Setting the 469 Motor Management Relay for a Cycling Load Application

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Overview

INTRODUCTION

The 469 relay provides thermal motor protection based on an approach similar to a single time constant thermal model. This document analyzes the behavior of the 469 and compares it with a single time constant thermal model under a variety of load dynamic conditions. It is shown that the behavior of the 469 is approximately the same as that of a thermal model under any loading condition, provided the implicit time constant of the overload curve is matched to the explicit cooling time constant. In particular, it is shown that when the time constants are properly matched, the relay works correctly on cyclic loads. This application note also provides practical examples of how to set up the 469 for cyclic load applications using either standard overload curves or custom overload curves.

Application

SINGLE TIME CONSTANT THERMAL MODEL

First, we will compare the 469 with a simple, single time constant thermal model under constant load.

A simple thermal model is sometimes used to approximate the thermal behavior of a motor as an aid in understanding motor thermal protection. The model often has the following features:

- Heating arises from I^2R losses in the motor. During steady state loading, the temperature of the motor reaches its maximum capability (rated temperature rise) when the motor is drawing rated current.
- During transient conditions, two thermal processes are considered: heat storage in the motor, and heat transfer from the motor to the ambient.

- Heat storage in the motor is proportional to the heat capacity of the motor times the time rate of change of the motor temperature.
- Heat transfer from the motor out to the ambient is proportional to the motor temperature rise above the ambient.
- When the motor thermal model temperature exceeds the maximum allowable value, thermal protection is provided by shutting the motor off.

The transient behavior of the model can be summarized by the following equation:

$$C \cdot \frac{dT'}{dt} = I'^2(t) \cdot R - H \cdot T'(t) \qquad \text{(EQ 1)}$$

where: $T'(t)$ = motor temperature rise above ambient
$I'(t)$ = motor current
C = specific heat capacity of the motor
H = running heat dissipation factor
R = electrical resistance.

The left side of equation (1) represents heat storage in the motor. The first term on the right side of the equation represents heat generated in the motor due to I^2R losses. The second term on the right represents heat transfer from the motor to the ambient.

It is convenient to rewrite equation (1) in terms of per unit temperature rise and per-unit current by expressing the current as a fraction of rated current and the temperature as a fraction of the thermal limit temperature. In this case, we use:

$$T(t) = \frac{T'(t)}{T_{max}} = \text{per-unit temperature rise}$$
$$I(t) = \frac{I'(t)}{I_{rated}} = \text{per-unit current} \qquad \text{(EQ 2)}$$
$$I_{rated} = \text{rated current}$$
$$T_{max} = \text{motor temperature at thermal limit trip condition}$$

In this case, equation (1) can be rewritten as:

$$\tau \cdot \frac{dT(t)}{dt} = I^2(t) - T(t), \text{ where } \tau = \frac{C}{H} \qquad \text{(EQ 3)}$$

Equation (3) can be used to analyze the thermal response of an overloaded motor. It can be shown that the temperature rise above ambient for the solution of equation (3) for a steady overload from a cold start is given by:

$$T(t) = I^2 \cdot (1 - e^{-t/\tau}) \qquad \text{(EQ 4)}$$

where: I = per-unit motor current (a constant)
$T(t)$ = per-unit motor temperature rise.

Next, equation (4) can be solved for the time required for the temperature rise to reach the thermal limit of the motor; i.e., $T(t) = 1$:

$$t_{max}(I) = \tau \cdot \ln\left(\frac{I^2}{I^2 - 1}\right) \qquad \text{(EQ 5)}$$

where $t_{max}(I)$ is the time estimated by a simple thermal model for the motor temperature to reach the thermal limit.

