KEEP ON RUNNING—SELECT MOTOR RELAY SETTINGS TO BALANCE PROTECTION AND OPERATION

Paper No. PCIC-TBD

Jim Payne
Phillips 66
2331 CityWest Blvd
Houston, TX 77042, USA
Jim.R.Payne@p66.com

Edgardo Miguel, Jr.
Phillips 66
1660 W. Anaheim Street
Wilmington, CA 90744, USA
Edgardo.Miguel@p66.com

Krithika Bhuvaneshwaran
Schweitzer Engineering Laboratories, Inc.
101 E Park Blvd, Suite 1180
Plano, Texas 75074, USA
KritBhuv@selinc.com

Derrick Haas
Schweitzer Engineering Laboratories, Inc.
5850 Rogerdale, Suite 150
Houston TX 77072, USA
Derrick_Haas@selinc.com

Abstract—Electric motors are essential for industrial processes. Incorrect operation of motor protective relays could remove essential motors from service, resulting in economic loss due to process interruptions. Motor protection schemes should cause minimum process downtime while providing adequate protection. These schemes should allow operators to maximize process availability. Thermal overload protection is a critical part of any motor protection scheme. This paper presents methods to set the thermal overload trip and reset settings correctly and provides examples of their application to several real-world installations. It discusses how the thermal overload settings can be developed from the motor data sheets when available. It also discusses how the settings can be developed for retrofit applications where complete motor thermal information might not be available. Additionally, this paper discusses how these settings affect motor operation and provides case studies of real-world motors.

Index Terms—Motor protection, thermal model, and thermal lockout.

I. INTRODUCTION

Thermal protection settings of electric motors can often be challenging to set in a way that maximizes motor availability while providing adequate protection. This paper describes the thermal element that uses a first-order thermal model and provides guidelines on creating the settings. It addresses common challenges in creating settings using the information provided by a manufacturer. Additionally, it provides equations to calculate the reset time after a motor stop or trip. Calculating these values before the motor is commissioned can help operators understand how long the relay will lockout the motor and how often the motor can be started.

II. MAXIMIZE PROCESS AVAILABILITY

Properly functioning primary equipment and protective and control devices are critical components of maintaining a process. There are two main scenarios to consider for motor availability:

1. Failure of primary equipment: the relay must trip and take the motor offline quickly when an abnormal operating condition is present to limit or prevent damage and outage time.
2. Normal day-to-day operation: after a motor is stopped, some relays can prevent a new start until the motor has sufficient thermal capacity to start up successfully. If this time is too short, the relay might trip the motor during start up; and if this time is too long, the motor availability is limited and the process might be offline for too long.

A. False Trip vs. Failure to Trip

A motor protective relay, like any protective relay, can have an operation classified as a correct operation or undesired operation.

This paper focuses on the two categories related to tripping or stopping the motor—a failure to trip and a false trip.

When a protective relay fails to trip during a fault or abnormal condition, there is a risk of damage to the motor. This damage comes with added repair downtime, cost, etc.

Conversely, if a protective relay trips when no faults or damaging abnormal operating conditions are present, the motor is taken offline unnecessarily. Depending on the mechanical load coupled with that motor and that load's criticality to the process, it could lead to interruption of the industrial production process.

Minimizing all undesired operations of a protective system is the goal. A part of this involves the proper setting, commissioning, and maintaining of protective relay systems. A discussion of commissioning and maintenance is beyond the scope of this paper; however, normative references discussing this topic at length are available [1] [2].

For microprocessor-based motor protective relays, additional features can sometimes allow for issues to be discovered before an undesired operation occurs. One key feature is the reporting feature available in motor protective relays. Proper analysis of oscillographic event reports and motor start reports can help identify potential problems before they result in an undesired operation. Scheduling maintenance to correct those problems minimizes process downtime. Reference [3] highlights several cases in which analyses of event and motor start reports have helped identify root causes that are otherwise inconspicuous. In addition, this paper cites examples of real-world data captured from microprocessor relays, particularly data captured from winding resistive temperature detectors (RTDs).

It is important to understand that the settings are also a critical component to proper operation of protective relays. For motor relays, the thermal overload element is of interest and discussion in this paper. It is essential for relays to trip quickly enough to protect the motor against thermal damage, while waiting long enough to account for any mechanical anomalies associated with things like normal starting or oscillating loads. Other motor protective elements, such as overcurrent and current unbalance, are discussed in detail in [4] and [5].

B. Time to Restart

This paper discusses the importance of ensuring the motor protection elements perform their tripping functions adequately. However, it is of equal importance to determine how long the operator must wait to attempt a restart after a stop or thermal overload trip has occurred. Not every thermal overload trip is the result of a mechanical or electrical failure. For example, some thermal overload trips are the result of an overload due to a process error, such as an incorrect valve position. After the error is corrected, the mechanical system is ready to resume operations. However, the motor must be adequately cooled to prevent thermal damage from jogging.

Fig. 1 shows the motor thermal capacity recorded by a motor protective relay protecting a 2,000 kW, 3,300 V, and 50 Hz medium-voltage motor.

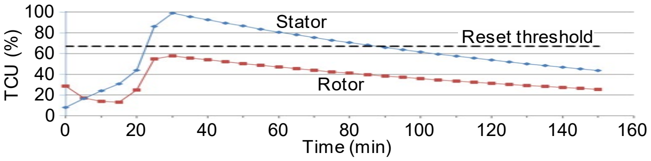


Fig. 1. Thermal Capacity for 2,000 kW Medium-Voltage Motor

At about 20 minutes on the graph, the motor experienced an overload to approximately 200 percent of its rated value. The overload resulted in the rapid rise in the stator thermal capacity to 100 percent, its trip level, in the next 10 minutes. The stator cooled below the reset threshold of 67 percent at about 83 minutes or roughly 53 minutes after the trip occurred. The operations team was accustomed to waiting only 8 minutes before restarting this motor following a normal stop. Having to wait an extra 45 minutes caused the team to question whether the motor settings were appropriate. In this example case, the settings were appropriate. An understanding of the time required to wait to restart the motor following an overload condition versus a normal stop was all that was required. The goal in the following sections is to highlight how to create thermal element settings to ensure proper tripping, allow appropriate cool time, and maximize the availability of the motor running.

