Motor Thermal Capacity Used – How Does the Relay Know When I've Reached 100%?

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Abstract

How does a motor thermal overload element know when the motor has used 100% of its thermal capacity? In this paper the authors explore the answer to this question as it relates to the proper selection of the thermal overload curve. We also explore the coordination relationship between the overload curve and upstream time-overcurrent protective devices to better understand the 3-dimensional nature of the thermal over-load curve. Several real-life examples are used to illustrate the issues, challenges and consequences of curve selection.

Introduction

Modern micro-processor motor protection relays use the stator current to calculate the stator winding temperature. RTDs imbedded in the stator can be used to bias the calculated temperature if the RTDs indicate that the stator temperature is hotter than the calculated value. Measured imbalances in the stator 3-phase current are used to add heat to the calculation caused by the associated rotor bar current. Harmonics may also be used to add heat to the calculation caused by stator core heating. The function trips the motor when the calculated temperature reaches the insulation's limiting temperature. Running and stopped cooling time constants are used to remove heat from the calculation during steady state operation and when the motor is stopped. This heat calculation is performed continuously, regardless of the motor loading.

The heat energy released by the stator current is proportional to I^2*t*R where I is the stator current, R is the stator resistance and t is time. The relay measures current and time but it does not know the resistance. So, how does it know the relationship between stator current, time and stator heating? The answer lies in the selected thermal overload curve.

The starting point temperature is required to calculate the stator temperature caused by the heat energy released. As a result, thermal overload curves are three dimensional and the time to trip is a function of the current magnitude and the starting point temperature. Many modern relay coordination software packages offer the option of drawing the motor thermal curve on the time current coordination (TCC) diagram. However, the other time-overcurrent devices on the TCC diagram are 2 dimensional and the time to trip is simply a function of the current. This causes undo concern about the speed of upstream devices relative to the motor thermal trip time, especially in the over-load portion of the curve.

Review of motor thermal capability curves

Typical motor thermal capability curves are shown in Figure 1. These curves show us the time required for the stator to reach the insulation's limiting temperature. The cold locked rotor curve is shown with the stator initial temperature of 40 °C (cold). In this example, it tells us that when the motor is started cold with 100% of rated voltage the stator will reach the insulation's limiting temperature in approximately 8 seconds and when the motor is started cold with 80% of rated voltage the stator will reach the insulation's limiting temperature in approximately 15 seconds.

In this example, the hot locked rotor curve tells us that when the motor is started hot with 100% of rated voltage the stator will reach the insulation's limiting temperature in approximately 6 seconds.

When the motor is started hot with 80% of rated voltage the stator will reach the insulation's limiting temperature in approximately 12 seconds.

