Induction Motors: Part II – Protection

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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 1. 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.
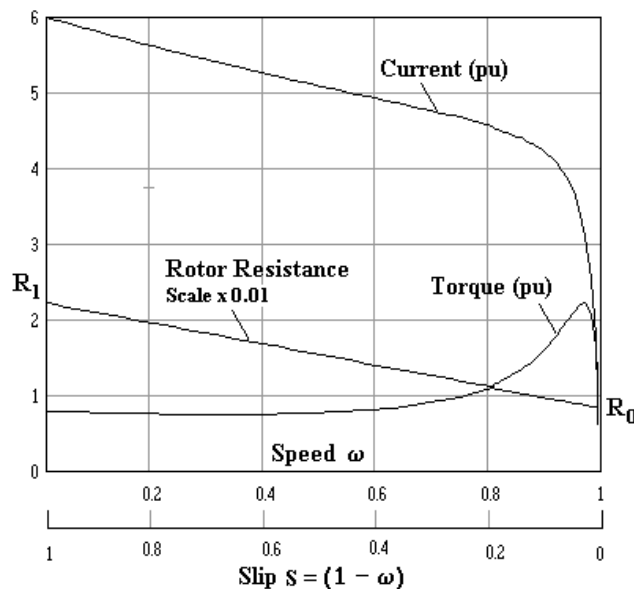

**Figure 1: Current, Torque, and Rotor Resistance
of an Induction Motor Versus Speed**

1

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^2r heating to be 6^2 x 3 or 108 times normal. Consequently, an extreme temperature must be tolerated for a limited time to start the motor. A high emergency I^2t 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 1 and is calculated using current I, torque Q_M, and slip S in the following equation:

$$R_r = \frac{Q_M}{I^2}S \tag{1}$$

It is represented by the linear function of slip shown in Figure 1. The positive-sequence resistance R_{r+} is a function of the slip S:

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

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

$$R_{r-} = (R_1 - R_0)(2 - S) + R_0 \tag{3}$$

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.

$$\frac{R_{r+}}{R_0}\Big|_{S=1} = \frac{R_{r-}}{R_0}\Big|_{S=1} = \frac{R_1}{R_0} = 3 \tag{4}$$

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

$$\frac{R_{r+}}{R_0}\Big|_{S=0} = 1 \qquad \frac{R_{r-}}{R_0}\Big|_{S=0} = 2\left(\frac{R_1}{R_0}\right) - 1 = 5 \tag{5}$$
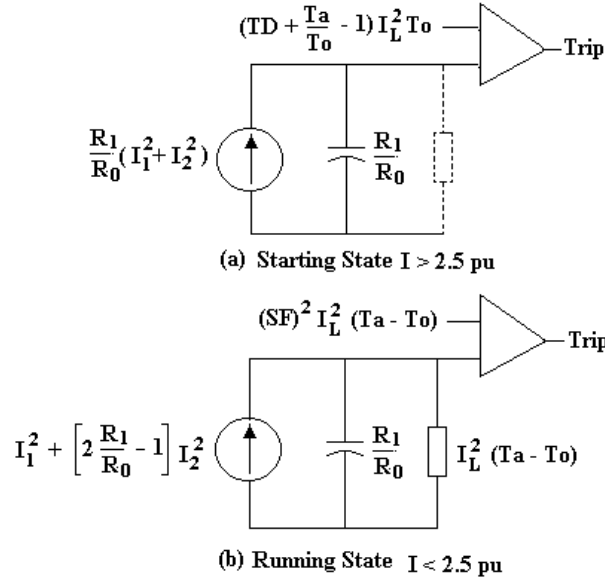
These factors are the coefficients of the positive and negative currents of the heat source in the thermal model.

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 current magnitude. The two states of the thermal model are shown in Figure 2. The thermal model is actually a difference equation executed by the micro-processor. However, it can be represented by the electrical analog circuit shown in Figure 2.

In this analogy, the heat source is represented by a current generator, the temperature is represented by voltage, and thermal resistance and capacitance are represented by electrical resistance and capacitance. The parameters of the thermal model are defined as follows:

- R1 = Locked rotor electrical resistance (per unit ohms)
- R0 = Running rotor electrical resistance also rated slip (per unit ohms)
- IL = Locked rotor current in per unit of full load current
- Ta = Locked rotor time with motor initial at ambient
- To = Locked rotor time with motor initially at operating temperature

$$(TD + \frac{Ta}{To} - 1)\, I_L^2\, To \longrightarrow \text{Trip}$$

$$\frac{R_1}{R_0}(I_1^2 + I_2^2) \qquad \frac{R_1}{R_0}$$

(a) Starting State $I > 2.5$ pu

$$(SF)^2\, I_L^2\, (Ta - To) \longrightarrow \text{Trip}$$

$$I_1^2 + \left[2\frac{R_1}{R_0} - 1\right] I_2^2 \qquad \frac{R_1}{R_0} \qquad I_L^2\,(Ta - To)$$

(b) Running State $I < 2.5$ pu

**Figure 2: States of the Thermal Model**

The starting state is shown in Figure 2a 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 2b, 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 which cools to the steady state running condition.

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:

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

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 3. Figure 3 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 $I_L^2 \cdot Ta,$ and the motor service factor is 1.2.
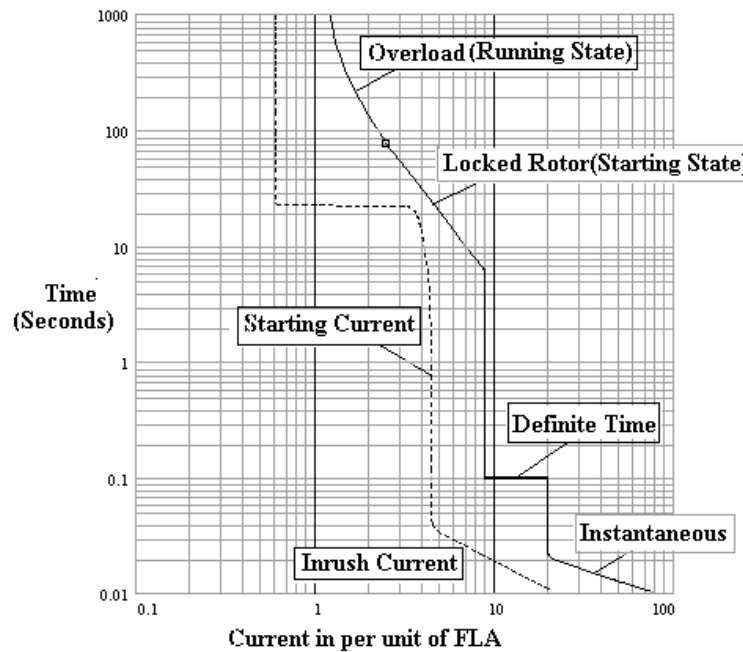
Figure 3: Motor Characteristic and Starting Current

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

The thermal circuit derived in this paper and shown in Figure 2 is covered by U.S. Patent No. 5,436,784.

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 3. 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.