III. THERMAL ELEMENT

A. Thermal Model

When the motor is running, current flows through the stator and the rotor and the resistance of the stator and rotor result in losses. These losses cause heating. The motor is designed to withstand normal operating temperature. However, if the temperature exceeds design limits due to any abnormal conditions, the motor could get damaged, leading to reduced life or failure.

A first-order thermal model is used to estimate the temperature of the stator and rotor. The motor is tripped when the per-unit (pu) temperature calculated by the model exceeds the thermal limit of the stator or rotor. The first-order thermal model is described in detail in [6] and [7]. A brief description is provided to illustrate the data required to set the thermal element for the stator and rotor. The major components of the model shown in Fig. 2 are as follows:

1. Heat source: heat flow from the source is $I^2 \cdot r$ watts (J/s). This includes the heating effect due to positive-sequence current and negative-sequence current.
2. Thermal capacitance (C_{th}): this represents the capacity of the motor to absorb heat from the heat source. The unit of thermal capacitance is J/°C.
3. Thermal resistance (R_{th}): this represents the heat dissipated by a motor to its surroundings. The unit of thermal resistance is °C/W.
4. The comparator: this creates a trip condition when the calculated motor pu temperature (U) exceeds a trip value (U_{trip}).

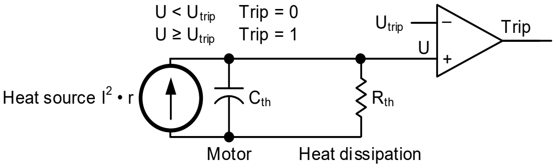


Fig. 2. First-Order Thermal Model

The TCU can be calculated as follows (1):

$$TCU = \frac{U}{U_{trip}} \cdot 100\% \tag{1}$$

Once the TCU reaches 100 percent, the relay will trip. One implementation includes a separate model for the stator and the rotor in which both models are always active. The model components (R_{th}, C_{th}, and U_{trip}) are different for the stator and rotor models and vary depending on the state of the motor: starting, running, and stopped states.

The components of the rotor thermal model depend on the following variables:

1. Locked rotor amperes (LRA) in pu of full-load amperes (FLA)
2. Hot locked rotor time (LRTHOT) in seconds

The model components (R_{th} and U_{trip}) are calculated from the LRA and LRTHOT values that are provided by the manufacturer, as described in [5].

The components of the stator thermal model depend on the following variables:

1. Overload pickup (OLPU)
2. LRA
3. LRTHOT
4. Running time constant (RTC)

The relay setting engineer can calculate the OLPU and RTC values using the manufacturer’s thermal limit curves (which represent how quickly the stator heats up). The RTC value may be provided by the manufacturer.

Fig. 2 is applicable to the stator model in the starting and running states. It is also applicable to the rotor model in the running state. However, the circuit in Fig. 2 is modified for the rotor model in starting state. During the starting state, the resistance value in the rotor model is infinite, which represents an adiabatic system, as heat dissipation in this state is negligible compared to the heat produced. The rotor TCU increases rapidly during a motor start.

B. Stopped Model

When the motor is stopped, there is no current flowing through the windings, the heat source is disconnected, and the motor dissipates heat to its surroundings. The dissipation of heat to the surroundings is represented by the capacitor discharging through the resistor, as shown in Fig. 3. The initial charge on the capacitor is equal to the pu temperature at the time it stopped.

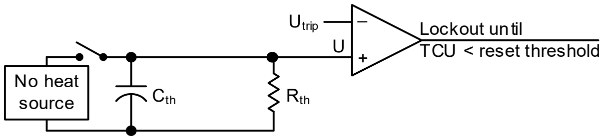


Fig. 3. Stator Thermal Model in Stopped State

After a motor is stopped, it is not necessary for the stator and rotor temperatures to decrease to ambient before issuing a new start. Instead, the temperature only needs to decrease enough to ensure a new start would not cause the stator or rotor temperature to exceed its thermal limit. The motor should only be locked out in the stopped state until it is possible to safely restart the motor. Some relays have the ability to inhibit starting until the thermal capacity drops below a settable threshold. Thus, the reset thresholds to remove the thermal element lockout must be defined based on the temperature rise during a motor start. The typical start time of the motor can be used to determine the reset thresholds.

For most motors, the time constant in the stopped state is higher than the time constant in the running state. It takes more time for the motor to cool down in the stopped state than in the running state. When the motor is stopped, the cooling fans are stationary and air cannot flow through the motor as efficiently. Both the stator and rotor use the same stopped time constant equal to COOLTIME / 3, where COOLTIME is settable.

However, immediately after a stop command is issued, the motor takes several seconds to slow down to a standstill. During this coast-down period, air circulates through the motor and helps cool down the stator and rotor at a faster rate. Some relays have the option to specify the coast-down time (COASTIME). When the motor is stopped, these relays initially use the faster cooling rate, equal to the running time constant (stator or rotor, respectively), for the duration of the coast-down period. After the coast-down timer expires, the relay switches to the slower cooling rate defined by the COOLTIME / 3 time constant.

The reset TCU for the stator depends on the $\text{RESET}_{\text{STR}}$ setting. The stator TCU must decrease below the $\text{RESET}_{\text{STR}}$ setting to ensure that the motor can be started without causing thermal damage to the stator.

The reset TCU for the rotor depends on the $\text{START}_{\text{TCU}}$ setting. The $\text{START}_{\text{TCU}}$ setting is equal to the rotor TCU required for a normal start. The rotor TCU must decrease below 100% – $\text{START}_{\text{TCU}}$ to ensure that the motor can be started without causing thermal damage to the rotor.

Studies show that the stator temperature rise is a function of four thermal time constants, and the cooling curve is a function of three or more thermal time constants [8]. The thermal model used for protection uses one time constant for temperature rise in the running state and up to two time constants for cooling in the stopped state. Accurately modeling the thermal characteristics of the motor during heating and cooling requires multiple time constants, and this will make the thermal element too complex and difficult to set. Using one heating time constant and up to two cooling time constants is sufficient to protect the motor.

