WHY CAN'T I START MY MOTOR? DEMYSTIFYING MOTOR RELAY LOCKOUTS

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***Abstract* – As the driver of many vital processes, motors are by far the most proliferous heavy machinery found in industrial facilities. Protection & control is key to maximizing operational life and process availability. Motor protection relays often employ thermal modeling and start inhibits to estimate the motor's thermal state and block restart attempts to prevent overheating of the stator windings. Adequately and accurately setting a motor's thermal protection is both an art and science – one that can cause confusion for operators if not correctly executed. This paper reviews the fundamental concepts and configuration of motor thermal protection. Various factors that play into typical restart blocking logic will be discussed, accompanied by case studies illustrating the consequences of improper configuration. Methods of troubleshooting will be examined and suggestions for configuration with limited motor data will be provided to avoid inadvertent and unnecessary motor lockouts.**

Index Terms — Motor Protection, Thermal Protection, Motor Relays, Motor Relay Lockout, Motor Thermal Model

I. INTRODUCTION

In industrial facilities, electric motors are the most abundant and critical machinery to plant operations. Proper motor management is key to maximizing life expectancy and process uptime, as well as reducing maintenance expenditures and efforts. Unexpected motor replacement or repair is costly and often incurs extended lead times.

Studies performed by the IEEE Motor Reliability Working Group and EPRI [1] indicate that the second most common failure mode among medium-voltage motors is stator failures, as summarized in Figure 1 below. Several components may fail within a stator assembly; however, the primary cause of failure is normally due to insulation degradation, which is most often directly or indirectly caused by excessive winding temperature.

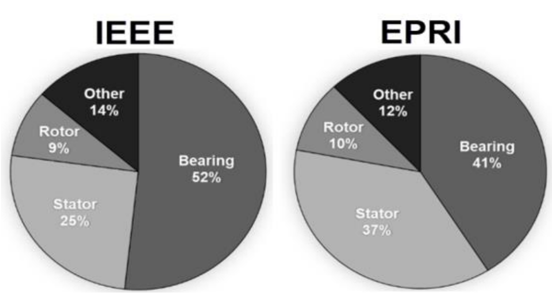
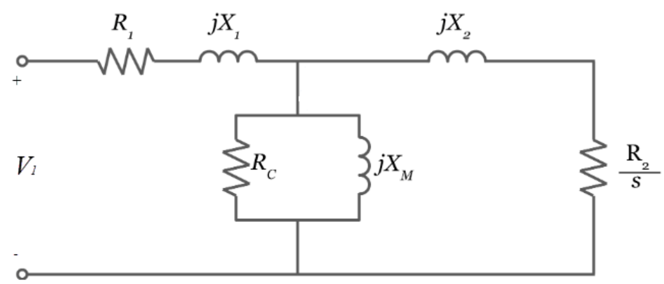


Fig. 1 Results of Reliability Surveys [1]

A. Characteristics of Motor Heating

Several factors contribute to heat generation within a motor, the most significant being the stator current. Consider the induction motor equivalent circuit, shown in Figure 2.



Where,

V_1 = *Applied Voltage*
R_1 = *Stator Resistance*
X_1 = *Stator Leakage Reactance*
R_C = *Stator Iron Core Loss Resistance*
X_M = *Stator Core Leakage Reactance*
X_2 = *Rotor Leakage Reactance Referred to the Stator*
R_2 = *Rotor Resistance Referred to the Stator*
S = *Slip*

Fig. 2 Induction Motor Equivalent Circuit

The most extreme operating conditions occur during motor starting. On initial application of the terminal voltage (V_1), the rotor is at a standstill. The rotor slip (s) is at a maximum of 1, rendering a minimum referred rotor resistance (R_2/s). After approximately one-half cycle, the stator magnetizing branch current becomes negligible. All current is directed to induce magnetization of the rotor field and generate torque to overcome the shaft's inertia and force it to rotate. As the rotor speed increases, the slip decreases, the rotor produces a back EMF opposing the stator EMF, and the inrush current gradually subsides. Due to the initially low rotor resistance, a current inrush of 4 to 6 times rated full load amps (i.e., the rated locked rotor current) may be drawn during acceleration. Significant thermal energy from I^2R copper losses is accumulated during this time, most notably in the stator windings (R_1).

During normal operation, the heat accrued during startup gradually sinks into the body of the motor. Minimal additional heat is accumulated. Although heat is still generated from losses, built-in cooling mechanisms eventually bring the temperature to a steady state and ensure that the motor may be safely loaded and run up to its rated service factor without overheating. Should the load current exceed the service factor, heat will once again begin to accumulate in the motor. Although not typically an immediate concern, caution must be followed to ensure the overload is not sustained for an extended duration to cause the motor's temperature to exceed its rated insulation thermal limit. Should this occur, it does not cause immediate insulation failure, however, prolonged or repeated overloads do eventually cause degradation and decrease the insulation's life expectancy [2]. Studies indicate that for each temperature increase of 10°C above the rated thermal limit, the insulation life is halved [3]. The relationship between the operating temperature versus the percentage of remaining insulation life is shown in Figure 3, for several common insulation classes. Ultimately, it is important to consider the motor's recent operational history. Heat dissipation does not occur instantly. Should a motor start or overload condition have recently occurred, the motor may not be capable of sustaining another start attempt or overload for some time without incurring damage.

