EXTENDING MOTOR LIFE WITH UPDATED THERMAL MODEL OVERLOAD PROTECTION

Paper No. PCIC-(do not insert number)

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Abstract – Thermal issues shorten motor life. Modern motor relays must protect for these effects, which can occur for motors from small to large (50 HP and greater), and for all voltage operational levels. However, being too conservative on thermal limits decreases motor productivity. An ANSI/IEEE 49 thermal element creates a realistic thermal model of the motor because the element takes the load level and negative-sequence currents into account. The 49 thermal element is superior to older methods using inverse-time overcurrent elements (51).

This paper discusses updates in the existing 49 thermal model implementation. Also discussed are resistance temperature detector (RTD) biasing, resistance temperature detector voting and the role of transducers in the modern motor relay.

Index terms – Motor protection, thermal model, RTD, emergency start, transducers

I. INTRODUCTION

Thermal protection of a motor is vital to motor longevity. Older motor protection methods used the Institute of Electrical and Electronics Engineers (IEEE) 51 elements instead of the 49 thermal model and had no resistance temperature detector (RTD) temperature data[1]. Comparing these two methods of motor protection, IEEE device numbers (51 or 49), demonstrates the benefits of the 49 thermal model response for motor protection versus using a 51 overcurrent method.

The modern motor thermal model uses an "equivalent current," I_{eq}, calculation that best represents the actual motor flux dynamics. This equivalent motor current accounts for the heating effects of negative-sequence current present in induction motor applications. Explanation of the thermal model formula includes the factor *k* user setting.

Actual temperature measurements from RTDs placed in the motor stator windings in cases of high ambient operation conditions bias the thermal model. RTDs on the stator and other locations, such as the motor shaft bearings, can serve as backup protection.

Transducers with inputs and outputs of 4—20 mAdc and 0—10 Vdc also contribute to motor protection. Transducers gather additional operating data, such as bearing oil level, and can be used to control motor cooling via air intake dampers and valves.

Well recommended for medium-voltage and larger motor protection, the protection engineers can choose external motor protection relays for motors of any size, especially for valuable processes; increasing the likelihood that an important process will continue.

II. MOTOR PROTECTION CHALLENGES

Motor protection is a challenge because there are so many different things that can go wrong with a motor and its associated load; thus, increasing motor heating and possible damage. High internal temperature causes stator winding insulation breakdown, resulting in turn-to-turn shorts or turn-to-ground shorts. This insulation breakdown can cause runaway motor heating and further damage, including bearing failure from leakage currents as the rotor heats beyond design limits and, eventually, mechanical failure.

Motors perform well in the proper design environment Examples of good design are supplying ample cooling, choosing the correct indoor/outdoor enclosure, selecting environmental motor types—ODM (open drip-proof) or totally enclosed, matching the motor and load, and analyzing the supply power system so that the motor can operate effectively. Examples of improper design are high ambient temperatures and loss of the ventilation medium (air, water) can cause excessive heating and possible damage in a motor. Another example is motors not designed for cold or wet conditions can experience life-shortening events such as slow starting, an increased low-ambient temperature effect, which can lead to insulation and mechanical damage.

Abnormal power system conditions can create unbalanced voltages and currents at the motor terminals. Motors operating in harsh environments might have connecting cable and terminal corrosion which create negative-sequence imbalances.

A. Starting Requirements

Failure to start occurs when stator start current is applied but the rotor does not turn or is slow to accelerate. When the rotor does not begin to turn immediately or stays too long at some reduced speed, sufficient motor fan or fluid cooling does not take place and the motor heats very quickly toward destructive failure. In addition, at zero speed, all the energy that crosses the air gap becomes heat in the rotor. As the machine goes to operating speed, the generated heat decreases. Rotor heating is made worse by increases in rotor losses caused by the skin effect at large slip frequencies (100 Hz or 120 Hz). Motor protection should ensure sufficient voltage to start the motor quickly based upon manufacturers' recommendations.

Locked rotor current and heating follow the law of Conservation of Energy where energy going in must match energy going out. If electrical energy is going in and mechanical energy is not produced, then energy is converted into heat which can cause damage.