OVERLOAD CURVES

To develop a comparison between a simple thermal model and the 469, we now turn our attention to overload curves, which the 469 uses to determine how long a motor can safely withstand motor overload at a specific value of motor current. The standard overload curves are given by:

$$t_{max}(I) = \frac{87.4 \cdot \text{CM}}{I^2 - 1} \qquad \text{(EQ 6)}$$

where: $t_{max}(I)$ is the trip time, in seconds
CM is the curve multiplier

To compare the overload curves with the behavior of a simple thermal model, it is useful to start by recognizing that the numerator of the right hand side of equation (6) corresponds to the time constant of the thermal model:

$$t_{max}(I) = \frac{\tau_{\text{CM}}}{I^2 - 1} \qquad \text{(EQ 7)}$$

where: τ_{CM} = 87.4 × CM

Equations (5) and (7) are plotted in Figure 1 on page 4. To ensure the curves align for large values of current, it is necessary to satisfy the following constraint:

$$\tau = \frac{C}{H} = \tau_{\text{CM}} = 87.4 \cdot \text{CM} \qquad \text{(EQ 8)}$$

In other words, in order for an overload curve to match a simple thermal model during a step overload, the time constant implied by the curve multiplier must be set equal to the time constant of the thermal model.

In the following figure, the ratio of the time divided by the time constant is plotted against per unit current. Although equation (7) is not exactly the same as equation (5), the approximation is very close, particularly for large values of current. For values of current overload closer to the motor rating, the standard overload curves produce longer times than those of the simple thermal model. However, in that region it is the value of the current rather than the value of the time that is important, because the temperature of the motor is changing slowly. In any case, neither curve exactly matches the actual thermal behavior of a motor, which is described by a multiple time constant thermal model. Either curve can approximate the manufacturer's published curve by adjusting parameters to shift the curve vertically or horizontally.

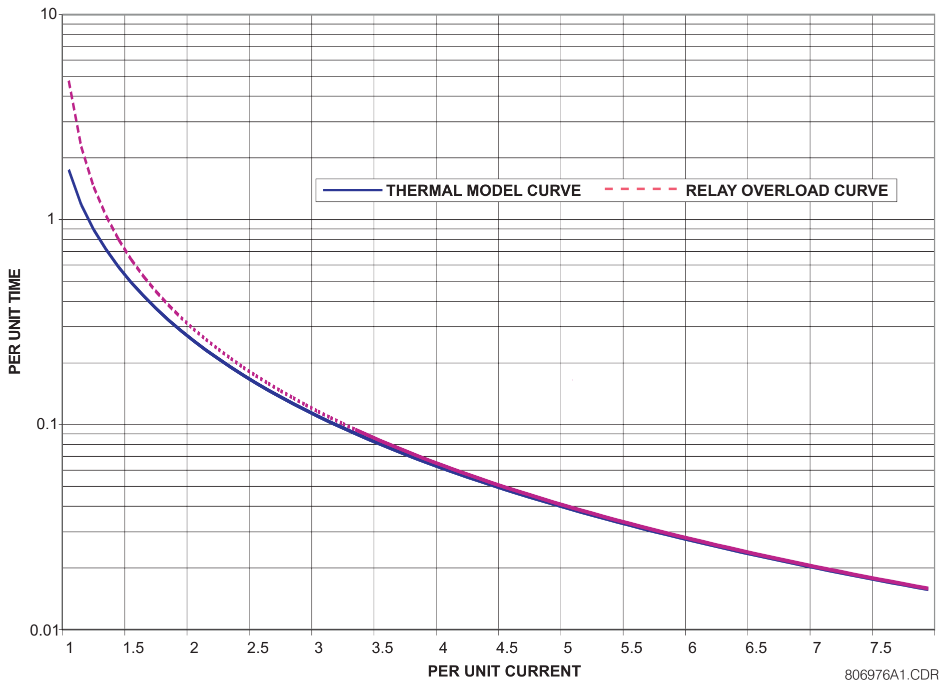

FIGURE 1. Thermal Model versus Relay Overload Curves Comparison

Equation (6) describes the time for the 469 to reach thermal limit for a constant overload. We now turn our attention to how the 469 behaves during transient overload conditions in general, by starting with the differential equation that is used within the 469 to implement standard overload curves:

$$\frac{dT(t)}{dt} = \frac{I^2(t) - 1}{\tau_{CM}} \qquad \text{(EQ 9)}$$

Equation (9) can be rearranged as follows:

$$\tau_{CM} \cdot \frac{dT(t)}{dt} = I^2(t) - 1 \qquad \text{(EQ 10)}$$

From equation (3), recall that the simple thermal model is described by:

$$\tau \cdot \frac{dT(t)}{dt} = I^2(t) - T(t) \qquad \text{(EQ 3)}$$

For large values of overload, such as would be encountered during stalled operation of a motor, the temperature changes in a time frame that is much shorter than the time constant of the motor. In that case the first term on the left sides of equations (10) and (3) dominates, so that both equations are approximated by:

$$\tau_{CM} \cdot \frac{dT(t)}{dt} = \tau \cdot \frac{dT(t)}{dt} \approx I^2(t),\ \ I^2(t) >> 1 \qquad \text{(EQ 11)}$$

In other words, for large values of current, the standard overload curves and a simple thermal model will behave almost identically, provided the overload curve multiplier is set according to equation (8).

For values of overload current close to rated, the relay overload curves take somewhat longer to trip than the a simple thermal model with the same constant, because of the difference between the second terms in equations (3) and (10).

SIMPLE CYCLING LOAD ANALYSIS

So far, the analysis has considered situations in which the current exceeds the motor rating. To gain insights into what happens when the current also drops below full load, we now turn our attention to a simple cycling load in which the current alternates between zero and an overload value:

$$\begin{aligned} I_{low} &= 0 \approx \text{motor current during the low cycle} \\ I_{high} &= \text{motor current during the high cycle} \\ t_{low} &= \text{time interval for the low cycle} \\ t_{high} &= \text{time interval for the high cycle} \end{aligned} \quad \text{(EQ 12)}$$

The motor heating is proportional to the square of the current, so the effective current for heating over the cycle is:

$$H_{effective} = I^2_{effective} = \frac{t_{high} \cdot I^2_{high} + t_{low} \cdot I^2_{low}}{t_{low} + t_{high}} \quad \text{(EQ 13)}$$

where: $I_{effective}$ = effective value of the load current
$H_{effective}$ = effective heating value of the load

Equation (13) can also be expressed in terms of a duty cycle ratio:

$$H_{effective} = D \cdot I^2_{high} + (1 - D) \cdot I^2_{low} \quad \text{(EQ 14)}$$

where: $D = \text{duty cycle ratio} = \dfrac{t_{high}}{t_{low} + t_{high}}$

If the current and heating are expressed in per-unit values and low cycle current is approximately equal to zero, the steady state boundary condition for tripping the motor becomes:

$$1 = D \cdot I^2_{high} \quad \text{(EQ 15)}$$

Analysis of the 469 under load cycling conditions will reveal how to set it properly to match the behavior specified by equation (15). We start by extending the previous analysis to values of current below pickup, during which the 469 motor thermal model is defined by the following differential equation that describes thermal cooling when motor loading is below pickup:

$$\frac{dT(t)}{dt} = \frac{1}{\tau_{cool}} \cdot \left(I \cdot \left(1 - \frac{\text{hot}}{\text{cold}} \right) - T(t) \right) \quad \text{(EQ 16)}$$

where: τ_{cool} = cooling time constant
hot = hot stall time
cold = cold stall time

The (1 – hot/cold) factor is included to match the hot and cold stall times specified by the motor manufacturer. By including the factor in the cooling computation, the hot overload curve is effectively shifted down by the correct amount relative to the cold overload curve to account for the difference in ‘time to trip’ of hot and cold motor conditions.