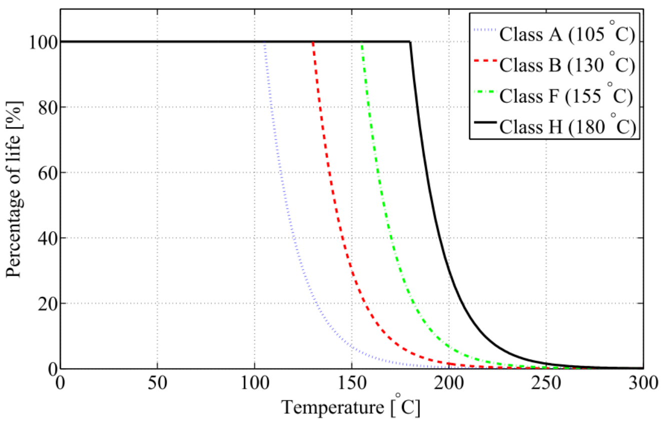


Fig. 3 Temperature vs. Percentage of Life [3][4]

Although to a lesser extent than overloading, several other factors may further exacerbate the thermal state of the motor. Stator current unbalances, for example, result in a negative sequence stator current that induces a rotor current flowing in the opposite direction, which results in additional losses. An abnormally high ambient temperature also fundamentally biases the motor's thermal state. While less substantial sources of heating, it is prudent to still consider them, if possible, especially if the motor is to be operated rigorously.

B. Motor Protection & Control

Applying adequate protection & control to the motor is crucial to ensure safe operation and functional longevity. Motor protection relays typically employ several methods to safeguard the motor from overheating under different operating conditions. The most direct element is resistance temperature detector (RTD) monitoring. RTD probes are often installed internally throughout the circumference of the stator and wired to the protection relay for monitoring. As the winding temperature fluctuates, so does the resistance of the probe. The protection relay interprets the measured resistance as it relates to the temperature and may be configured to alarm and/or shutdown the motor should the measured temperature exceed a set limit. While RTDs provide concrete measurements, they also have a slow response time, and hence are normally reserved for backup protection and to account for scenarios that other elements may not react to such as an abnormally high ambient temperature or a cooling system failure.

The primary method of motor thermal protection is typically by means of thermal modeling. Thermal modeling dynamically uses the metered load current along with the motor's specified thermal characteristics to develop a rolling register of the estimated thermal state of the motor and force a shutdown should it too closely approach its thermal limit. Modern protection relays often incorporate additional data into the modeling algorithm to enhance its estimate, including the metered current unbalance, the motor's cooling rate, the specified steady state thermal usage, and in some cases a biasing derived from the RTD temperature measurements. The resultant of the thermal algorithm is the Thermal Capacity Used (TCU): a percentage value that represents the present thermal state of the motor, 0% being a completely cold (ambient temperature) motor, and 100% indicating the motor has reached its thermal limit. The TCU of a running motor will culminate at some level between 0% and 99%.

A vital counterpart to the main protection is the start inhibit function that prevents a motor from being restarted should it exceed its allowed starting frequency, not have sufficient thermal capacity available to safely sustain a starting condition, or any other miscellaneous electrical or operational issue be present.

Ultimately, the thermal model and start inhibit elements will only be as accurate as the information and configuration supplied. Motor datasheets will not always provide complete information or may be unavailable. Engineers who are not familiar with the operating requirements may configure the setpoints as conservative as possible since that is typically the approach with other methods of protection. Conversely, plant personnel may tend to err on the side of operations and select settings that are more liberal. Both cases can cause problems. It is important to understand the relay configuration effects on the thermal calculation and determine a balance where the protection is reasonable, but the motor is still permitted to start and adequately operate. The approach also depends on the criticality of the process being run. The following discussion provides guidance and recommendations on how to properly develop the protection relay's configuration to ensure accurate thermal protection and start inhibit control. Common mishaps along with examples and methods of troubleshooting will also be provided. Note, recommendations and best practices are often subject to engineers' familiarity and practical experience. The following aims to provide a general understanding of the background and tools required to successfully implement motor protection and control.

I. Motor Thermal Modeling

Motor thermal modeling has been employed by various means throughout history, starting with basic long-time overcurrent relays, and advancing to more complex microprocessor-based algorithms capable of considering numerous operational factors. However, much of the underlying concepts and theory remain the same. Below describes the main parameters found in a typical modern motor protection relay's thermal model algorithm, and how to configure proper setpoints both with and without an available manufactured specification.

A. Overload Curve & Overload Pickup

The overload curve selection, sometimes called the "curve number" or "time-dial multiplier", is arguably the most important setting in the relay. Its purpose, in essence, is to emulate a long-time overcurrent trip characteristic: the higher the load current, the faster the relay will trip. The overload curve number shifts the curve up or down to increase or decrease the overall time to trip. Ultimately, the relay's TCU calculation is dependent on the selected overload curve number. The time to trip is directly tied to the TCU. The lower the overload curve, the faster the TCU increases and the faster the relay will trip. The higher the curve, the slower the TCU increases and the slower the relay will trip. The relay will issue a trip the moment the TCU reaches 100%, which corresponds to the moment the overcurrent characteristic reaches the selected overload curve.