When the motor is started the locked rotor amps (LRA) is typically 4 to 6 times the full load amps (FLA) of the motor. The heating effect of LRA current will be approximately 16 to 36 times full load thermal capability. Motor stator damage can occur if the induced rotating magnetic field experiences too long a period of a stationary or slow-moving rotor. This condition creates high temperatures in the stator because the rotating magnetic field finds no or insufficient rotor movement and heats the stator windings as well. This heating significantly reduces normal stator winding insulation life. In addition, heating causes mechanical stress, fatiguing the stator windings in their slots [3].

Another effect of overheating is mechanical through differential expansion within the rotor cage. Each of the cage bars and end rings will experience expansion as some portions reach higher temperatures than others. Rotor bars bend, lift out of their slots, or break loose from attachment to the rings. Fatigue is the failure mechanism because repeated bending back and forth eventually causes breakage [3].

Obviously, locked rotor currents must be limited to the short period that the motor can withstand.

Calculating motor starting times can be done when the motor torque curve and the load torque curve (including load inertia) are known. Fig. 1 illustrates that the torque applied to acceleration is the difference between the motor torque and the load torque; this acceleration time is where a majority of motor heating occurs. Where the two curves cross, the motor will stop accelerating and will run at that speed. Total start time must also take into account applied motor voltage, as can be seen from Fig. 2 (typical currents and voltages from IEEE 620-1996 [4]). The starting time is required to coordinate the locked rotor protection.

B. Running Thermal Issues

A loss of field in a synchronous motor causes the synchronous machine to consume vars from the system, removing the necessary reactive system support. Synchronous machines quickly overheat from the induced current in the rotor. These machines require a minimum level of excitation to remain stable throughout the load range; a system impedance swing and out-of-step condition can result. In addition to these problems, operating at less than rated lagging power factor, for example, can cause significant heating in the laminations at each end of the stator, because of the change in flux patterns in the underexcited state.

Motors and synchronous machines develop heat while in the running mode. Monitoring heating, air and water flow, ambient air conditions, temporary overloads, intake air plenum damper positions is important. Also using an accurate model of the motor heating (using equivalent motor current) yields benefits in using the motor to maximum effect without damage.