For the load cycle under consideration, the current during the unloaded part of the cycle is approximately equal to zero, so the differential equation given by (16) reduces to:

$$\frac{dT(t)}{dt} = -\frac{T(t)}{\tau_{cool}} \qquad \text{(EQ 17)}$$

Taken together, equations (17) and (10) describe the behavior of the 469 during the assumed load cycle. During the overload portion of the cycle, the temperature computed according to equation (10) rises. During the unloaded portion of the cycle, the temperature computed according to equation (17) falls. For a heavy-duty cycle situation, the temperature increase during overload is greater than the temperature decrease during zero load. The temperature gradually ratchets upward until it reaches the maximum allowable value and the 469 shuts off the motor.

Whether or not the temperature reaches a tripping condition depends on the severity of the duty cycle. For a severe overload, the temperature ratchets up past the maximum value. For a load just below the threshold of tripping, the temperature reaches a steady state cycle just below the maximum value, and the 469 allows the motor to continue to operate. The approximate boundary between overload and normal operation can be determined by analyzing the steady state limit cycle, as the temperature approaches 1 per unit.

The approximate temperature rise during the overload portion of the load cycle estimated by the overload curve is computed by multiplying equation (10) by the overload time:

$$\Delta T_{high} \approx \frac{1}{\tau_{CM}} \cdot (I_{high}^2 - 1) \cdot t_{high} \qquad \text{(EQ 18)}$$

The approximate temperature drop estimated by the cooling model during the unloaded portion of the duty cycle is computed by multiplying equation (17) by the appropriate time, with per unit temperature equal to 1, because that is what it will be approximately equal to during a limit cycle that approaches tripping:

$$\Delta T_{low} \approx -\frac{1}{\tau_{cool}} \cdot t_{low} \qquad \text{(EQ 19)}$$

The overload detection boundary is determined by setting the net temperature change equal to zero. This implies that the total of the right hand sides of equations (18) and (19) is equal to zero:

$$\Delta T_{high} + \Delta T_{low} = \frac{1}{\tau_{CM}} \cdot (I_{high}^2 - 1) \cdot t_{high} - \frac{1}{\tau_{cool}} \cdot t_{low} = 0 \qquad \text{(EQ 20)}$$

Equation (20) can be rearranged to highlight how to properly set the 469 for load cycling applications:

$$1 = \frac{\tau_{cool}}{\tau_{CM}} \cdot D \cdot I_{high}^2 \quad \text{(EQ 21)}$$

Equation (21) expresses the actual overload detection boundary of the SR469 in terms of its settings, the duty cycle, and the amount of overload. Except for the factor of τ_{cool} / τ_{CM}, equation (21) is the same as ideal overload detection boundary, specified by equation (15). Equations (21) and (15) will be identical, provided that τ_{cool} / τ_{CM} is set equal to one. This makes sense from a physical point of view. The cooling time constant as well as the overload curve time constant arise from the same physical parameters, so they should come out to be the same. In other words, in order for the 469 to provide appropriate thermal protection during load cycling applications, it is necessary to satisfy the following constraint.

$$\tau_{cool}(\text{min}) = \frac{87.4 \cdot \text{CM}}{60} \quad \text{(EQ 22)}$$

Equation (22) represents a consistency constraint relating the cooling time constant and the overload curve. For most applications, it is not necessary to satisfy the constraint. However, in the case of a load that cycles above and below pickup, equation (22) should be approximately satisfied. Otherwise, the computed motor temperature will tend to ratchet up or down. The following figure illustrates what can happen. There are three cases shown for a cycling load with an approximate per unit heating value of one. In the first case, the cooling time constant is set too long resulting in over-protection and early motor tripping. In the second case, the cooling time constant is set to match the implied time constant of curve multiplier, and the protection is correct. In the third case, the cooling time constant is set too short, resulting in under-protection and possible motor overheating.

