Understanding Service Factor, Thermal Models, and Overloads

S. E. Zocholl
Schweitzer Engineering Laboratories, Inc.

Presented at the
60th Annual Georgia Tech Protective Relaying Conference
Atlanta, Georgia
May 3–5, 2006

Previously presented at the
59th Annual Conference for Protective Relay Engineers, April 2006

Originally presented at the
32nd Annual Western Protective Relay Conference, October 2005

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I. Introduction

A problem occurred while a customer was testing the motor relay that provides protection using a thermal model. This occurred when the relay SF was set at 1.0 and the relay tested with 1.0 p.u. of FLA. The complaint was that the relay tripped instantly on overload when the thermal damage curve showed considerable time delay available in the overload region.

Our task was to prove that the thermal damage curve did not apply with the current at 1.0 p.u. and that it was plotted for a specific current that was less than 1.0 p.u. Here is how the initial current was determined.

II. Motor Analysis

Fig. 1 shows the thermal limit curve for WEG 1600 kW motor with SF = 1 and Fig. 2 shows the Current and Torque versus speed curve for the motor. Note that in Fig. 1, the starting current goes below 1.0 p.u. Also, in Fig. 2, the load torque curve intersects the motor torque curve at 78.6% at full speed. A motor study determined that the running current for this torque is 0.9695 p.u.

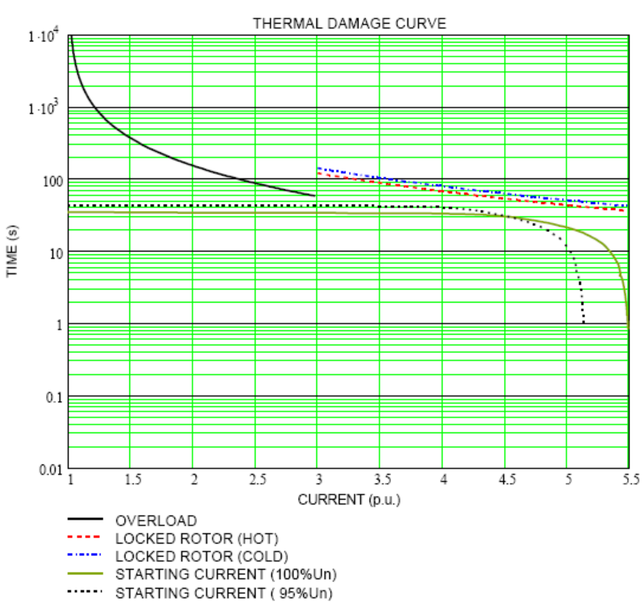

Fig. 1 Thermal Damage Curve for WEG 6600V, 1600 kW, 1000rpm Induction Motor

The Mathcad® plot of Equation (1) superimposed on the WEG graph in Fig. 1 proves it to be a perfect match.

According to the Thermal Relay Standard IEC-255-8, when a hot curve is given, the manufacturer is obligated to state the initial current for which the curve is plotted. In this case the initial current is 0.9695, and not the service factor current of 1.00 used to test the relay.

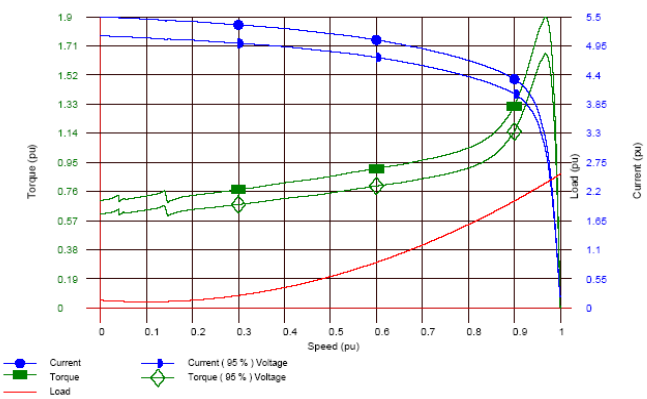

Fig. 2 Current and Torque versus Speed for the WEG 1600 kW Induction Motor

The heating time constant of 130 minutes (7800 seconds) is given in the manufacturer's motor data. Using this initial current, the time constant, and the SF = 1 in the heat equation gives the overload curve:

$$t = 7800 \cdot \ln\left(\frac{I^2 - (.9695)^2}{I^2 - 1}\right) \quad (1)$$

III. Thermal Model Overload Response

It is instructive to compare the thermal model response with that of a competitive relay when both relays are applied to provide overload protection. Fig. 3 shows the thermal model and the competitive relay superimposed on the thermal damage curve. The second relay characteristic with its TD setting of five has a similar shape and coordinates closely with the thermal damage. However, as explained in [1], the thermal model derives its dynamic properties from a first order differential equation while the second relay has the dynamic response of the adiabatic model explained in [1].