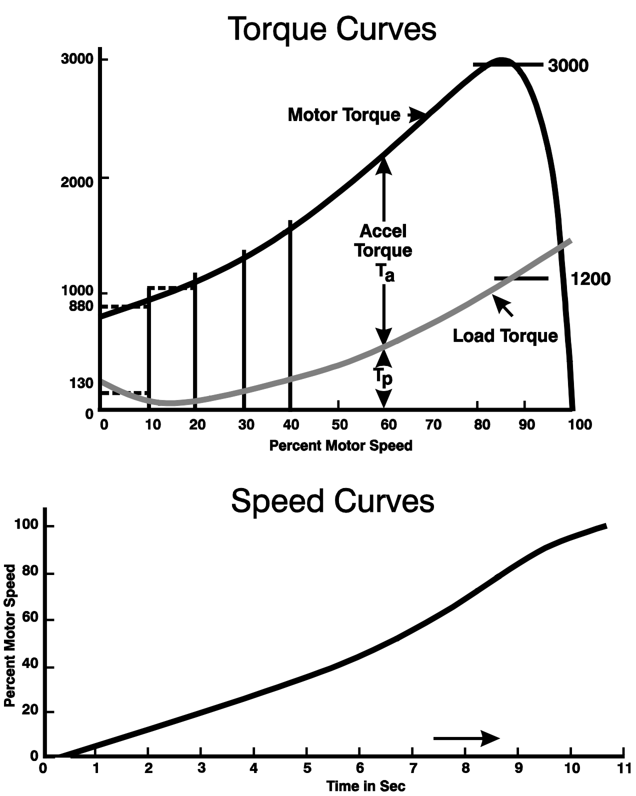

Fig. 1 Induction Motor Starting Time, Speed, and Torque

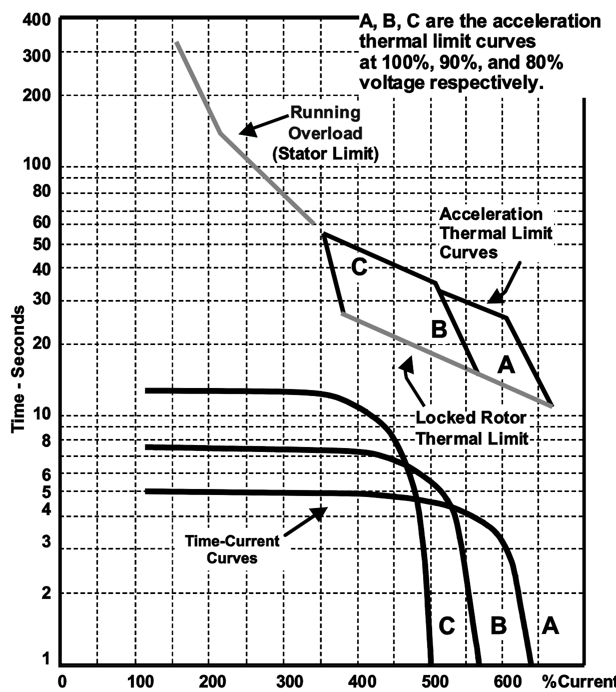

Fig. 2 Typical Thermal Limit Curves

C. 49 Thermal Model Versus Overcurrent Protection

Fig. 3 shows a typical coordination of 49 thermal model elements versus 51 time overcurrent and 50 instantaneous elements.

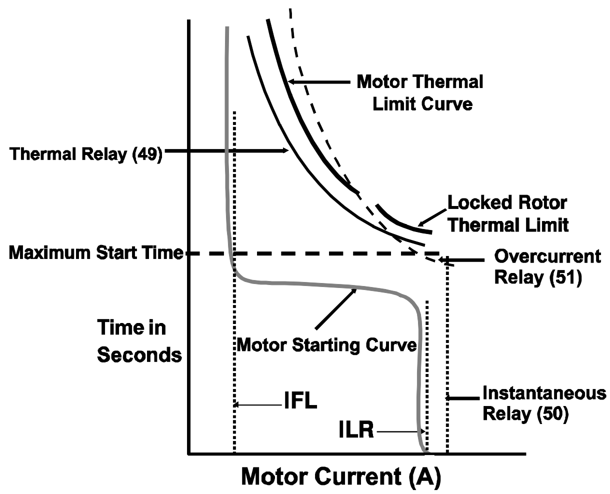

Fig. 3 Typical 49TC and 51 Element Protection

It should be noted that compromises must be made because typical 51 element curves do not match motor damage curves and do not take negative-sequence effects into account.

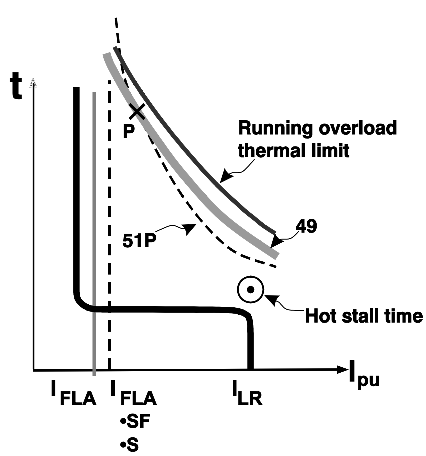

Fig. 4 Coordinated 49TC Thermal Element

Point P in Fig. 4 is the point at which to choose the standard 49 thermal protection curve. To force the characteristic to pass through point P, the time dial in a 51 element or the time constant in the 49 thermal element should be adjusted. The dynamic response of a 51 element to motor current is linear and uses uncompensated (positive-sequence only) motor current, whereas the 49 thermal model has an exponential response and uses the equivalent current, I_{eq}, which uses negative-sequence currents. The motor trip point is I_{FLA} • SF (Service Factor) • S, a scaling factor to adjust the motor trip point (further discussed in Section III.D).