Therefore, we can summarize that the reset characteristics for the stator and rotor use the following settings:

1. COOLTIME
2. COASTIME
3. $\text{RESET}_{\text{STR}}$
4. $\text{START}_{\text{TCU}}$

C. Steps to Create Trip and Reset Settings

Step 1) Enter Settings for the Rotor Thermal Element

The thermal element for the rotor uses the following settings:

1. LRA (pu of FLA)
2. LRTHOT (seconds)

LRA is the steady-state current drawn from the line when the rotor is locked with rated voltage applied to the motor. This setting can be entered directly from the motor data sheet.

LRTHOT can be calculated from the manufacturer’s data sheet based on the following guidelines.

1. If the data sheet provides a hot locked rotor time at 100-percent-rated voltage, use that value in the settings.
2. If the data sheet provides a locked rotor time without any information about hot or cold conditions, assume it is a cold condition. Assume the ratio of cold locked rotor time to hot locked rotor time is 1.2 [6]. Divide the locked rotor time by 1.2 and use that value as the hot locked rotor time.

In the case of older motor retrofits, a data sheet may not be readily available. In such applications, the nameplate and existing motor protection settings can be used to calculate the LRTHOT and the LRA values. Reference [7] provides detailed examples on creating settings for undocumented alternating current (ac) motors. In the case of high inertia applications, a slip-dependent thermal model should be used, as described in [9].

Step 2) Enter Settings for the Stator Thermal Element

The thermal element for the stator uses the following settings:

1. OLPU in pu of FLA
2. LRA (selected in Step 1)
3. LRTHOT (selected in Step 1)
4. RTC (minutes)

OLPU is the pickup setting of the thermal element and can be set using the following guidelines.

1. The pickup can be set to equal the service factor (SF) on the motor nameplate. It can be set higher than the nameplate SF based on motor design (e.g., insulation class and actual temperature rise) and applicable standards, such as [5] and [10]. Reference [10] permits a pickup of 125 percent of the rated full-load current for motors with a SF of 1.15. High pickup values can be considered, particularly on motors with winding RTDs, where a separate RTD protection element can trip the motor based on measured winding temperature and back up the thermal element. This provides additional flexibility in setting the pickup in applications where short duration overloads are expected.
2. If thermal limit curves are available, it may be possible to increase the overload pickup to the asymptote of the running overload limit curve as described in [11].

If RTC is provided by the manufacturer, that value should be used for the RTC setting. However, RTC can also be calculated from the thermal limit curves. The stator time to trip varies proportionally with the RTC setting as shown in Fig. 4. High RTC means that the stator takes a long time to heat up. The RTC setting can be determined in the following ways:

1. The relay setting engineer can set the RTC by coordinating the relay stator trip characteristic with the thermal limit curves provided by the manufacturer. Motor manufacturers may provide the stator or running thermal limit and the rotor or locked thermal limit under two initial machine conditions: ambient temperature and rated load operating temperature [12].

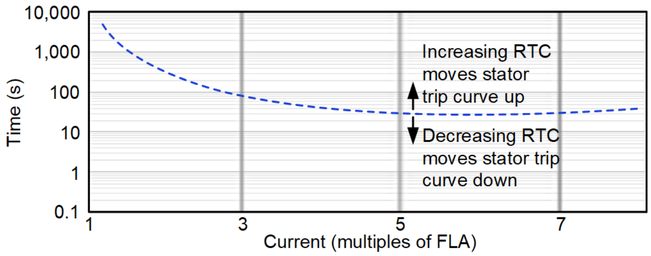


Fig. 4. Variation of Stator Trip Characteristic With RTC

The stator trip curve must be coordinated with the stator thermal limit curve at the same value of preload. Preload is the steady-state current drawn by the motor just before the overload occurred. Reference [11] provides information on calculating both the preload value and RTC value from the thermal limit curves.

2. In the case of older motor retrofits, the data sheet with thermal limit curves may not be available. The RTC for rotor limited motors can be set based on the LRA, LRTHOT, and OLPU settings using (2):

$$\text{RTC} = \frac{1.2 \bullet \text{LRTHOT}}{60 \bullet \ln\left(\frac{\text{LRA}^2 - (0.9 \bullet \text{OLPU})^2}{\text{LRA}^2 - \text{OLPU}^2}\right)} \qquad (2)$$

Reference [7] provides additional information on selecting RTC for undocumented ac motors.

Step 3) Enter the Reset Settings

The stopped thermal model for the stator and rotor uses the following settings:

1. COOLTIME (minutes)
2. COASTIME (optional setting in seconds)
3. $\text{RESET}_{\text{STR}}$—requires motor start time
4. $\text{START}_{\text{TCU}}$—requires motor start time

COOLTIME is set using the following guidelines:

1. If the data sheet specifies a cooling time constant, multiply this value by three to get the COOLTIME setting.
2. If the data sheet provides a cool time value, enter this value directly as the COOLTIME setting. The motor will not be locked out for the entire duration of the COOLTIME setting. It will only be locked out until the TCU decreases below the reset thresholds.
3. If one ambient and one winding RTD is available, some microprocessor relays can automatically calculate a COOLTIME setting based on the decrease in winding RTD temperature. This calculation is performed when the learned COOLTIME feature is enabled.
4. If winding RTDs are available but an ambient RTD is unavailable, use the microprocessor relay to record the winding RTD temperature during a normal motor start, run, and stop cycle. Select two points from the RTD measurement records in the stopped state. The first value is RTD_1, which should be taken when the motor has stopped. The second value is RTD_2, which should be taken when the RTD temperatures are close to steady state (ambient). The variable t represents time in minutes between RTD_1 and RTD_2 measurements. The ambient temperature is the RTD_ambient value. This value can be obtained by checking the weather reports for that location at the time of motor stop or using the RTD measurements at steady state after motor stop. The cooling time constant can be calculated using these data, as shown in (3).

$$\text{COOLTIME} = \frac{-3 \bullet t}{\ln\left(\frac{\text{RTD}_2 - \text{RTD}_{\text{ambient}}}{\text{RTD}_1 - \text{RTD}_{\text{ambient}}}\right)} \qquad (3)$$

5. If the data sheet does not provide any information about cooling time and if RTDs are unavailable, then the COOLTIME value should at least be equal to 3 • RTC. As mentioned in Section III Subsection B, the stopped time constant cannot be lower than the RTC due to reduced air flow. Setting the COOLTIME to equal 3 • RTC results in the fastest thermal reset in the stopped state. This option should be used only when there is no other information available. If possible, the COOLTIME can be set to a higher value based on the maximum reset time permissible for the motor after a stop or trip.