The overload curve is typically set according to the motor's specified thermal limit curves. Figure 4 below illustrates an ideal example of motor thermal limit curves provided by the motor manufacturer.

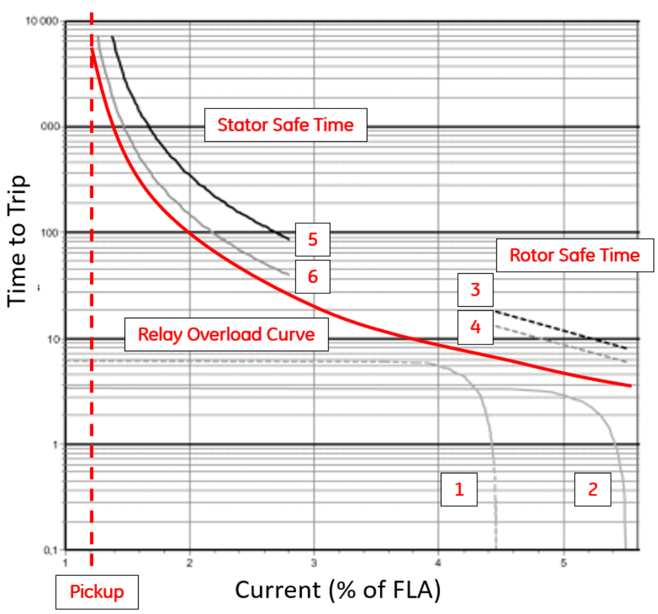


Fig. 4 Thermal Limit Curves with Overload Curve & Pickup

The components of the current versus time to trip/overload chart are identified as follows:

1. Acceleration characteristic at 80% starting voltage.
2. Acceleration characteristic at 100% starting voltage.
3. Locked rotor curve – cold motor
4. Locked rotor curve – hot motor
5. Running overload thermal limit – cold motor
6. Running overload thermal limit – hot motor

The two acceleration curves, 1 and 2, simply illustrate the initial inrush/locked rotor current and how long the motor takes to fully accelerate if started across the line at or near full voltage. These are provided for overload coordination purposes. Curves 3 and 4 essentially refer to the rotor and indicate the thermal limit in a locked rotor scenario if a mechanical jam or locked rotor were to occur during startup. Curves 5 and 6 refer to the stator and indicate the thermal limit during a situation when the motor is running overloaded.

The relay's set overload curve is shown in the middle of the chart. The load current level at which the overload curve takes effect is the relay's overload pickup setting – the dashed vertical line on the left of the chart. Below the pickup, the TCU does not increase. Above the pickup, the TCU commences accumulation. The pickup is typically set 10-15% above the motor's rated service factor. For example, a motor with a service factor of 1.0 may have a 1.10 overload pickup setting.

The overload curve configuration typically offers time-dial style options in a range of standard-shaped overload/overcurrent curves. The curve number should be selected such that the curve lies below the entirety of the thermal limit curves to shut down the motor in any scenario, prior to it reaching its thermal limit. The lower the set curve, the more conservative the protection; however, it must also be set high enough to not overlap the motor's acceleration characteristic. Should the curve be set too low, the relay will incorrectly trip the motor during acceleration. A general recommendation is if the process the motor is driving is critical and maximum motor operability is desired, a curve just below the thermal limits should be selected. However, if the motor itself (i.e., acquisition, maintenance, repair ability, etc.) is more critical, a lower, more conservative curve number may be selected.

In the case where the motor manufacturer does not provide any specified thermal limit curves, a curve number may be empirically estimated, *if* the motor is known to be in good operational condition. If the motor datasheet provides a start frequency specification, for example, 3 permissible consecutive starts, this may be interpreted as the maximum number of starts it would take for the TCU to reach 100%, or to not have enough margin left to permit an additional start. 3 consecutive starts allowed would equate to as high as 33% TCU registered for a single start. To empirically derive the curve number that would correspond to this, several start tests may be performed. During these tests, the relay's TCU reset (or "emergency restart") function will need to be used to clear the TCU after each start, which will render the protection null. Therefore, the following steps should be followed with caution.

1. Set the curve number to the lowest setting, curve 1.
2. Attempt to start the motor. If the relay does not allow the motor to start, increase the curve number by 1.
3. For conservative protection, increase the curve number until the motor is just able to fully start, or one curve number above that.
4. For a more typical setting, note the TCU accumulation that the relay registers for a single start, which will vary with changing the curve number. Increase the curve number until the relay registers an amount not exceeding the percentage corresponding to the number of allowable consecutive starts. I.e., ~33% for 3 consecutive starts, or ~49% for 2 consecutive starts.
5. Increasing the curve number beyond step 4 yields a more progressive setting, which *may* be acceptable – theoretically, 3 allowable consecutive starts may yield a starting TCU anywhere between ~26%-33%, or ~36%-49% for 2 starts, however, caution should be exercised, and the data sheets reviewed or the RTDs monitored for additional information, since the exact thermal limit remains unknown.