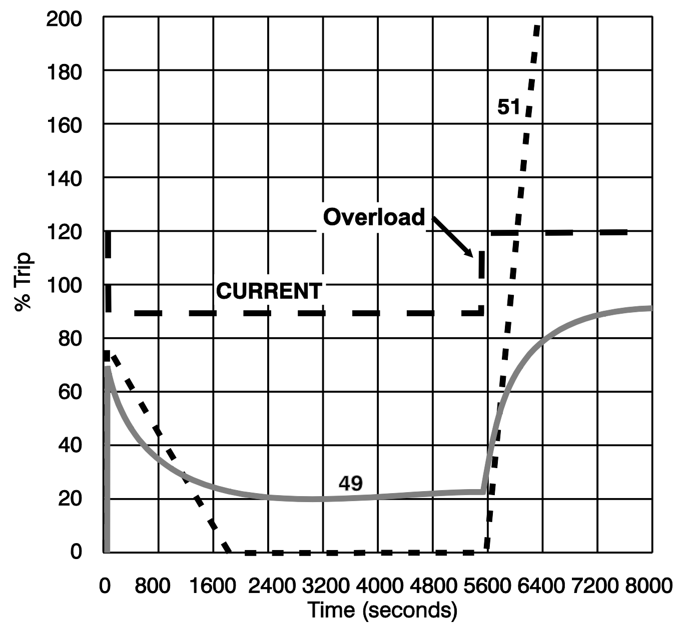

Fig. 5 49TC and 51 Element Responses

A comparison of the 51 and 49 responses for identical operation is shown in Fig. 5. The small dashed line is the 51 element response to a cyclic overload (represented by the large dashed line "CURRENT" as it goes above and below 100 percent Trip). When the 49 element found in dedicated motor relays (as opposed to general purpose overcurrent relays) takes the load level into account, it becomes a realistic thermal model of the motor. The 49 thermal model element performs better, especially when the process requires tolerating temporary overloads. The 49 thermal model element "remembers" the work (heat) in the motor. Also, the 49 element does not reset to zero when the current is below the overload limit as does the 51 element (see the 2400 second area). Instead, the 49 thermal model element settles at a value corresponding to the thermal capacity used (TCU) at the given load level.

The 51 element tends to trip faster than the 49 thermal model resulting in false tripping on short overloads and incomplete motor usage. With the 49 thermal model element, more work is obtained from the motor without damage (see the 6400 second area in Fig. 5).

However, a 51 relay can be a backup to the 49 thermal element and inexpensive protection for non-critical motors. Also, backing up the 49 thermal element are RTDs if supplied (RTDs are covered in greater detail later in this paper). The 49 thermal model gives a faster, more accurate representation of motor operation and heating. The 49 thermal model is better at reproducing the actual motor thermal limits and locked rotor modes by using I_{eq}, which increases motor life by 10 to 25 percent depending upon the application.

III. THE UPDATED THERMAL MODEL FOR MOTOR PROTECTION

The power system supplying the motor must meet certain requirements. All three phases must be present in a three-phase motor with voltage and current values within a few percent and in the correct sequence. Unbalanced voltages and currents result in excessive negative-sequence components (specifically I_2 current) which contribute greatly to motor heating. Voltage unbalance (47) and current unbalance (46) elements are used in the modern motor relay.

A. The 49 Thermal Model Equivalent Current

A 49 thermal element creates a realistic thermal model of the motor because the element uses the load level and negative-sequence current caused by the induced flux that rotates in the reverse direction of the rotor. The large change flux in the motor produces high heating current, which is very damaging to the motor, see Figure 6.

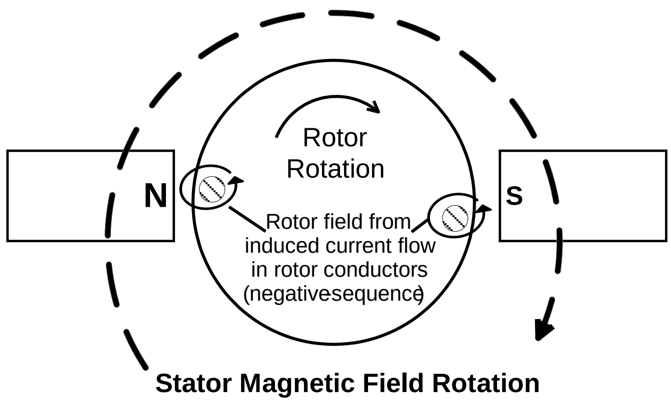

Figure 6. Negative-sequence rotor current from stator flux

The thermal model creates an "equivalent current," I_{eq} that best represents the actual motor flux dynamics (first two primary terms of actual effect).