The COASTIME value can be set to 90 percent of the time it takes for the rotor to come to a complete stop.

The stator reset TCU, $\text{RESET}_{\text{STR}}$, can be calculated using (4). Note that equation highlighted in gray is the stator TCU after one start.

$$\text{RESET}_{\text{STR}} = 100\% - \frac{\text{LRA}^2 \bullet \left(1 - e^{\frac{-\text{Typical start time}}{60 \bullet \text{RTC}}}\right)}{\text{OLPU}^2} \bullet 100\% \tag{4}$$

The starting TCU for the rotor, $\text{START}_{\text{TCU}}$, can be calculated using (5).

$$\text{START}_{\text{TCU}} = \frac{\text{Typical start time}}{\text{LRTHOT}} \bullet 100\% \tag{5}$$

Note that the $\text{START}_{\text{TCU}}$ and $\text{RESET}_{\text{STR}}$ values should be verified during normal motor operation and adjusted as needed. A 5 to 10 percent margin can be provided for these reset settings.

D. Calculating Thermal Lockout Time

This section shows how to calculate the reset time for the stator and rotor after a normal stop or trip. This information is useful for engineers and operators to ensure that the motor will not be locked out longer than necessary. These equations can also be used to calculate the number of starts permitted from ambient temperature and operating temperature. Reference [13] has the following starting requirements: two consecutive starts with motor coasting to rest between starts, three consecutive starts with motor coasting to rest and remaining idle for 20 minutes, and three evenly spaced starts in 1 hour. Motor manufacturers may deviate from these starting requirements for special motor applications.

The stator's steady-state TCU is calculated using (6):

$$\text{TCU}_{\text{stator}}(\%) = \frac{\text{I}^2}{\text{OLPU}^2} \bullet 100\% \tag{6}$$

where:

I is the current drawn by the motor in multiples of FLA.

When a motor with OLPU = 1.15 and drawing FLA has reached steady-state operating temperature, the stator TCU is approximately 76 percent. Therefore, when this motor has stopped after several hours of normal operation, the stator TCU at the beginning of the stopped state is 76 percent. If a new start is issued, the stator TCU at the end of the start is equal to the sum of (6) and the gray part of (4).

The rotor's steady-state TCU is calculated using (7):

$$\text{TCU}_{\text{rotor}}(\%) = \frac{\text{I}^2 \bullet 0.2}{1.2} \bullet 100\% \tag{7}$$

where:

I is the current drawn by the motor in multiples of FLA.

When a motor with OLPU = 1.15 and drawing FLA has reached steady-state operating temperature, the rotor TCU is approximately 16.67 percent. Therefore, when this motor has stopped after several hours of normal operation, the rotor TCU at the beginning of the stopped state is 16.67 percent. If a new start issued, the rotor TCU at the end of the start is equal to the sum of (5) and (7).

Equation (8) is used to calculate the time required for the stator and rotor TCU to decrease below the reset threshold, where the Reset TCU percent is equal to $\text{RESET}_{\text{STR}}$ for the stator and is equal to 100% – $\text{START}_{\text{TCU}}$ for the rotor.

$$\text{T}_{\text{reset}} = -\frac{\text{COOLTIME}}{3} \bullet \ln\left(\frac{\text{Reset TCU\%}}{\text{Initial TCU\%}}\right) \tag{8}$$

If the relay uses only one cooling time constant, then (8) will provide the reset time. However, if the COASTIME setting is enabled and set in the relay, a faster cooling time constant is used during the coast-down period. The reset time calculation for this case involves two steps.

1. Determine the TCU for the stator ($\text{TCU}_{\text{COAST,stator}}$) and rotor ($\text{TCU\_}_{\text{COAST,rotor}}$) at the end of the coast-down period by using (9) and (10), respectively. The stator and rotor TCU at the beginning of the stopped period is the $\text{TCU\_}_{\text{0,stator}}$ and $\text{TCU\_}_{\text{0,rotor}}$, respectively.

$$\text{TCU}_{\text{COAST, stator}}(\%) = \text{TCU}_{\text{0, stator}} \bullet e^{\left(\frac{-\text{COASTIME}}{60 \bullet \text{RTC}}\right)} \tag{9}$$

$$\text{TCU}_{\text{COAST, rotor}}(\%) = \text{TCU}_{\text{0, rotor}} \bullet e^{\left(\frac{-\text{COASTIME}}{0.6 \bullet \text{LRA}^2 \bullet \text{LRTHOT}}\right)} \tag{10}$$

If the calculated $\text{TCU\_}_{\text{COAST,stator}}$ is less than the reset threshold ($\text{RESET}_{\text{STR}}$) use (11) to calculate the reset time. If the calculated $\text{TCU\_}_{\text{COAST,rotor}}$ is less than the reset threshold (100% – $\text{START}_{\text{TCU}}$), use (12) to calculate the reset time.

$$\text{t}_{\text{reset, stator}} = -\text{RTC} \bullet \ln\left(\frac{\text{RESET}_{\text{STR}}\%}{\text{TCU}_{\text{0, stator}}\%}\right) \tag{11}$$

$$\text{t}_{\text{reset, rotor}} = \frac{-0.6 \bullet \text{LRA}^2 \bullet \text{LRTHOT}}{60} \bullet \ln\left(\frac{100\% - \text{START}_{\text{TCU}}}{\text{TCU}_{\text{0, rotor}}}\right) \tag{12}$$

In this case, the thermal lockout may reset before the motor comes to a complete stop.

