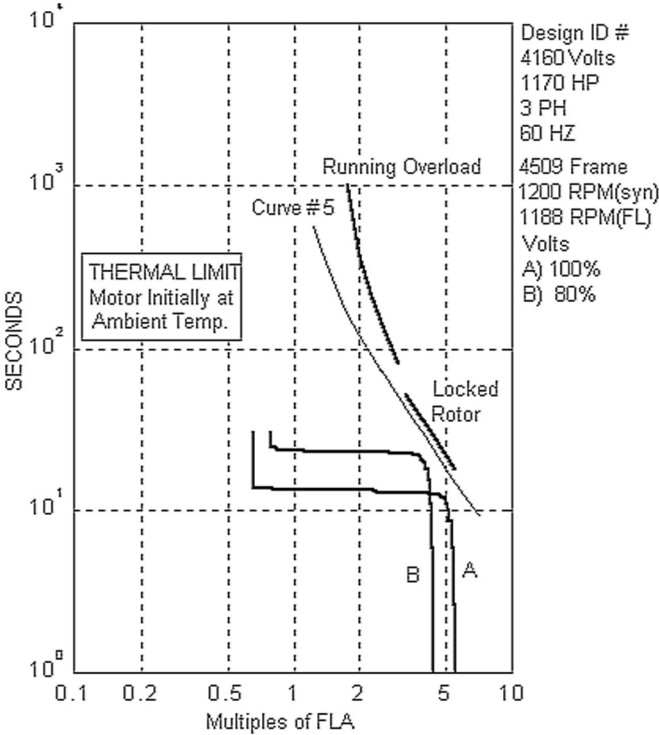


Figure 51 Thermal Curve Set by Generic Method

Guidelines for Calculating Settings for Motor Protection Relays

USER METHOD: In this method, you enter a series of time-current points from along the running overload and the locked rotor curve. The relay uses the points to create the characteristic curve. This method is useful where the overload and locked rotor curves do not form a continuous curve and where close coordination with the overload curve is needed to fully utilize the full overload capacity.

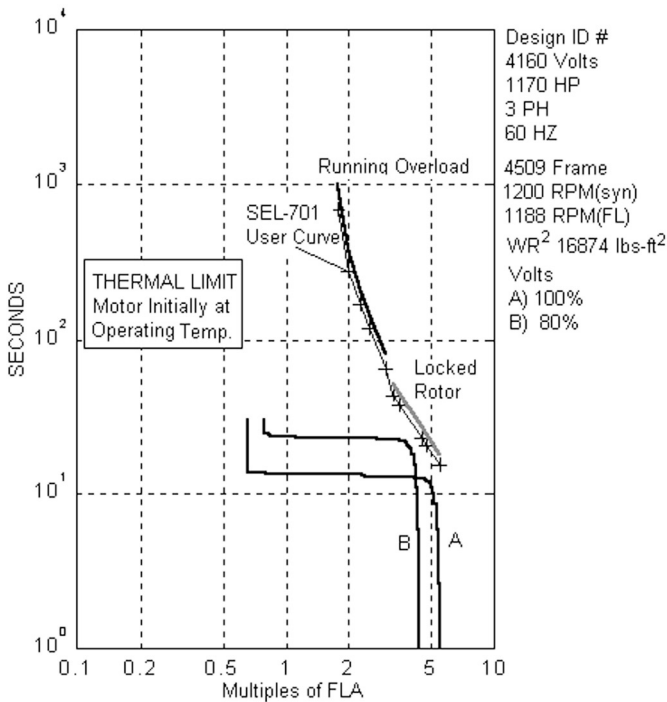


Figure 52 Thermal Curve Set by User Method

Guidelines for Calculating Settings for Motor Protection Relays

STATOR TIME CONSTANT SETTING: An advanced version of the RATING METHOD provides the option of entering the stator time constant as an additional setting when this value is known. The running thermal model then becomes an accurate first order thermal model of the stator and provides protection for cyclic overloads. Figure 53 shows the characteristic used for a 440-V, 400-hp motor.

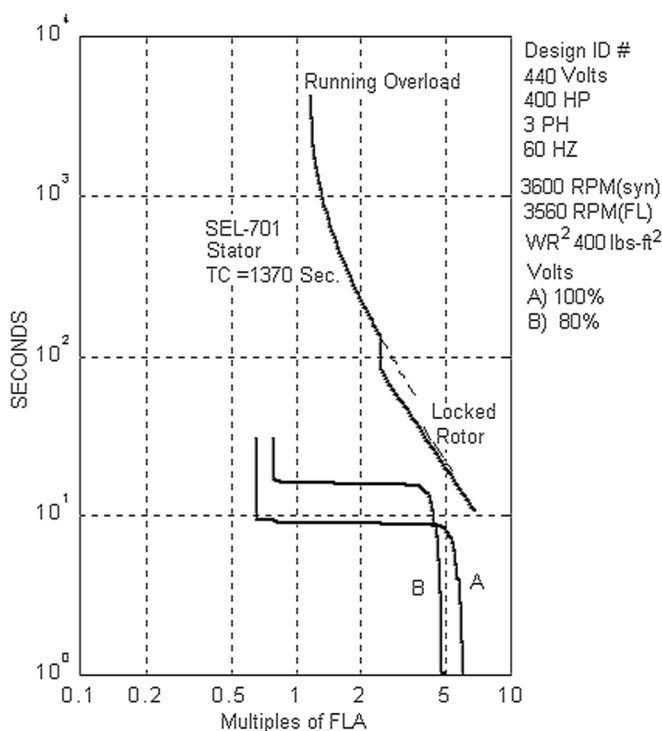


Figure 53 Rating Method using Stator Time-Constant Setting

References

- [1] ANSI/IEEE C37.96-1988, “IEEE Guide for AC Motor Protection,” IEEE, New York, 1988.
- [2] IEEE Std 620-1996, “IEEE Guide for the Presentation of Thermal Limit Curves for Squirrel Cage Induction Machines,” IEEE, New York, 1996.
- [3] NEMA MG-1-1998, “Motors and Generators,” National Electrical Manufacturers Association, New York, 1998.
- [4] IEC International Standard 255-8 1990, “Electrical Relays—Part 8: Thermal Electrical Relays,” IEC, Geneva, 1990.