In particular, the thermal model calculation uses equivalent thermal current, I_{eq}, with unbalance biasing (k), the selected thermal curve, pickup current, motor cooling constant(s), RTD biasing based upon measured ambient temperature and the hot/cold safe stall ratio.

The equivalent thermal current, I_{eq}, formula is the following:

$$I_{eq} = I\sqrt{1 + k\left(\frac{I_2}{I_1}\right)^2} \qquad (1)$$

where

- I_{eq} Equivalent thermal current in pu (unit of thermal pickup current)
- I Maximum measured phase current in pu
- I_1 Positive-sequence fundamental component of current in pu
- I_2 Negative-sequence fundamental component of current in pu
- k Constant determines additional heating caused by negative-sequence current in pu

Because voltage sensing is optional in newer generation motor relays, the thermal model shown in (1) uses the unbalance ratio of negative-sequence to positive-sequence current (I_2/I_1) instead of voltage unbalance.

The factor k is a user setting. With k set to 8, the formula gives a derating factor closely matched to the NEMA MG1-2009 Motor Guide derating factor (from voltage unbalance; see 14.36, 20.24.2). A larger k makes the estimation of equivalent current, I_{eq} more conservative. When k is 0, (1) reduces to I_{eq} equals I, where I is the maximum measured phase current.

B. Thermal Curves

Motor relays curves are selected to match the motor manufacturer's thermal limits. Apply the best-fit curve that is closest to the running overload thermal curve recommended by the motor manufacturer. Programmable curves are available for special cases.

From studying thermal damage curves from motor manufacturers, a "best fit" equation was developed from that analysis for the running overload curves.

$$t = TD \cdot 88.744131 \cdot ln\left(\frac{\left(\frac{I_{eq}}{S \cdot SF \cdot FLA}\right)^2}{\left(\frac{I_{eq}}{S \cdot SF \cdot FLA}\right)^2 - 1}\right) \qquad (2)$$

where

- TD Curve time dial
- I_{eq} Equivalent thermal currents
- S Load scalar

IEC 60255-8 thermal curves have two formulas, one for hot and one for cold. The cold curve is:

$$t = \tau \cdot ln\frac{{I_{eq}}^2}{{I_{eq}}^2 - (S \cdot k \cdot I_B)^2} \qquad (3)$$

The IEC 60255-8 hot curve is:

$$t = \tau \cdot ln\frac{{I_{eq}}^2 - {I_p}^2}{{I_{eq}}^2 - (S \cdot k \cdot I_B)^2} \qquad (4)$$

where

- τ Motor running time constant
- I_{eq} Equivalent thermal current
- k The constant that multiplies the basic current to obtain the current value at which the accuracy of the minimum operating current is referred [This IEC 'k' is not the same one as used in Eq (1).]
- I_B Full Load Amperes (FLA) multiplied by the motor service factor (SF)
- I_P Load current before the overload occurs, which is specified in National Standards, declared by the manufacturer, or calculated from manufacturer provided thermal curve
- S Load scalar

The IEC hot and cold curves describe a relationship between specified operating time and current. The hot curve is the thermal effect of a specified steady-state load current before an overload occurs. The IEC cold curve is with the relay at reference and steady-state conditions with no-load current. The IEC model uses both curves depending on the 49 thermal model heat capacity (a user setting).

Setting programmable curves has become as easy as using drag-n-drop points to match special starting situations such as high-inertia starts. Fig. 6 shows an example of a programmable curve. Examination of the figure shows that sometimes the starting current can invade the locked rotor thermal limit. This situation can happen for motors connected to high-inertia starting loads. In this case, a custom starting curve directs the thermal model to accept this high-inertia start case.