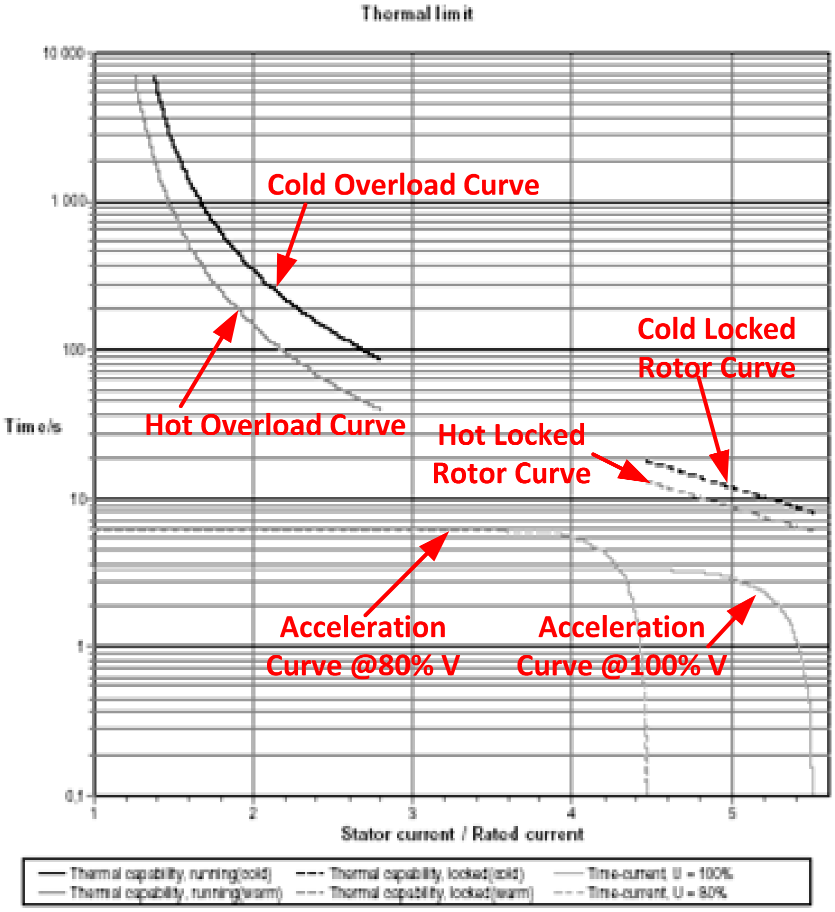


Figure 1: Typical motor thermal overload curve

Many motors are rated for two consecutive cold starts per hour and one hot start per hour. Only the first cold start is truly a cold start. The second consecutive cold start is actually a hot start. This rating also assumes that each start is successful. If the first cold start attempt results in a locked rotor trip, then the stator temperature will be at the insulation's limiting temperature and no further starts are possible until the motor cools down. It also assumes that the acceleration time for the connected load is equal to or less than the acceleration time shown on the 100% and 80% voltage curves provided (2.8 seconds and 6 seconds respectively). If the first cold start attempt takes longer than the acceleration curve time, then the second consecutive start may not be possible until the motor has cooled some.

Similarly, overloads typically occur with hot stators. If the motor goes into overload (motor load exceeds service factor) shortly after starting, then the stator is still hot from the acceleration. If the motor has been running for a long time carrying a steady state load and then goes suddenly into overload the stator temperature will also be hot due to the loading prior to the overload. The stator will also be hot if the load on the motor gradually increases until it is in overload. Consequently, the cold overload curve has limited applicability.

The motor’s thermal capability curves define how long the motor can operate without thermally damaging the insulation as a function of starting temperature where the cold curves assume the stator is at 40 °C.

The nature of relay thermal overload curves and how the relay uses them

Modern micro-processor motor protection relays use the stator current to calculate the stator winding temperature. This heat calculation is performed continuously, regardless of the motor loading.
RTDs imbedded in the stator can be used to bias the calculated temperature if the RTDs indicate that the stator temperature is hotter than the calculated value. Measured imbalances in the stator 3-phase current are used to add heat to the calculation caused by the associated rotor bar current. Harmonics may also be used to add heat to the calculation caused by stator core heating. The function trips the motor when the calculated temperature reaches the insulation’s limiting temperature. To simplify settings, the temperature of the stator is normalized into a unit of Percent Thermal Capacity. When the stator is cold (40 °C) the motor has 100% Thermal Capacity available and 0% Thermal Capacity used. When the stator temperature is at the insulation’s limiting temperature the motor has 0% Thermal Capacity available and 100% Thermal Capacity used.

To achieve this normalization, the relay uses a family of standard thermal overload curves which, when properly selected, matches the motor thermal capability curves. Figure 2 shows a typical family of standard thermal overload curves. These curves are drawn for a cold stator (100% Thermal Capacity available and 0% Thermal Capacity used). The equation for time to trip is:

$$t_{trip} = \frac{\mathrm{TDM} \times 2.2116623}{0.02530337 \times \left(\frac{I_{motor}}{\mathrm{FLA}} - 1\right)^2 + 0.05054758 \times \left(\frac{I_{motor}}{\mathrm{FLA}} - 1\right)} \qquad \text{Eq. 1}$$

Where:
t_{trip} = time to trip for a cold stator
TDM = time dial multiplier
I_{motor}/FLA = normalized motor stator current

The actual time to trip will typically be less than shown in figure 2 based on the Thermal Capacity used when the overload occurs. The element uses memory in the form of a Thermal Capacity used register. This register is updated every power cycle using the following equation:

$$TC_{used(t)} = TC_{used(t-1)} + \frac{T_{system}}{t_{trip}} \times 100\,\% \qquad \text{Eq. 2}$$

Where:
$TC_{used(t)}$ = current power cycle thermal capacity used
$TC_{used(t-1)}$ = previous power cycle thermal capacity used
T_{system} = period of one power system cycle
T_{trip} = time to trip for a cold stator

The overload element will trip when the TC_{used} = 100%.