Note, this test should be performed with usual starting conditions. If the motor will always start coupled with load, the test should follow that setup as the motor will take longer to accelerate in that case, which needs to be accounted for in the selected overload curve.

B. Unbalance Bias K Factor

A motor protection relay's thermal algorithm will often include an optional provision to account for the heating effect of unbalanced current, which is not otherwise considered in the current-based thermal model or the provided thermal limit specifications, which assume a balanced system. As explained in [6], negative sequence current caused by unbalances induces a rotor voltage that produces a substantial rotor current at twice the line frequency. Due to the skin effect in the rotor bars at this frequency, the rotor resistance increases, therefore causing an increase in rotor heating.

NEMA has studied and provided recommendations for motor derating as a function of voltage unbalance, as shown in Figure 7. Modern protection relay thermal models can incorporate this derating into its estimate by using the Unbalance Bias K Factor setting. This derating characteristic, shown in Figure 8, is designed to closely match the NEMA recommendations, with some more and less conservative options available.

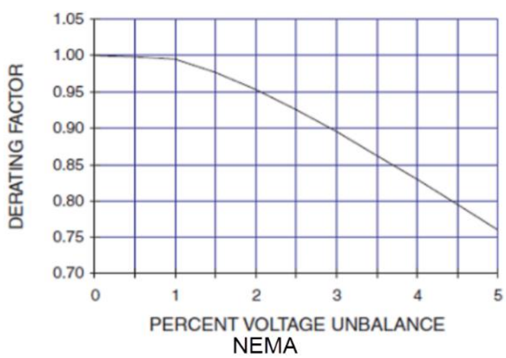


Figure 7. NEMA Motor Derating for Voltage Unbalance

Fig. 8 Relay Thermal Model Derating for Voltage Unbalance

The Unbalance Bias K Factor setting can be calculated using (1) or (2) below. (1) represents a typical estimate, whereas (2) represents a conservative estimate. Both are based on the rated locked rotor current.

$$K = \frac{175}{I_{LR}^2} \quad (1) \qquad\qquad K = \frac{230}{I_{LR}^2} \quad (2)$$

In a scenario where the rated locked rotor current data is unavailable, this setting should be set to "0". This value causes the effects of unbalanced currents to be omitted, and the thermal model will only consider the metered positive sequence current.

C. Stopped and Running Cooling Time Constants

The cooling time constants are implemented to emulate the characteristics of motor cooling. Two time constants are to be configured: one for a running condition, where cooling systems assist with motor cooling, and one for a stopped condition, when the motor is at standstill with less ventilation and slower cooling.

In basic terms, motor cooling is a decaying exponential characteristic involving $e^{-\frac{1}{\tau}}$, where τ is the time constant. In the first iteration of the time constant, the motor cools by approximately 63% of its original temperature. Subsequent iterations see an exponentially decreasing change. Ultimately, the motor will reach a steady state temperature after 5 iterations of the time constant. Figures 9 and 10 illustrate this concept.

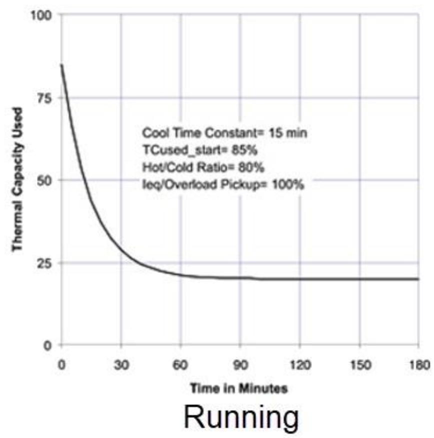


Figure 9. Motor Cooling While Running

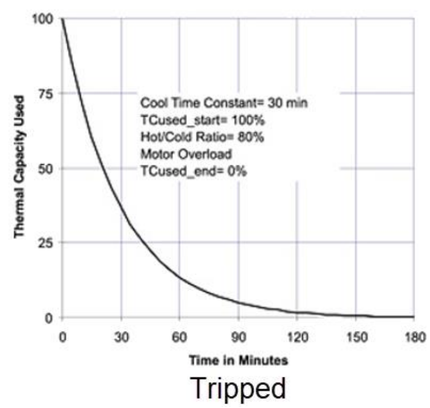


Fig. 10 Motor Cooling While Stopped/Tripped

To configure the protection relay's two cooling time constants, it is imperative to understand what information is provided on the motor data sheet and what exactly the relay requires. Some relays require the time constant, while others require the *total cooling time*. If the time constant is required and the motor data sheet states the total cooling time, the time constants are 1/5th of these values. In addition, time constants stated on the data sheet may refer to other unrelated cooling characteristics. Discretion should be taken to ensure the values stated are understood and used correctly.

In a scenario where cooling time constant specifications are unavailable, default settings of 15min stopped and 30min running can be used, or 20min stopped and 40min running for a more conservative estimate. These are commonly used values for most typical motors – that is, small-to-mid-sized motors generally rated less than 10000 HP and not driving a specialized type of load. However, this is not always the case. It is recommended to research the motor specifications and its application, if possible, to make a proper assessment.