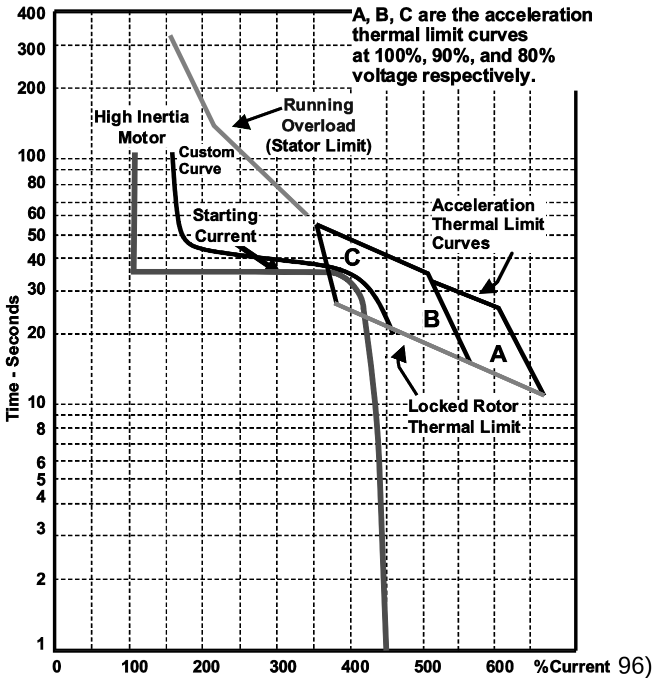

Fig. 6 Programmable Thermal Curve

C. Cooling Time Constants

Motor cooling time constants are very important input data for the 49 thermal model. The TCU (thermal capacity used) is reduced when the motor equivalent current is below the thermal pick up current S • I_{tpu}, (for example, S • FLA • SF). Usually, there are two cooling constants of interest; running and stopped time constants.

Settings of cooling constant for a running motor and cooling constant for a stopped motor are needed. These constants are expressed usually in units of minutes. Running cooling times are shorter than stopped cooling times because the motor cooling media is flowing over or through the motor. Equation (5) indicates that the TCU is taken sample by sample based upon the previous sample over time, t. In (6), motor manufacturers supply the hot safe stall time and the cold safe stall time, giving a solid foundation to the thermal capacity calculation.

$$TCU = (TCU_{start} - TCU_{end})e^{-t/\tau} + TCU_{end} \quad (5)$$

and

$$TCU_{end} = \left(\frac{I_{eq}}{S \cdot I_{tpu}}\right) \cdot \left(1 - \frac{hot\ safe\ stall\ time}{cold\ safe\ stall\ time}\right) \quad (6)$$

where

TCU	Thermal Capacity Used
TCU_{start}	The last calculated TCU value by (5)
TCU_{end}	TCU value computed by (6)
τ	Cooling Time Constant (either running or stopped)
I_{eq}	Equivalent thermal current
I_{tpu}	Thermal pickup current
S	Load scalar

From the TCU cooling equation (7), we can compute the cooling time needed to meet the minimum TCU required for a successful motor start. The cooling time is the following:

$$t = \tau \bullet ln\left(\frac{TCU_{now} - TCU_{end}}{TCU_{Start} - TCU_{end}}\right) \quad (7)$$

Note that $TCU_{max\ for\ start}$ is 1 – $TCU_{required\ for\ start}$

D. Other Updates In The Newer Generation Thermal Model

The new thermal model implementation has two unique features. One is the ability to tailor the 49 thermal model pickup with the load scalar (S) setting. The range of this setting is 0.9–1.2. The normal thermal curve pickup is at SF · FLA. With the new S setting, the thermal curve pickup becomes S · SF · FLA. Using this load scalar setting, the thermal model pickup can be fine tuned for lightly or heavily loaded applications.

Another update is a unique setting that gives the ability to set the thermal capacity at a point which the motor will perform an emergency start. This setting, the max emergency thermal capacity, affects the trip point of the thermal model.