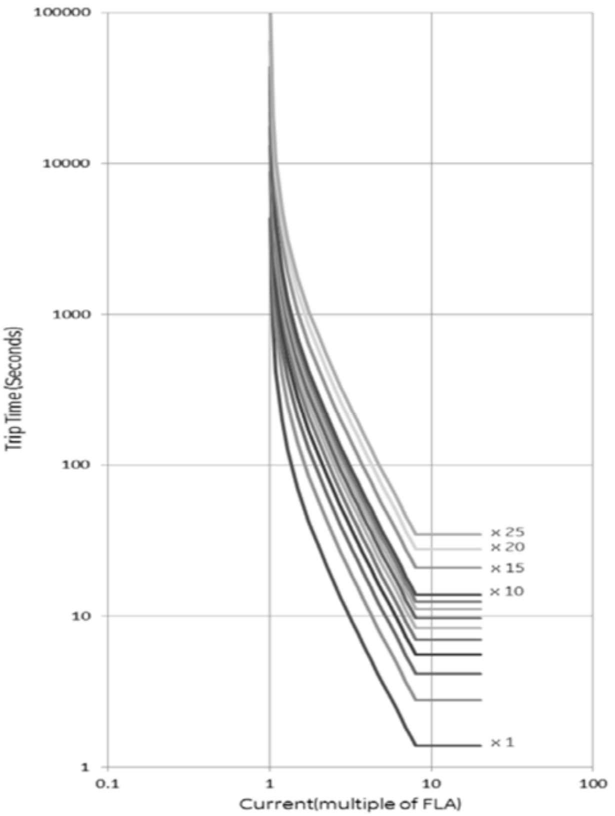


Figure 2: Typical family of thermal overload curves

A close inspection of Equations 1 and 2 reveal that as the Thermal Capacity used increases, the actual time to reach 100% Thermal Capacity used get shorter. In other words, as the motor heats up, the curves in Figure 2 shift down, reducing the trip time.

Since the relay uses the selected overload curve as a definition of 100% Thermal Capacity used, it is critically important to select an overload curve that correctly matches the motor overload capability curves. If the selected curve is above the motor curve then the stator will be hotter than the relay’s calculated temperature and the motor insulation could be damaged before the relay trips. RTD biasing might help mitigate this condition during steady state operation by returning a higher Thermal Capacity used than the current based model, however, it will not be able to help during transient overloading conditions due to thermal lag. Selecting a curve that is significantly below the motor curve causes the relay to calculate excessive Thermal Capacity used, allowing inadequate overload time and causing false locked rotor trips during acceleration, especially on a second consecutive cold start attempt.

In some cases, it is not possible to select a single overload curve that properly matches both the overload and locked rotor sections of the motor capability curves. It might be OK to use a single overload curve properly matched to the motor locked rotor capability curves if it falls slightly below the motor overload capability curves and the motor is not subjected to overloading. If the selected single overload curve falls above the motor overload capability curves then the motor might be damaged during overloading and it is necessary to use a single custom overload curve or separate overload curves for the overload and locked rotor portions of the motor capability curves. Use setting groups to change the overload curve during running and stopped/starting if the relay does not offer the option of separate overload curves.

Coordinating thermal overload curves with upstream devices

Many modern relay coordination software packages offer the option of drawing the motor thermal curve on the time current coordination (TCC) diagram. If the upstream device(s) plot below the thermal curve it creates the appearance of mis-coordination. The software may confirm this apparent mis-coordination when a coordination check is run by showing the upstream device operating faster than the thermal curve. While the other devices on the TCC diagram are time-overcurrent devices with a fixed time to trip for a given amount of current, the thermal curve is a time-temperature-current device with a variable time to trip for a given amount of current based on the initial stator temperature. If the motor is hot when the coordinating event occurs, then the thermal curve will trip substantially faster than the TCC plot indicates and no mis-coordination exists. This is the typical case for a running motor which is always hot. As a result, there is little concern about mis-coordination with upstream devices for a running motor.