D. Hot/Cold Safe Stall Ratio

To distinguish between a cold (ambient) or hot (ambient + rated temperature rise) motor, the motor manufacturer will sometimes include two rotor thermal limit curves/safe stall times. The difference between them defines the relative increase in TCU of the motor fully loaded at a settled temperature versus the ambient temperature motor at rest [2]. The relay thermal model incorporates this information via the Hot/Cold Safe Stall Ratio parameter, represented by the "Hot/Cold" term in (3) below. This setting, in addition to the present load current versus the pickup setting, dictate the TCU at which the motor will settle during steady state operation, after it has otherwise cooled.

$$TCU_{end} = \left(\frac{I_{eq}}{OL \times FLA}\right)\left(1 - \frac{hot}{cold}\right) \times 100\% \qquad (3)$$

This setting is simply determined by dividing the specified hot locked rotor time by the cold locked rotor time, or if not stated explicitly, the end-point times of the hot and cold locked rotor thermal limit curves.

If no locked rotor times are provided, or if only the hot locked rotor time is specified, this setting should be set to "1", which essentially disables this feature and renders the steady state TCU to be 0%. While this will not be completely accurate for a running motor, the effect it will have on the time to trip is likely not a critical factor.

E. RTD Biasing

If a full set of 6 RTDs (2 per phase) are being monitored by the protection relay and sufficient data is available to enable proper configuration of the Hot/Cold Safe Stall Ratio, RTD biasing may be used to include actual temperature measurements into the thermal modeling – a very useful tool to account for scenarios such as a loss of cooling or unusually high ambient temperature. With this feature enabled, the relay registers a second TCU based on the RTD temperature measurements. If the overload pickup has been exceeded, the relay will consider *both* the current-based TCU and the RTD-based TCU. Should the RTD-based TCU be higher, the relay may issue a thermal trip quicker than it would using only the current-based TCU. The RTD Bias setpoints are configured as follows:

1. *RTD Bias Minimum:* Set to rated ambient temperature, or 40°C, if unspecified.
2. *RTD Bias Center:* Ambient temperature + rated temperature rise of stator + 10°C safety margin.
3. *RTD Bias Maximum:* Set at or slightly below stator insulation rating. E.g., Rating - 10°C.
4. *RTD Bias Pickup Delay:* Set at or greater than 2s to assist in avoiding misoperation due to failed RTDs.
5. *RTD Bias Voting & Voting Band:* Enabling voting requires two RTDs to read hot for the biasing to be valid. A single hot RTD will not cause a thermal model trip. This is another measure to help avoid a false biasing due to an RTD failed open.

Based on the configuration above, the relay builds its second RTD-based thermal characteristic as shown in Figure 11, relating RTD temperature readings to a registered TCU. Note: the mid-point TCU takes into account the temperature rise of the stator, which means the Hot/Cold Safe Stall Ratio setting must be configured and set correctly. If this setting is unable to be properly configured, RTD Biasing should not be used.

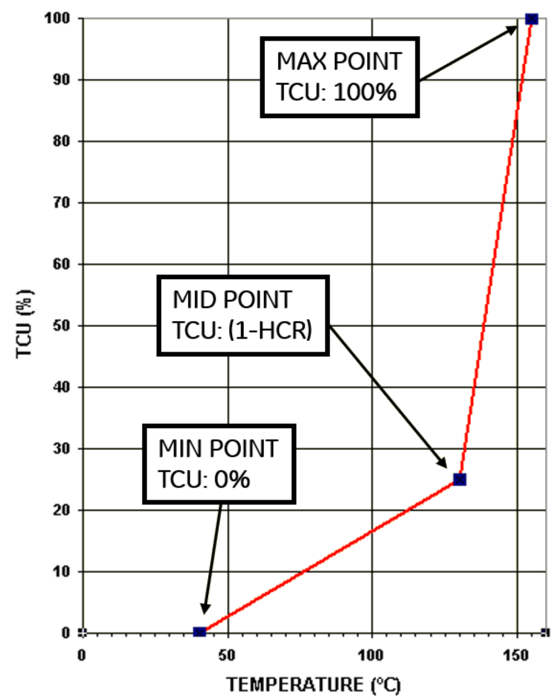


Fig. 11.RTD Biased Thermal Model Characteristic

II. Motor Start Supervision

With the thermal model properly configured, the relay will successfully trip the motor should an overload be sustained for too long or the RTD measurements indicate an excessive temperature. The other major stipulation to adequate motor protection is to ensure the motor cannot be restarted if it is already too hot. For this function, most protection relays employ a start inhibit or restart block function. The start inhibit logic monitors the factors below – if any of these factors become active, a start inhibit is issued and the relay will block a restart for an appropriate duration. Physically, the trip circuit will be held asserted to prevent closure of the motor contactor or breaker.

A. Thermal Inhibit

The thermal inhibit is the primary supervisory element of the relay's TCU, ensuring enough thermal capacity is available to permit a motor restart. Modern relays have a feature to automatically record the TCU registered for a set number of previous motor starts. It uses this data to "learn" the motor's starting characteristics and apply more accurate restart blocking. Typically, data from 3-5 starts is recorded, then either averaged or the highest logged value identified. A small margin, usually 25% of the value, is added for contingency, and the result is stored as the TCU required to be available to permit a start. If this TCU required to start is not fully satisfied, a thermal inhibit will be active and a lockout timer will be indicated on the relay, according to how quickly the TCU is configured to cool.