Setting this thermal capacity to a large percent of thermal capacity can keep the process running. This parameter can be as great as ten times nominal tripping level of thermal capacity; this case would be one in which the process is more important than the motor. Conversely, a low setting for this maximum emergency start allows operators to start the motor only under the conditions the protection engineer has decided are prudent.

Once the emergency start is made, the updated thermal model expands to retain thermal data and thus protects the motor as the motor cools into the nominal thermal range. Fig. 7 illustrates the new method of temporarily expanding the model while retaining thermal capacity while in emergency start mode. Enlarging the “bucket” drops the TC away from the tripping point (100 percent full bucket), to allow for emergency operation. The motor relay thermal mode returns to the nominal trip point of S • SF • FLA as the motor cools after the emergency start condition.

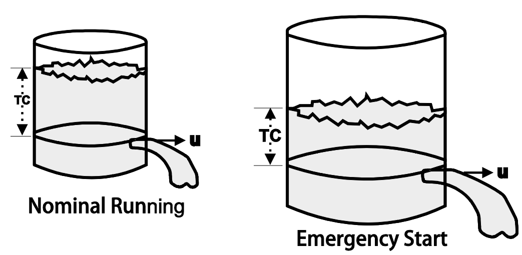

Fig. 7 Emergency Start Increases Relay Tripping Level

IV. RTD TEMPERATURE MEASUREMENTS AIDS MOTOR PROTECTION

Typically, motors are cooled by means of a rotor-mounted fan blade which forces air through the motor frame while the motor is running. Thermal limits and temperature rises are based on this cooling functioning as designed with a known level of ambient air temperature. If normal cooling is blocked, overheating at normal load current is possible.

A. RTD Usage

Temperature data from the RTDs backup the thermal model. An RTD alarm notifies operators of an impending motor shutdown because of high-heat operation.

RTD biasing modifies the thermal model by taking temperature data from the stator RTDs as additional inputs to the thermal capacity calculations. RTD biasing accounts for motor operation in high ambient temperatures or after experiencing a cooling loss and is conservative motor protection.

1) RTD Alarm: Typically, the motor relay accepts two setting levels for each monitored point: a low setting for alarm and a high setting for shutdown. The specific settings are derived from the winding insulation class, defined in NEMA MG1, and judgment based on the plant operating conditions.

The recommended setting for alarm temperature level is the sum of the maximum ambient, plus 10 percent hot spot allowance, plus the full-load stator temperature rise (given by the manufacturer).

$$\begin{matrix}\textit{Alarm}\\ \textit{RTD}\\ \textit{Temp.}\end{matrix} = \begin{matrix}\textit{Max.}\\ \textit{Ambient}\\ \textit{Temp.}\end{matrix} + \begin{matrix}\textit{Stator}\\ \textit{Hot}\\ \textit{Spot}\end{matrix} \bullet 1.10 + \begin{matrix}\textit{Full-Load}\\ \textit{Temp.}\\ \textit{Rise}\end{matrix} \qquad (8)$$

The stator hot spot in (8) is typically at the top of the windings and can be estimated or measured. This value should be below the stator insulation class rating.

2) Traditional RTD Biasing: Traditionally, three points are defined at Minimum RTD Bias Temperature, Center RTD Bias Temperature, and Maximum RTD Bias Temperature. Set the Minimum RTD Bias at ambient (40°C).

A good starting point for the center point Thermal Capacity (%TC) is the percentage difference between Hot Stall time and Cold Stall time. Later, the point can be modified based on learned observation and from motor monitoring.

Determine center point temperature from manufacturer's data: Temperature Rise of Stator multiplied by 10 percent margin plus the rated operation Ambient Temperature as illustrated in (9).

$$\begin{matrix}\textit{Center RTD}\\ \textit{Bias Temp.}\end{matrix} = \begin{matrix}\textit{Temp. Rise}\\ \textit{of Stator}\end{matrix} \bullet 1.10 + \begin{matrix}\textit{Ambient}\\ \textit{Temp.}\end{matrix} \qquad (9)$$

Traditionally, the third and end point, Maximum RTD Bias Temperature, is set for maximum insulation temperature. For example, if maximum insulation factor of the motor is Class F (most used), then 155°C and 100% TC is the end point of RTD biasing.