2. If the TCU calculated using (9) and (10) are greater than the respective reset threshold, the motor needs to cool down further before a new start can be permitted. The stopped cooling time constant must

be used to calculate the remaining reset time because the COASTIME has expired. The total reset time for this case can be calculated, as shown in (13) and (14).

$$t_{\text{reset, stator}} = -\left(\frac{\text{COOLTME}}{3}\right) \bullet \ln\left(\frac{\text{RESET}_{\text{STR}}}{\text{TCU}_{\text{coast, stator}}}\right) + \frac{\text{COASTIME}}{60} \qquad (13)$$

$$t_{\text{reset, rotor}} = -\left(\frac{\text{COOLTME}}{3}\right) \bullet \ln\left(\frac{100\% - \text{START}_{\text{TCU}}}{\text{TCU}_{\text{coast, rotor}}}\right) + \frac{\text{COASTIME}}{60} \qquad (14)$$

IV. MOTOR PROTECTION EXAMPLES

A. Example 1: 4,000 V, 500 Horsepower (hp) Air Compressor Protection

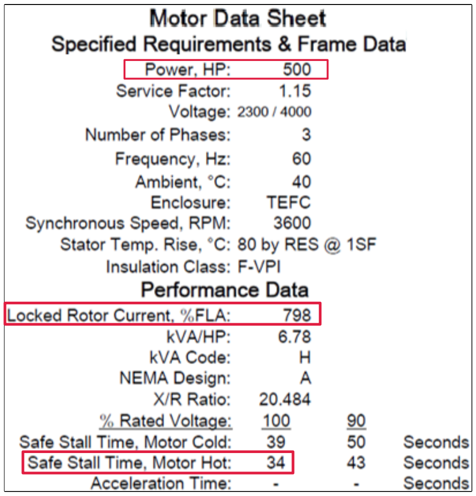
In this example, trip and reset settings are derived for a 500 hp air compressor using the steps described in Section III Subsection C.

Step 1) Enter Settings for a Rotor Thermal Element

1. LRA (pu of FLA)
2. LRTHOT (seconds)

The data sheet in Fig. 5 shows that the locked rotor current or LRA value is equal to 798 percent of FLA or 7.98 pu of FLA.

The locked rotor time can also be referred to as the safe stall time on the motor data sheet. Fig. 5 shows two values of safe stall time, the cold time is 39 seconds and hot time is 34 seconds. The thermal model requires the hot-stall time. Therefore, LRTHOT is set to 34 seconds.



Motor Data Sheet

Specified Requirements & Frame Data

Power, HP:	500		
Service Factor:	1.15		
Voltage:	2300 / 4000		
Number of Phases:	3		
Frequency, Hz:	60		
Ambient, °C:	40		
Enclosure:	TEFC		
Synchronous Speed, RPM:	3600		
Stator Temp. Rise, °C:	80 by RES @ 1SF		
Insulation Class:	F-VPI		
Performance Data			
Locked Rotor Current, %FLA:	798		
kVA/HP:	6.78		
kVA Code:	H		
NEMA Design:	A		
X/R Ratio:	20.484		
% Rated Voltage:	100	90	
Safe Stall Time, Motor Cold:	39	50	Seconds
Safe Stall Time, Motor Hot:	34	43	Seconds
Acceleration Time:	-	-	Seconds

Fig. 5. Motor Data Sheet for Example 1

Step 2) Enter Settings for the Stator Thermal Element

1. OLPU
2. LRA (PU of FLA) = 7.98
3. LRTHOT (seconds) = 34 seconds
4. RTC (minutes)

The LRA and LRTHOT values are already determined in Step 1. The additional settings required for the stator element are OLPU and RTC. As shown in the data sheet in Fig. 5, SF equals 1.15; therefore, OLPU can be set to 1.15. This motor has a SF of 1.15 and a Class F insulation. The permissible temperature rise at the rated load for this insulation class is 115°C. The actual stator temperature rise at this rated load is 80°C. There is a margin of 35°C temperature rise built into this motor at the rated load. The pickup value could be increased above the nameplate SF if needed. If the motor is operated at winding temperature above the maximum permissible value for Class F insulation, it results in loss of insulation life.

The RTC setting can be determined by using the thermal limit curves from the data sheet, shown in Fig. 6.

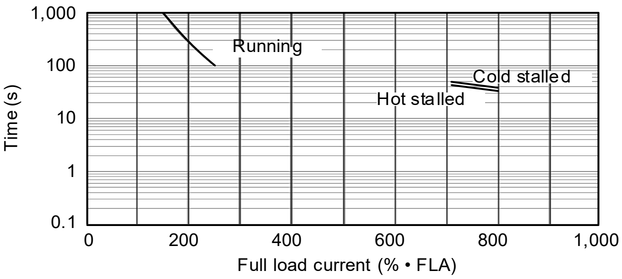


Fig. 6. Motor Thermal Limit Curves for Example 1

The stator trip characteristic of the relay must be coordinated against the thermal limit curves provided by the manufacturer. The RTC value can be varied to achieve coordination. In this example, the stator thermal limit is a straight line on the semi log scale graph, similar to the rotor thermal limit. The stator thermal limit is not derived from a first-order thermal model. The manufacturer did not provide additional details about the thermal limit curves such as operating temperature. Due to insufficient details about the thermal limit curves, we used the winding RTD data to confirm the value of RTC.

The coordinated thermal limit curves are shown in Fig. 7 for an RTC value of 50 minutes and preload of 1.05 • FLA. This results in miscoordination above 2 • FLA. In such a case, jam trip protection or definite time overcurrent protection with a pickup of 2 • FLA can be used to protect the motor against thermal damage in the running state. Alternatively, you can set RTC to a more sensitive value of 40 minutes, which moves the entire trip curve below the thermal limit curve; however, it will provide quicker time to trip in the range of currents between OLPU and 2 • FLA. This is a choice between sensitive versus secure protection, and good engineering judgement must be used to set the RTC value.