Typically, there is an option to disable the relay from learning the motor's starting data. In the case of not enough starts having been performed yet, the learned data will also not be available. If the learning feature is disabled or not enough starts have been logged, the thermal inhibit will still be active, however, it will be forced to assume a worst-case scenario and deem the TCU required to start to be 85%. This means that the TCU must decrease to 15% for a single restart to be permitted. In most cases, this is a gross overestimate and will render a much longer lockout time than required. Provided that the motor is not applied to a high-inertia application (in which case the motor will take a long time to start and may actually use 85% or more TCU), it is always recommended to enable the thermal inhibit feature and allow it to make use of the learned data.

B. Other Start Inhibits

Several other more straightforward start inhibit functions may be also implemented as a backup to the thermal model and its thermal inhibit. Often, these are required to be set simply for motor warranty purposes. If active, the following will block a restart and display a corresponding lockout timer.

1. *Maximum Starting Rate:* Typically expressed as the number of allowed starts per hour. This is normally either set to 2 or 3 starts, as indicated on the motor data sheet. If both the hot and cold number of starts is provided and the relay only has a single setpoint, the number of allowed hot starts should be used.
2. *Time Between Starts:* The motor manufacturer's recommended down time prior to a restart.
3. *Restart Delay:* Available on select relays, an intentional time delay enforced after a shutdown. This is used for specific flow-type applications, e.g., down-hole pumps or bearing lubricant pumps, where material may backflow and spin the motor in the opposite direction for a moment. To prevent damage, the motor should not be restarted until the backspin has ceased.

III. Troubleshooting & Implications of Erroneous Configuration

While start inhibits can sometimes be a source of confusion, excessive or erroneous lockouts are almost always caused by a misunderstanding of what exactly is causing the start inhibit and/or an incorrectly configured thermal model setting that skews the TCU accumulation or rate of cooling. Understanding of the settings discussed previously is imperative to facilitate proper troubleshooting to determine if the thermal trip and/or lockout are legitimate, and otherwise how to rectify the problem. The following discussion reviews several case studies illustrating common areas of erroneous relay configuration, how it manifested as a relay trip and/or lockout, and the troubleshooting steps that were followed or recommended to correct the issue.

A. Overload Curve Set Too Low

As mentioned in section II. A., selection of a proper overload curve number is by far the most vital task in configuring a motor protection relay. Quite often, unexpected or incorrect operations are due to an inaccurately set overload curve. If difficulties arise the first time a motor start attempt is performed with a new relay or settings applied, the overload curve should be the first point of investigation.

Many instances arise where an overload curve is arbitrarily set to the lowest option, curve 1, to err on the side of conservancy. However, as already discussed, too conservative a curve may pose an issue for some motors and may not allow the motor to start. Consider the configuration shown in Figure 12.

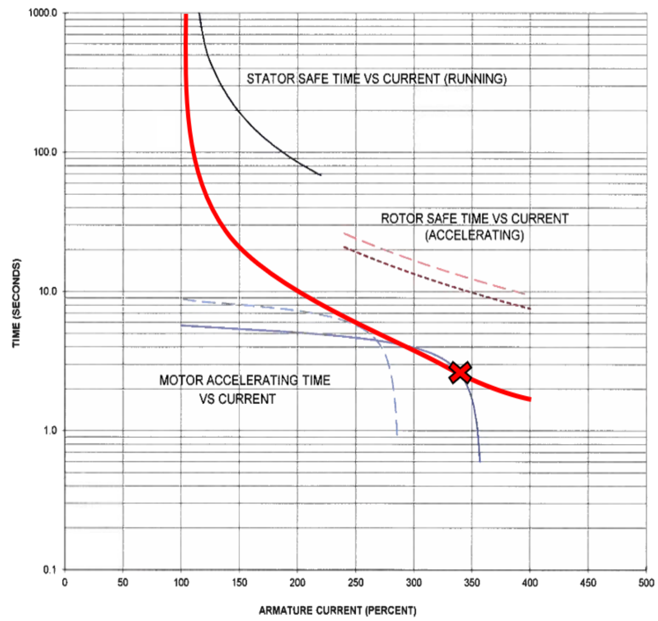


Fig. 12 Incorrectly Configured Overload Curve

Plotting the relay's set overload curve on the motor thermal limits graph, an intersection of the overload curve with the acceleration curves is clearly visible. In this case, the total acceleration time required to start is almost 6s, however the relay will trip 2.5s after voltage is applied to the motor. This motor would require a slightly higher minimum overload curve selection to allow operation. It is always recommended to check the overload curve selection against the specified thermal limit curves, or, if the specifications are unavailable, select the overload curve according to the process described in II. A.

Caution should always be exercised when troubleshooting and re-evaluating the relay's configuration to ensure the issue isn't mechanical related. Another plausible explanation for a trip while performing a start attempt is that the relay is carrying out its intended purpose, such as in the case of a jam or mechanical problem prohibiting the shaft from rotating. For example, an incident was reported where the facility could not start the motor without the protection relay tripping. The relay overload curve was set to 1. The motor data sheets were reviewed, and it was determined that a more proper curve selection would be curve 4, as shown in Figure 13.