The trip level should be at the insulation class temperature; however; this setting can be as much as 50°C above the class rating if the process is critical because the loss of life from occasional short overload periods is insignificant. Setting the trip temperature at the insulation class limit is a conservative setting.

3) Improved RTD Biasing: More than three points for RTD biasing can now be set to better emulate a real-world, exponential thermal-increase curve and benefit from more safe motor productivity in high-temperature environments.

Because thermal biasing is an exponential temperature phenomenon, newer motor protection provides more than three points for more accurate biasing. Typically, these points are set by programming table curves, inserting points and dragging these points on a map, or copying and pasting to/from Excel™ or other programs.

B. RTD Voting

Typically, motor relays monitor the RTD temperature data, usually with six RTDs embedded in the stator windings (two per phase) as well as one or two on the motor bearings. RTD systems are fragile mechanical devices subject to failure. The motor relay uses RTD voting to force concurrence among the different blocks of RTD data. For example, if stator RTD voting is set for 3, then 3 or more temperatures must exceed the pickup level and not exhibit RTD failure before the relay takes action. With this setting, two or three of the typical six stator RTDs can be malfunctioning and the motor relay continues to use correct temperature data and the process remains operating.

V. TRANSDUCERS WITH RTD REMOTE MODULES ADD FLEXIBILITY

Newer motor relays include 4–20 mAdc and 0–10 Vdc analog transducer inputs and outputs in the remote modules used to connect RTDs to bring these signals and other process transducers back to the motor relay. In this manner, the motor relay directs and modifies the production process, acting to replace some functions of a programmable logic controller (PLC).

For example, to minimize damage caused by bearing failure, protective devices can sound an alarm or de-energize the motor. Input transducer bearing protective devices respond to one or more of the following conditions:

(1) Low oil level in reservoir: (71) level switch
(2) Low oil pressure: (63) pressure switch
(3) Reduced oil flow: (80) flow switch
(4) High temperature: (38) thermocouples
(5) Rate of temperature rise
(6) Vibration (used on motors with anti-friction bearings in place of thermal devices)
(7) Vibration transducers (RF proximitors) on hydrodynamic motor bearings

Remote transducers are very useful for process control. Some of the capabilities of output transducers include valve control or air damper control. Because of the many different protection and control scenarios in which motors are used; numerous other applications, motor-life benefits, and cost-savings are available as well.

VI. CONCLUSIONS

The 49 thermal model is better than traditional time overcurrent 51 elements because more motor work is available with less false tripping, especially during temporary overloads.

The updated 49 thermal model provides superior motor protection because motor heating is adequately modeled with the equivalent current, I_{eq}, which uses negative-sequence current (I_2) effects.

Any IEEE or IEC motor manufacturer's thermal curve can be matched by the modern motor thermal model which includes custom curves provided by the updated model.

Adding the load scalar S setting modifies thermal model pickup to address motor longevity or process continuation.

The newer emergency start method retains existing motor heating and better models the actual motor heat. It can also prevent excessive motor heating by limiting operator start attempts based upon the motor temperature (49TC thermal model).

RTD biasing keeps the motor protected in high ambient conditions. The updated model provides more work while keeping the motor safe by emulating real-world temperature increases. RTD voting keeps the motor running when fragile RTDs fail.

Applying input and output transducers in the 4—20 mAdc and 0—10 Vdc range at the remote RTD modules increases protection and control opportunities throughout the plant for the motor relay protection engineer.

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VIII. VITA

Daniel (Dan) Ransom, PE has 40 years of industrial and utility electronics experience; including many years in motor protection development and application support. He has extensive experience in consulting engineering for power and communications systems. Dan is an engineering graduate (BSEE) of Gonzaga University, Spokane, Washington; he also holds a liberal arts degree from Washington State University. He is a member of the IEEE IAS (Industry Applications), PES (Power Engineering), Communications, and Standards societies. To date he has one US patent. He is a Professional Electrical Engineer in numerous states. Dan joined Basler Electric in 2010 and is Principal Application Engineer for the West Coast region.

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