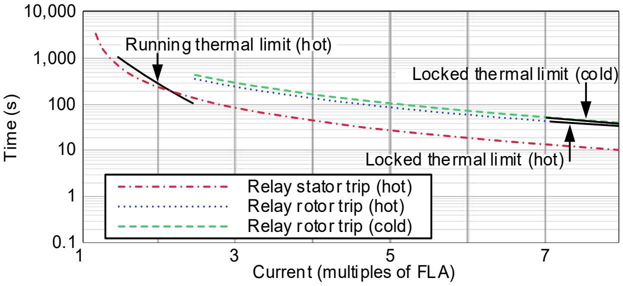


Fig. 7. Trip Characteristic

The heating curve of the motor using a time constant (τ) can be plotted by calculating the temperature (Temp) at time (t) using (15):

$$\text{Temp}(t) = \text{Temp}(0) \bullet e^{\frac{-t}{\tau}} + \text{Temp}(\text{final}) \bullet \left(1 - e^{\frac{-t}{\tau}}\right) \qquad (15)$$

The value of τ is equal to RTC during the running condition. Temp(0) is the initial ambient temperature and Temp(final) is the steady-state operating temperature to which the motor heats up. The relay recorded six winding RTD temperatures during a start, run, and stop cycle. The average winding RTD temperature is shown in Fig. 8. The initial and final temperatures are obtained from these data. The RTC value of 50 provides a good curve fit between (15) and the RTD data. In cases when the thermal limit curves are not available or if the data provided is unclear, the RTD data can be used to verify the RTC.

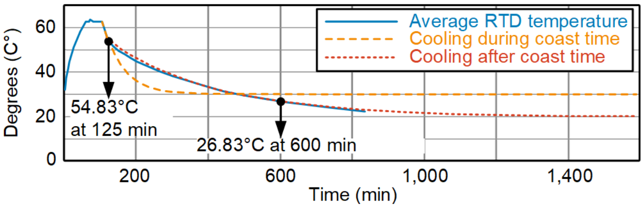


Fig. 8. Average RTD Temperature Compared to Two Cooling Curves

Step 3) Enter the Reset Settings

1. COOLTIME (minutes)
2. COASTIME (optional setting in seconds)
3. $\text{RESET}_{\text{STR}}$ (% TCU)
4. $\text{START}_{\text{TCU}}$(% TCU)

This data sheet does not provide any information about cool time or the cooling time constant. The initial COOLTIME setting was programmed to the minimum permissible setting of 3 • RTC, which is 150 minutes. The RTD measurements recorded during the motor stop are used to modify the COOLTIME setting.

If the COASTIME setting is enabled and programmed, the initial cooling rate for the stator is equal to RTC. The exact COASTIME for this motor is unavailable; however, the RTD measurements show a faster decrease in temperature during the initial phase when the motor is spinning down, and these data are used to approximate the COASTIME value to show the difference in reset time when one or two cooling rates are used. A COASTIME of 900 seconds can be programmed and the cooling rate in this period is the same as the RTC.

The COOLTIME setting can be calculated using the RTD values after the COASTIME period has expired.

Average RTD value 15 minutes after stop = RTD_1 = 54.83°C

Average RTD value 490 minutes after stop = RTD_2 = 26.83°C

Time between these two RTD measurements = 475 minutes

The COOLTIME setting in this case can be calculated using (3) and is equal to 874 minutes, and the cooling time constant is 291 minutes, as shown in (16).

$$\text{COOLTIME} = \frac{-3 \bullet 475}{\ln\left(\frac{26.83-20}{54.83-20}\right)} = 874 \text{ minutes} \qquad (16)$$

Note that this does not mean the motor will be locked out for 874 minutes. The motor is only locked out until the TCU decreases below the reset threshold. Using two cooling time constants is sufficient to replicate the RTD cooling curve, as shown in Fig. 8. At 125 minutes (15 minutes after motor stop), the relay switches to the slower cooling rate.

Note that the ambient temperature changes throughout the day and the ambient temperature around the time the motor stopped is 30°C and this is used as the ambient temperature to plot the cooling during COASTIME. After several hours of cooling, the RTDs reach steady-state temperature of approximately 20°C; therefore, the ambient temperature for calculating the COOLTIME setting is 20°C. The cooling curve of the motor using a time constant (τ) can be plotted by calculating the temperature (Temp) at time (t), using (15).The value of τ is equal to RTC during the coast-down period and it is equal to COOLTIME / 3 after the coast-down period. Temp(0) is the initial temperature at which the cooling curve begins and Temp(final) is the ambient temperature to which the motor cools down.

If the COASTIME setting is not used and a single time constant is programmed for the cooling state, there is a larger error between the RTD measurements and cooling curve using a single time constant. The COOLTIME setting for this case can be calculated using the two measurements, shown in Fig. 9. The cooling curve using a single time constant of 267 minutes or a COOLTIME setting of 802 minutes is shown in Fig. 9.

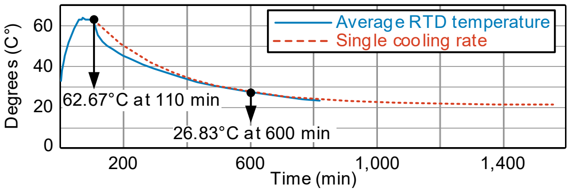


Fig. 9. Average RTD Temperature Compared to a Single Cooling Curve

$\text{RESET}_{\text{STR}}$, the stator reset setting, can be calculated using (4) and considers a typical start time for this motor of 10 seconds, as shown in (17):

$$\text{RESET}_{\text{STR}} = 100\% - \frac{7.98^2 \bullet \left(1 - e^{\frac{-10}{60 \bullet 50}}\right)}{1.15^2} \bullet 100\% \qquad (17)$$

$$\text{RESET}_{\text{STR}} = 100\% - 16\% = 84\%$$

The $\text{START}_{\text{TCU}}$ setting can be calculated using (5), as shown in (18):

$$\text{START}_{\text{TCU}} = \frac{10}{34} \bullet 100\% = 29\% \tag{18}$$

When this motor is drawing FLA, the steady-state stator TCU is 76 percent. The steady-state rotor TCU is 16.67 percent. These values are lower than the stator and rotor reset thresholds of $\text{RESET}_{\text{STR}}$ and 100% – $\text{START}_{\text{TCU}}$, respectively. This means that the relay permits a start immediately after the motor has stopped.