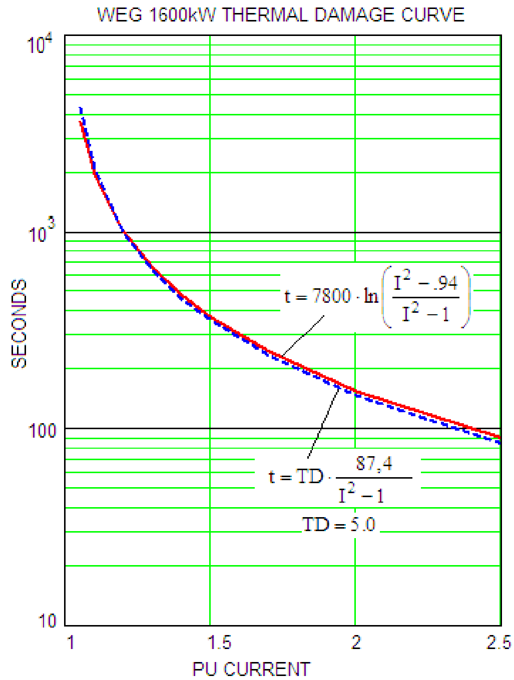

Fig. 3 Thermal Damage Curve with Thermal Model and a Coordinated Motor Relay Characteristic

Fig. 4 and Fig. 5 show the response of each of the test relays to a cyclic overload where the current alternates between a maximum of 1.4 p.u. to a minimum of 0.48 p.u. every 500 seconds. The cyclic current has an rms value of 0.98 p.u. current. The current produces an average heat value of 0.96 p.u. and consequently does not constitute an overload.

Fig. 4 clearly shows the dynamics of the thermal model where the response is the rise and fall of the temperature. Its 0.96 p.u. average allows the motor to run.

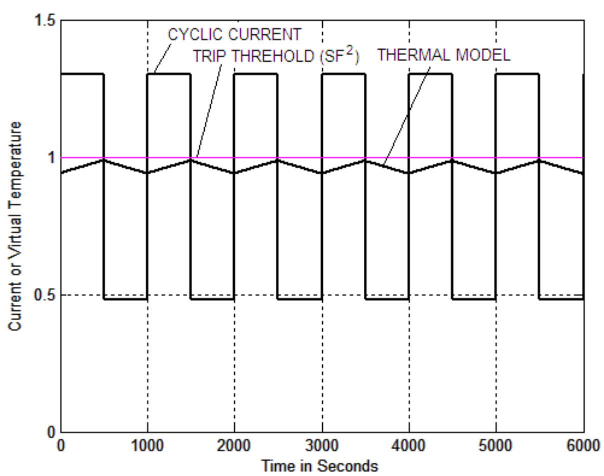

Fig. 4 Response of the Thermal Model to Cyclic Overload

In contrast, Fig. 5 shows that the overcurrent characteristic trips and disconnects the motor prematurely for cyclic currents that do not overheat the motor.

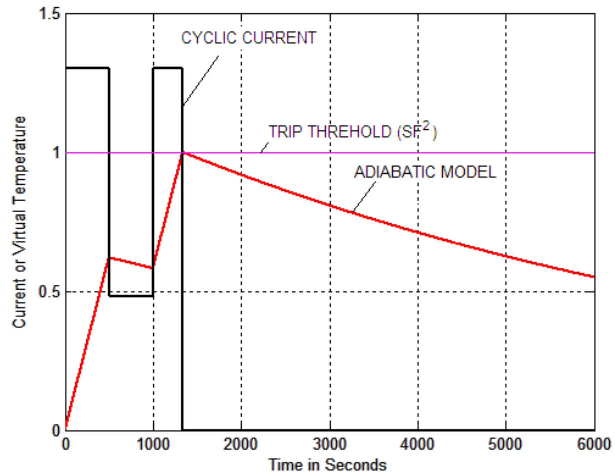

Fig. 5 Response and Premature Trip of the Overcurrent Relay to Cyclic Overload.

IV. Annex—The First Order Thermal Model

The first order thermal model is derived as follows:

$$\theta = \theta_w - \theta_A \tag{2}$$

where θ is defined as the winding temperature rise above ambient.

The rate of increase of the temperature is given by the equation expressing the thermal equilibrium.

$$\text{Power Supplied} - \text{Losses} = C_s m \frac{d\theta_W}{dt} = C_s m \frac{d\theta}{dt} \tag{3}$$

In this equation, C_s is the specific heat of the winding and m is the mass. The specific heat corresponds to the amount of energy needed to raise one kilogram of that material one degree centigrade. The losses or the quantity of heat transferred to the surrounding environment is expressed as:

$$\text{Losses} = \frac{\theta_W - \theta_A}{R} = \frac{\theta}{R} \tag{4}$$

where R is the thermal resistance in °C/Watt.

Equation (3) can be otherwise expressed as:

$$I^2 r - \frac{\theta}{R} = C_s m \frac{d\theta}{dt} \tag{5}$$

or:

$$I^2 r \cdot R = C_s m \cdot R \frac{d\theta}{dt} + \theta \tag{6}$$

The mass m multiplied by the specific heat C_s is known as C, the thermal capacity of the system with units of joules/°C. It represents the amount of energy in joules required to raise the system temperature by one degree centigrade.