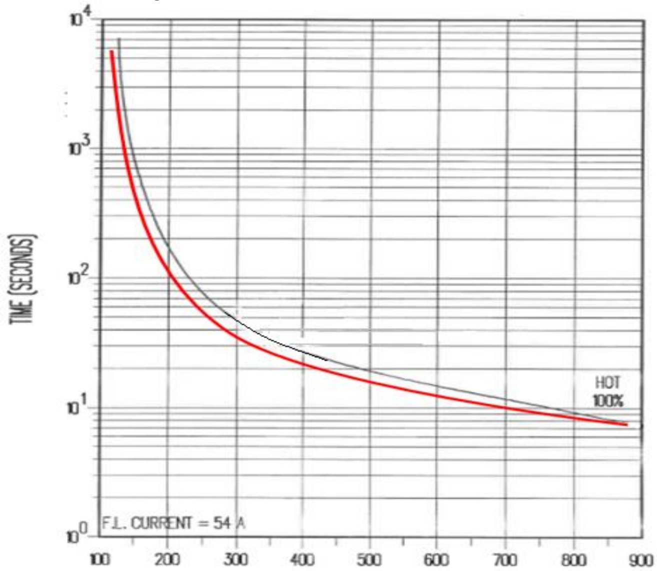


Fig. 13 Corrected Overload Curve Selection

Note how the acceleration characteristics are not shown. No information at all regarding the acceleration was provided on the data sheets, thus, the minimum permitted overload curve remained unknown. The curve in this case was corrected to the highest possible selection. After allowing the motor to cool, another start was attempted, and the relay once again tripped.

Without any leeway left to revise the overload curve again, the relay diagnostic data was reviewed. Figure 14 shows the motor start data captured by the relay. The duration of this log totaled approximately 9s. The log shows the initial inrush current. For a normal start, this current would slowly decrease and then quickly drop to a normal running current level once the motor has fully accelerated. In this case, however, the current barely decreases at all and stays consistently high.

Personnel later discussed that the plant had 4 additional, identical motors, driving identical loads, protected by identical relays with identical configurations. All the other motors successfully start within 2.3s. This motor also had recently underwent major maintenance, and this was the first time it was attempted to be started again. Considering all the evidence, the motor was examined for a possible mechanical problem – which was confirmed to be the cause. Ultimately, the relay was fulfilling its intended purpose, to protect the motor.

B. Total Cooling Time vs. Cooling Time Constant

While the previous case study examined the relay tripping, relay lockouts are also a common conundrum, most often involving an excessively long lockout timer. Recall from III. B., most of the start inhibit elements are straightforward and provide foreseeable lockout timers. The thermal inhibit, however, is not as predictable or consistent, since the exact level of required cooling often depends on recent operating conditions. Typically noticeable within the first few incurred thermal lockouts, if the indicated lockout timer appears to be excessive, it could infer an issue with the thermal model's cooling rate configuration. Per II. A., it is important to ensure that the proper cooling rate is used, according to the relay's requirements. Consider the following case: the relay's running and stopped cooling time constants were configured as 100 and 200 minutes, respectively. A thermal trip occurred, and the relay presented a thermal lockout. The motor was left to cool. After returning the next morning, personnel reported that the relay was still holding its thermal lockout, even though the motor was confirmed to be cool. After reviewing the thermal model settings along with the motor datasheets, it was discovered that the specifications were for *total cooling times*, not the time constants, which are less by a factor of 5. With the total cooling times entered in the relay configuration, the total lockout time after a trip (i.e., 100% TCU, stopped condition) equated to 200 x 5 = 1000 minutes, or approximately 16.6 hours – clearly excessive. Once these parameters were corrected to reflect time constants, no additional prolonged lockouts were incurred.