Consider a case where the motor is overloaded and draws 1.1 • FLA. The steady-state stator TCU is calculated using (6), and it is equal to 91.5 percent. The steady-state rotor TCU can be calculated using (7) and is equal to 20 percent. When this motor has stopped, the rotor TCU is below 100% – $\text{START}_{\text{TCU}}$. However, the stator TCU is above the $\text{RESET}_{\text{STR}}$ setting. This means that the stator needs to cool down before a new start can be permitted. The reset time for the stator considering a single cooling time constant, can be calculated using (8), as shown in (19).

$$T_{\text{reset}} = -\frac{802}{3} \bullet \ln\left(\frac{84\%}{91.5\%}\right) = 22 \text{ minutes} \tag{19}$$

If we enable and program a COASTIME setting to 15 minutes to obtain a faster cooling rate, the reset time can be calculated using the two steps involving (9) and (11) in (20).

$$\text{TCU}_{\text{COAST, stator}}(\%) = 91.5 \bullet e^{\left(\frac{-900}{60 \bullet 50}\right)} = 67.78\% \tag{20}$$

The result of (20) is lower than the $\text{RESET}_{\text{STR}}$ setting of 84 percent. Equation (11) can be used to calculate the reset time, as shown in (21):

$$t_{\text{reset, stator}} = -50 \bullet \ln\left(\frac{84\%}{91.5\%}\right) = 4.27 \text{ minutes} \tag{21}$$

Using a COASTIME setting or two cooling rates reduce the lockout time to 4.27 minutes. If the reset time of 22 minutes for this overload is acceptable to the operator, then a single time constant of 802 minutes can be used, and the COASTIME setting can be disabled. It is important to consider the life of the machine versus the importance of maintaining process continuity while deciding between selective or sensitive settings. If a faster restart is more desirable, the COASTIME setting should be enabled and programmed. Operators should take advantage of the monitoring capabilities of microprocessor relays and continue to record the RTD data and investigate if the cooling efficiency decreases suddenly. This could indicate that the cooling system is not functioning efficiently and requires maintenance.

B. Example 2: 2,300 V, 300 hp

In this example, trip and reset settings are developed for a 300 hp centrifugal pump using the steps described in Section III Subsection C.

Step 1) Enter Settings for Rotor Thermal Element

1. LRA (pu of FLA)
2. LRTHOT (seconds)

The data sheet states that the LRA = 419 A and FLA = 68.3 A. The LRA in pu of FLA can be set to 6.13.

This data sheet does not specify a locked rotor time directly. However, the thermal limit curve shows that the hot locked rotor time for a value of 613 percent of FLA is 21.3 seconds. The LRTHOT value can be set to 21.3 seconds.

Step 2) Enter Settings for the Stator Thermal Element

1. OLPU
2. LRA (pu of FLA) = 6.13
3. LRTHOT (seconds) = 21.3 seconds
4. RTC (minutes)

The LRA and LRTHOT values are determined in Step 1. The additional settings required for the stator element are OLPU and RTC. The data sheet states that the SF of this motor is 1.00. The OLPU setting can be set to 1.05. This motor has a SF of 1 and a Class F insulation. The actual stator temperature rise is same as Class B insulation. This means there is additional margin for the temperature rise at rated load, and the pickup value can be increased above 1.05 if needed.

The RTC setting can be determined by using the thermal limit curves from the data sheet shown in Fig. 10. The manufacturer confirmed that an adiabatic model is used for the running thermal limit. At low values of overload, the actual thermal limit is much higher than the thermal limit derived from the adiabatic model.

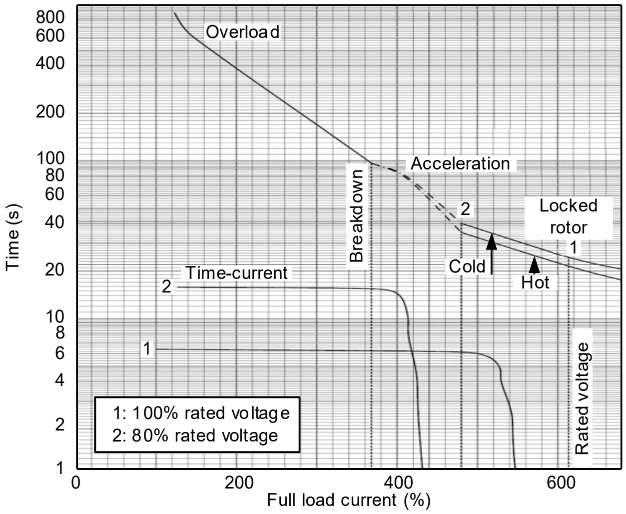


Fig. 10. Motor Nameplate for Example 2

The final coordinated thermal limit curves are shown in Fig. 11 for an RTC value of 60 minutes and a preload of 0.84 • FLA.

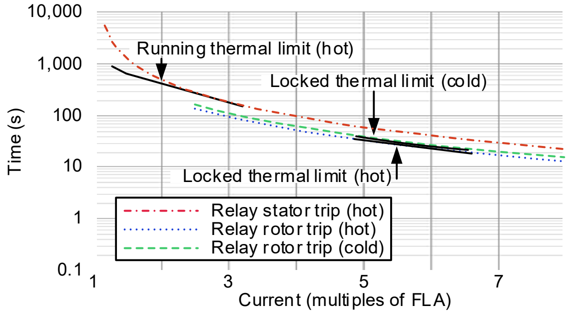


Fig. 11. Coordination of Thermal Limit Curve With Relay Trip Characteristic

Step 3) Enter the Reset Settings

1. COOLTIME (minutes)
2. COASTIME (optional setting in seconds)
3. $\text{RESET}_{\text{STR}}$ (% TCU)
4. $\text{START}_{\text{TCU}}$ (% TCU)

This data sheet does not provide any information about cool time or cooling time constant. The relay recorded six winding RTD temperatures during a start, run, stop cycle. The average winding RTD temperature is shown in Fig. 12.

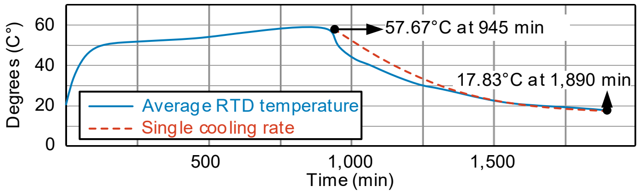


Fig. 12. Cooling Curve Without Coast Time

The COASTIME for this motor was not obtained at commissioning and this option was disabled. Fig. 12 shows that the RTDs reach steady-state temperature of approximately 16°C, and we can assume the ambient temperature is 16°C.