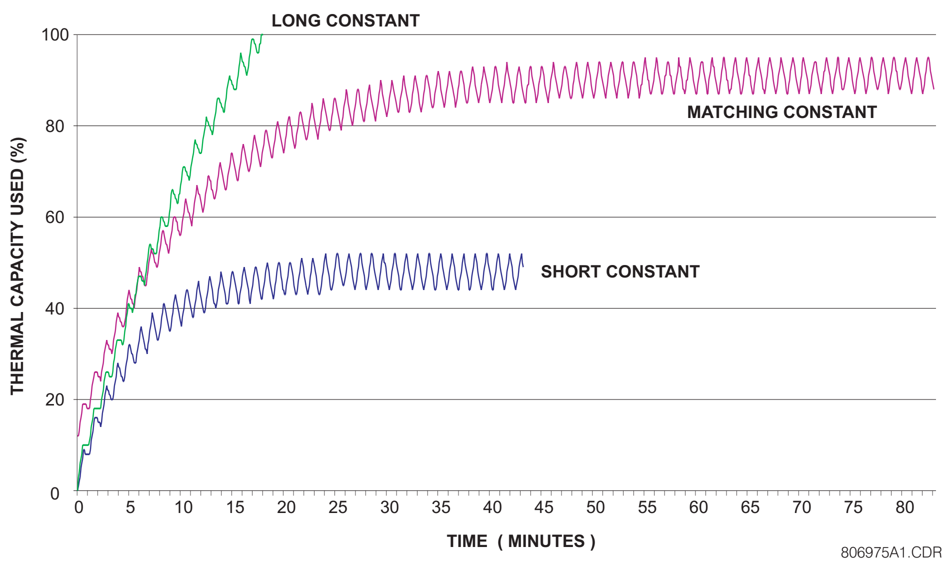

FIGURE 2. 469 Relay Response to Cyclic Load with Different Cooling Constants

NOTE

When setting the 469 for a cyclic loading application, the constraint specified by equation (22) should be satisfied.

CUSTOM OVERLOAD CURVES

For custom overload curves, the cooling and overload time constants can be matched using a graphical procedure. The goal is to match the explicit cooling time constant to the time constant that is implied by the overload curve in the vicinity of rated current. The key to achieving the match is equation (7), repeated here for convenience:

$$t_{max}(I) = \frac{\tau_{CM}}{I^2 - 1} \qquad \text{(EQ 7)}$$

Equation (7) applies to standard overload curves. It is simple enough to extend it to custom curves by allowing the implied time constant to be a function of current:

$$t_{max}(I) = \frac{\tau_{CM}(I)}{I^2 - 1} \qquad \text{(EQ 23)}$$

The implied time constant can then be computed as a function of current from the overload curve as follows:

$$\tau_{CM}(I) = (I^2 - 1) \cdot t_{max}(I) \qquad \text{(EQ 24)}$$

According to equation (24), the implicit time constant is a function of the motor load. For the purposes of the cooling portion of the thermal model, a single number is needed. The most appropriate number to use is one that will result in well-behaved response to a duty cycle. In that case, we are interested in the values produced by equation (24) as the load current approaches full rated. This suggests a graphical technique for determining the appropriate cooling time constant: Plot the quantity given by equation (24) as a function of per unit load current, using the custom overload curve to determine $t_{max}(I)$. The appropriate time constant is the value of the curve as the current approaches the maximum overload value during the load cycle.

The following example is given to clarify the procedure. Let us consider an example of cyclic load application with maximum overload current excursions of 1.5 of motor rating. For this particular example, suppose that the motor thermal limit is represented in the 469 relay by the custom overload curve in Figure 3 on page 9.