The product of the thermal resistance R and the thermal capacitance C has units of seconds and represents the thermal time constant τ of the system:

$$\tau = R \cdot m \cdot C_s \tag{7}$$

The fundamental Equation (6) can be expressed in a simpler form:

$$I^2 = C_s m \cdot R \cdot \left(\frac{1}{r \cdot R} \cdot \frac{d\theta}{dt}\right) + \frac{\theta}{r \cdot R} \tag{8}$$

$$\tau = C_s m \cdot R \tag{9}$$

let

$$U = \frac{\theta}{r \cdot R} \tag{10}$$

and

$$\frac{dU}{dt} = \frac{1}{r \cdot R} \cdot \frac{d\theta}{dt} \tag{11}$$

Therefore the first order thermal model equation becomes the simple form:

$$I^2 = \tau \frac{dU}{dt} + U \tag{12}$$

The solution of the first order equation is:

$$U = I^2 \cdot \left(1 - e^{\frac{-t}{\tau}}\right) \tag{13}$$

With initial current I_0

$$U = I^2 \cdot \left(1 - e^{\frac{-t}{\tau}}\right) + I_0^2 \cdot e^{\frac{-t}{\tau}} \tag{14}$$

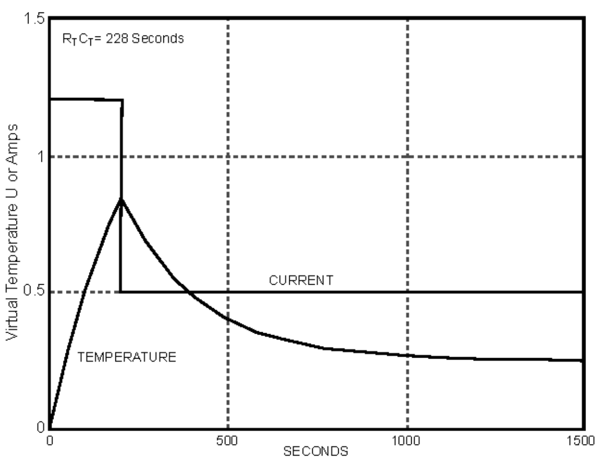

Fig. 6 Dynamic Response of the First Order Thermal Model

When using Equation (13) to calculate U over a small time increment Δt, the exponentials can be replace with the first two terms of the infinite series as follows:

$$e^{\frac{-\Delta t}{\tau}} = \left(1 - \frac{\Delta t}{\tau}\right) \tag{15}$$

Substituting Equation (15) in Equation (14) gives

$$U_n = I^2 \cdot \left(1 - \left(1 - \frac{\Delta t}{\tau}\right)\right) + U_{n-1} \cdot \left(1 - \frac{\Delta t}{\tau}\right) \tag{16}$$

This incremental form of the equation is ideal for use in the processor for the continuous real-time calculation of temperature:

$$U_n = \frac{I^2}{\tau} \Delta t + \left(1 - \frac{\Delta t}{\tau}\right) \cdot U_{n-1} \tag{17}$$

where U_n is the virtual temperature at sample n

U_{n-1} is the virtual temperature at the previous sample.

V. Conclusions

1. Induction motors require thermal protection to prevent overheating to cyclic as well as steady state overloads.
2. The heat rise in a motor due to I^2R watts is a first order process described by a first order difference equation. The equation constitutes the thermal model that a motor relay uses to continuously calculate the temperature in real time. The virtual temperature is monitored and trips to prevent overheating.
3. An overcurrent implementation used in motor relay cannot measure temperature. Such characteristics appear to coordinate well with motor thermal damage curves. However, such relays trip prematurely when subjected to cyclic loads that do not overheat the motor.

VI. References

[1] S.E. Zocholl, "Comparing Thermal Models," Proceedings of the 31st Annual Western Protective Relay Conference, Spokane, WA, October 19-1, 2004.

[2] S.E. Zocholl, G. Benmouyal, "Using Thermal Limit Curves to Define Thermal Models of Induction Motors," Proceedings of the 28th Annual Western Protective Relay Conference, Spokane, WA, October 23–25, 2001.

[3] L.C. Grainger, M.C. McDonald, "Increasing Refinery Production by Using Motor Thermal Capacity for Protection and Control," *IEEE Transactions on Industry Applications*, Vol. 33, No. 3 May/June 1997.

VII. Biography

Stanley (Stan) Zocholl has a B.S. and 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 and past chair of the Relay Input Sources Subcommittee. 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 Best Paper Award of the 1988 Petroleum and Chemical Industry Conference and the Power System Relaying Committee's Distinguished Service Award in 1991.

Previously presented at the 2006 Texas A&M
Conference for Protective Relay Engineers.

20051020 • TP6190-01