The COOLTIME setting can be calculated as shown in (22).

Average RTD value when the motor is stopped = RTD_1 = 57.67°C

Average RTD value 945 minutes after stop = RTD_2 = 17.83°C

Time between these two RTD measurements = 945 minutes

$$\text{COOLTIME} = \frac{-3 \bullet 945}{\ln\left(\frac{17.83 - 16}{57.67 - 16}\right)} = 907 \text{ minutes} \tag{22}$$

The COOLTIME setting in this case is 907 minutes (22), and the cooling time constant is approximately 302 minutes. This does not mean the motor is locked out for 907 minutes. The motor is only locked out until the TCU decreases below the reset thresholds.

The cooling curve using this COOLTIME value is shown in Fig. 12.

$\text{RESET}_{\text{STR}}$, the stator reset setting, can be calculated using (4), as shown in (23), considering a typical start time for this motor of 6.5 seconds. The stator TCU after a start is 6.14 percent.

$$\text{RESET}_{\text{STR}} = 100\% - \frac{6.13^2 \bullet \left(1 - e^{\frac{-6.5}{60 \bullet 60}}\right)}{1.05^2} \bullet 100\% \tag{23}$$

$$\text{RESET}_{\text{STR}} = 100\% - 6.14\% = 93.85\%$$

The $\text{START}_{\text{TCU}}$ setting can be calculated using (5), as shown in (24):

$$\text{START}_{\text{TCU}} = \frac{6.5}{21.3} \bullet 100\% = 30.5\% \tag{24}$$

When this motor is running at FLA, the steady-state stator TCU is 90.7 percent, and the steady-state rotor TCU is 16.67 percent. These values are lower than the stator and rotor reset thresholds of $\text{RESET}_{\text{STR}}$ and 100% – $\text{START}_{\text{TCU}}$, respectively. This means that the relay permits a start immediately after the motor has stopped. A second hot start is permitted approximately 10 minutes after the motor is stopped and can be calculated using (8). When the motor is started from ambient temperature, three consecutive starts will be permitted (30.5% • 3 < 100%).

A motor trip caused by a thermal overload event could be due to a stator TCU of 100 percent or rotor TCU of 100 percent. The stator or rotor needs to cool down before a new start can be permitted. Equation (8) can be used to calculate the reset time for the stator considering a single cooling time constant (COASTIME disabled), as shown in (25).

$$t_{\text{reset, stator}} = -\frac{907}{3} \bullet \ln\left(\frac{93.85\%}{100\%}\right) = 19.2 \text{ minutes} \tag{25}$$

The reset time for the rotor trip is calculated, as shown in (26):

$$t_{\text{reset, rotor}} = -\frac{907}{3} \bullet \ln\left(\frac{69.5\%}{100\%}\right) = 109.8 \text{ minutes} \tag{26}$$

When the motor has tripped due to stator overload, the reset time is equal to 19.2 minutes. When the motor has tripped due to rotor lockout, the reset time is equal to 109 minutes. An operator who is accustomed to restarting the motor immediately after a normal stop may be surprised at the longer wait time after a motor trip. However, the longer time is justified in the case of a true overload or locked rotor trip. The root cause of the trip should be determined before restarting the motor to ensure that it does not occur again.

V. CONCLUSION

In this paper, we discuss the need to maximize motor usage and illustrate steps needed to set the trip and reset settings for motor thermal protection. The time to reset after a normal stop, overload, or trip condition can be calculated using the equations provided in this paper. The equations for a single cooling rate or for two cooling rates (COASTIME setting) are shown. We use these steps to create settings for two motors. The impact of the reset settings on the restart times for these two motors is shown. These guidelines can be used with good engineering judgement to maximize motor operation.

VI. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the motor data shared by Mr. Jixil Johnson from Chevron Phillips Chemical, which made it possible to provide a real-world example of motor protection.

VII. APPENDIX A

A list of key variable names along with their description is provided as follows, in order of appearance:

RTD: resistive temperature detector
TCU: thermal capacity used
LRA: locked rotor amperes
FLA: full-load amperes
OLPU: overload pickup
LRTHOT: hot locked rotor time
RTC: running time constant
COOLTIME: cooling time
COASTIME: coast-down time
$\text{RESET}_{\text{STR}}$: stator reset TCU threshold
$\text{START}_{\text{TCU}}$: rotor TCU after start
τ: time constant

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IX. VITAE

Jim Payne is a director for electrical equipment and renewable power at Phillips 66, focusing on electrical safety, reliability, and sustainability. Jim began his career as an electrical engineer at Dow Chemical in 1999 and has held positions at Eaton Corporation and Valero Energy. He earned his BSEE from New Mexico State University in 1998.

Edgardo Miguel, Jr., is the electrical superintendent at the Phillips 66 Los Angeles Refinery, responsible for the safety, maintenance, and reliable operation of electrical systems. Edgardo started his career as an electrical engineer at Gekko Engineering in 2007 and then at Phillips 66 Los Angeles Refinery in 2011. He earned his BSEE from the California State University of Long Beach in 2009.

Krithika Bhuvaneshwaran received her BS in electrical engineering from Sardar Patel College of Engineering in Mumbai, India, in 2012, and her MS from the Georgia Institute of Technology in Atlanta, Georgia, in 2016. She currently works for Schweitzer Engineering Laboratories, Inc. (SEL) as an application engineer in Plano, Texas. She can be contacted at KritBhuv@selinc.com.

Derrick Haas graduated from Texas A&M University with a BSEE. He worked as a distribution engineer for CenterPoint Energy in Houston, Texas, until 2006 when he joined Schweitzer Engineering Laboratories, Inc. (SEL). Derrick has held several titles including field application engineer, senior application engineer, team lead, and his current role of regional technical manager. He is a senior member of the IEEE and involved in the IEEE Power System Relaying Committee. He can be contacted at Derrick_Haas@selinc.com.