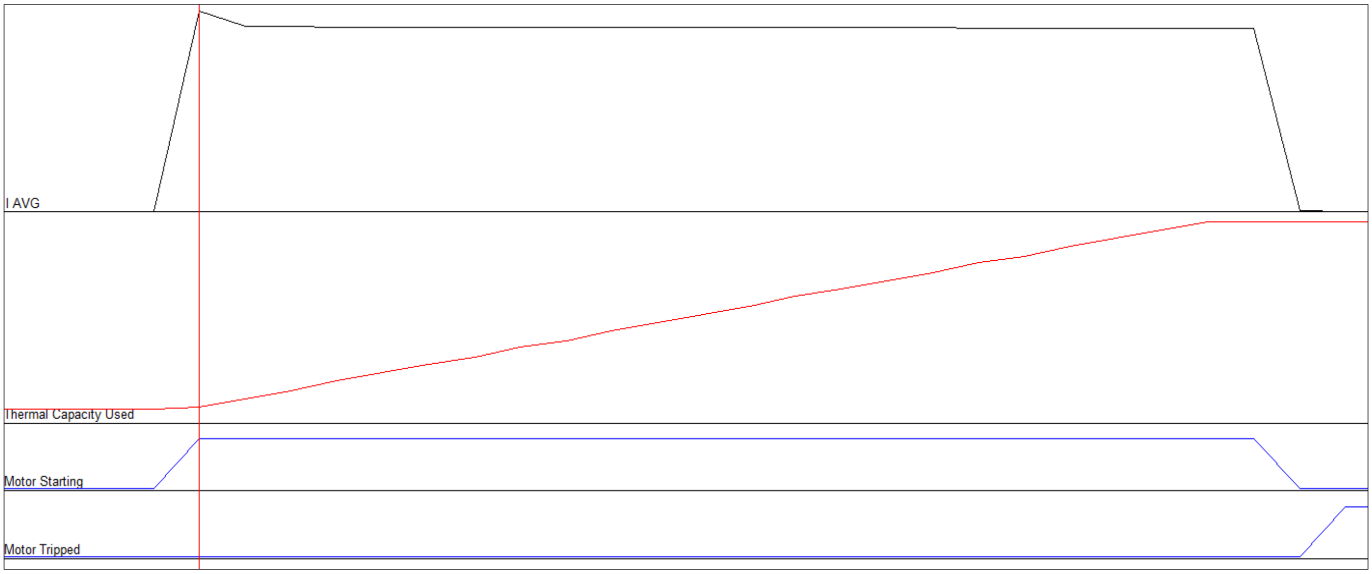


Fig. 14 Relay Motor Start Record

C. Incorrect Hot/Cold Safe Stall Ratio

Although a less common scenario due to the required data often not being available in general, incorrect setting of the Hot/Cold Safe Stall ratio could result in some less obvious, but significant problems. A common oversight is to calculate the ratio of cold/hot stall times instead of hot/cold. The greatest concern with this is that it would cause the TCU to settle at an inversely high value. As noted in [6], for example, if the ratio was supposed to yield 0.87, but was incorrectly calculated to be 0.13, this would cause the steady state TCU to settle at 87% (1 – hot/cold ratio, assuming full loading) instead of 13%, which is a major difference. In a scenario, for instance, when the motor is started and a single start only consumes 20% TCU, instead of then slowly cooling to 13%, it would continue to slowly rise to 87%. If an overload condition then occurs, the time to trip will be significantly reduced. The time to rise from 13% to 100% versus 87% to 100% is vastly different. This would certainly not be a desired operation.

In addition, if RTD biasing is used in the thermal model, an error in the hot/cold safe stall ratio configuration could skew the RTD biased thermal estimate. With the example above, RTD biasing was also in-use. As noted in II. E., the hot/cold safe stall ratio is used to determine the RTD-biased TCU at the midpoint temperature measurement. If the midpoint temperature is registered as 87% instead of 13%, this would significantly skew the entire characteristic and cause the RTD biasing to always register much higher values than normal. In this case, the discrepancy was significant enough to cause the relay to continuously hold a thermal lockout – once the motor was shutdown, it could not be restarted, since at an otherwise normal RTD temperature measurement, the RTD-biased TCU was extremely high and rendered the TCU supervision to deem not enough TCU available to permit a restart.

D. RTD Biasing & Failed RTDs

While RTD biasing incorporated into the thermal model feature can be a beneficial addition, it is crucial that the health of the RTDs be considered, and the available voting and time delay options be included to prevent a misoperation due to faulty RTDs. The following case study illustrates the need for these safeguards.

Plant personnel reported that the motor was running without an issue, however the protection relay recently had been consistently holding a thermal lockout. The TCU displayed on the relay HMI seemed abnormally high, but with no apparent cause. Upon review of the relay event logs, it was seen that the TCU kept randomly spiking to 100%; however, no trip was issued since the load current remained well below the overload pickup – a seemingly peculiar occurrence. Knowing that RTD biasing was being implemented, the relay records and data captures were examined for high RTD readings, nothing unusual of which was found. During discussion, the RTD metering screens were displayed to review real-time readings. By chance, it was noticed that intermittently, for a split moment, one of the RTD readings was increasing to 400°C, then returning to normal. The investigation revealed that an intermittent failure of this RTD was repeatedly biasing the relay's TCU to 100%. Because the intermittency was extremely brief, none of the relay diagnostics were able to capture the phenomenon, however the relay's core processing (which is faster) was still affected. Ultimately, if RTD voting and/or an intentional RTD biasing delay were used, the relay would not have triggered the RTD-based TCU consideration and no unintentional lockouts would have been experienced.

IV. Conclusions

While the principals and algorithms involved in motor protective relaying may at first seem a dauting task to navigate, with careful consideration of the background theories and the lessons learned from others' experience, a successful application and implementation is achievable for any experience level. Understanding the main failure modes and stresses to motors – namely, thermal losses and insulation constraints – is first and foremost. When approaching a protective relay, it's crucial to understand its method of thermal modeling, how to configure each major setpoint, and exactly how each setpoint ties into the overall thermal estimation algorithm. Furthermore, a grasp of common errors made during configuration, how they manifest in the relay operation, and what diagnostics to review will significantly aid in successful troubleshooting and correction of any inadvertent operations or lockouts, should one occur. Inevitably, motor protective relaying truly is an art as much as it is a science -- although there is no one-fits-all approach, by following a well-established set of guidelines and lessons learned, a successful motor protection implementation is certainly achievable.

V. References

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VI. Vitae

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