The appropriate value of the time constant can be derived by defining the maximum time value (t_{max}) matching 1.5 per unit current from Figure 3 on page 9. The time constant is computed from equation (24):

$$\tau_{CM}(I) = \frac{(1.5^2 - 1) \cdot 420 \text{ sec}}{60} = 8.7 \approx 9 \text{ minutes} \qquad \text{(EQ 25)}$$

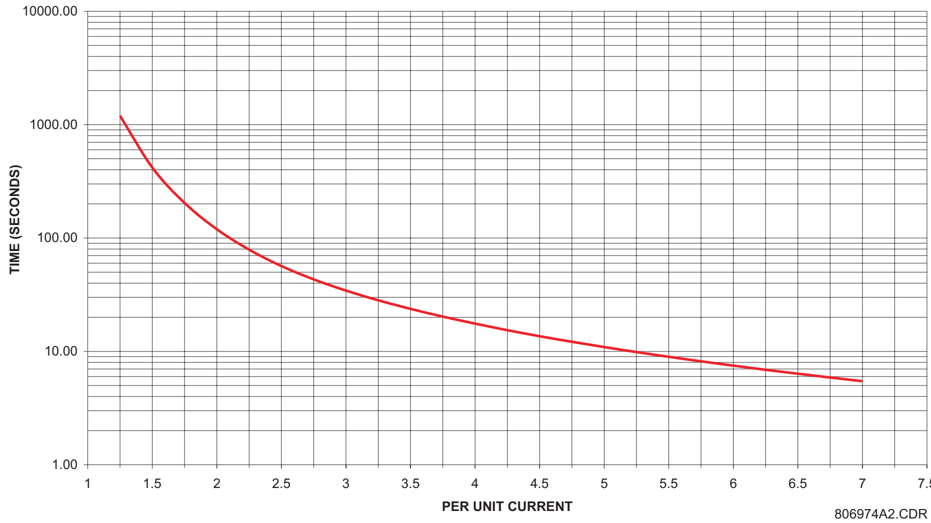

FIGURE 3. Example of a Custom Overload Curve

SUMMARY

In summary:

- The thermal algorithm in the 469 relay approximates the behavior of a traditional single time constant thermal model under any loading condition. Relay overload curves provide an implied thermal time constant for this algorithm.
- For the relay to work correctly on balanced cyclic loads, the cooling time constant must be set in conjunction with the overload curve. When the time constants are properly matched, the relay presents a realistic motor thermal image in pulsating load applications.
- The practical example provides the guidelines of how to calculate the matching **COOLING TIME CONSTANT** setpoint for Standard and Custom overload curves.

COOLING CONSTANTS CALCULATION EXAMPLE FOR CYCLIC LOAD APPLICATION

Consider motor load cycles every 30 seconds between 20% and 140% of the rated current. The best match to the motor thermal limit curves provided by motor manufacturer is relay standard overload curve # 4.

First of all we should ensure that the cyclic load is within the steady state boundary condition for tripping the motor and per unit effective heating is not higher than 1. Per equation (14), the per unit effective heating is calculated as:

$$D = \text{duty cycle ratio} = \frac{t_{high}}{t_{low} + t_{high}} = \frac{30\text{ sec}}{30\text{ sec} + 30\text{ sec}} = 0.5$$

$$H_{effective} = 1.4^2 \cdot 0.5 + 0.2^2 \cdot 0.5 = 1 \qquad \text{(EQ 26)}$$

Now we see that the presented cyclic load satisfies the condition for constants matching. Per equation (22), the cooling constant setpoint is calculated as:

$$\tau_{cool} = \frac{87.4 \cdot \text{CM}}{60} = \frac{87.4 \cdot 4}{60} = 5.8 \approx 6\text{ min.} \qquad \text{(EQ 27)}$$

The thermal capacity graph *matching constant* for Figure 2 on page 7 presents 469 relay behavior under described load conditions and programmed per calculated setpoints.

NOTE

If in cyclic load applications hot/cold ratio setpoint is set lower than 0.8, then the running cooling constant should be set proportionally lower than calculated in equation (22) to achieve the adequate relay response.

For example if the hot/cold ratio setpoint is 0.7, then the cooling constant setpoint is calculated as follows:

$$\tau_{cool} = \frac{87.4 \cdot CM}{60} \cdot \frac{0.7}{0.8} = \frac{87.4 \cdot 4}{60} \cdot \frac{0.7}{0.8} = 5.1 \approx 5 \text{ min.} \qquad \text{(EQ 28)}$$