For an unsuccessful cold motor start with a locked rotor the thermal curve's time to trip will be consistent with the time shown on the TCC and the apparent TCC mis-coordination is real. The motor can still be started successfully if the TCC trip time of the upstream device is longer than the acceleration time. The risk is that the upstream device will operate faster than the thermal curve during an actual locked rotor event where the motor fails to accelerate. The most obvious solution to this problem is to choose a thermal curve that is faster than the upstream device for locked rotor currents. Unfortunately, since the thermal curve selection defines 100% Thermal Capacity used, this solution results in the calculation of an excessive amount of Thermal Capacity used during acceleration and general operation. While this might not prevent the successful acceleration of the motor for a cold start, it could unnecessarily delay a hot restart. An alternative to selecting a faster curve is to set the thermal curve correctly according the motor capability curve and use the Acceleration Timer feature of the relay to trip the motor faster than the upstream device for an unsuccessful start attempt. This allows the relay to correctly calculate Thermal Capacity used during acceleration. The main drawback of this is that the Acceleration Timer is a simple definite time element which may mis-operate during starts with unusually low starting voltage where the acceleration time of the motor is longer than normal (see Figure 3).

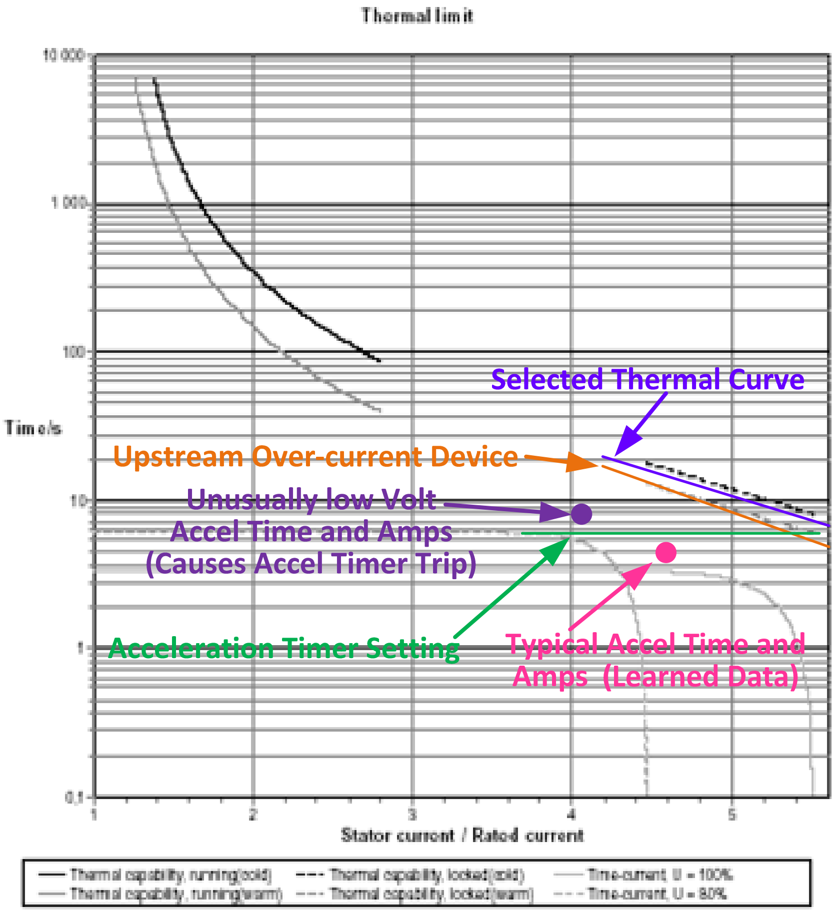


Figure 3: Thermal curve with fast upstream device and acceleration timer

An alternative to the Acceleration Timer is to use a phase time overcurrent (TOC) element for acceleration timing. Set the phase TOC faster than the upstream device but slower than the motor acceleration curves and block it when the motor is running (enable it when the motor is stopped or starting). This approach will allow more time for acceleration when the locked rotor current is less but still allow the thermal curve to correctly calculate Thermal Capacity Used during the acceleration (see Figure 4).

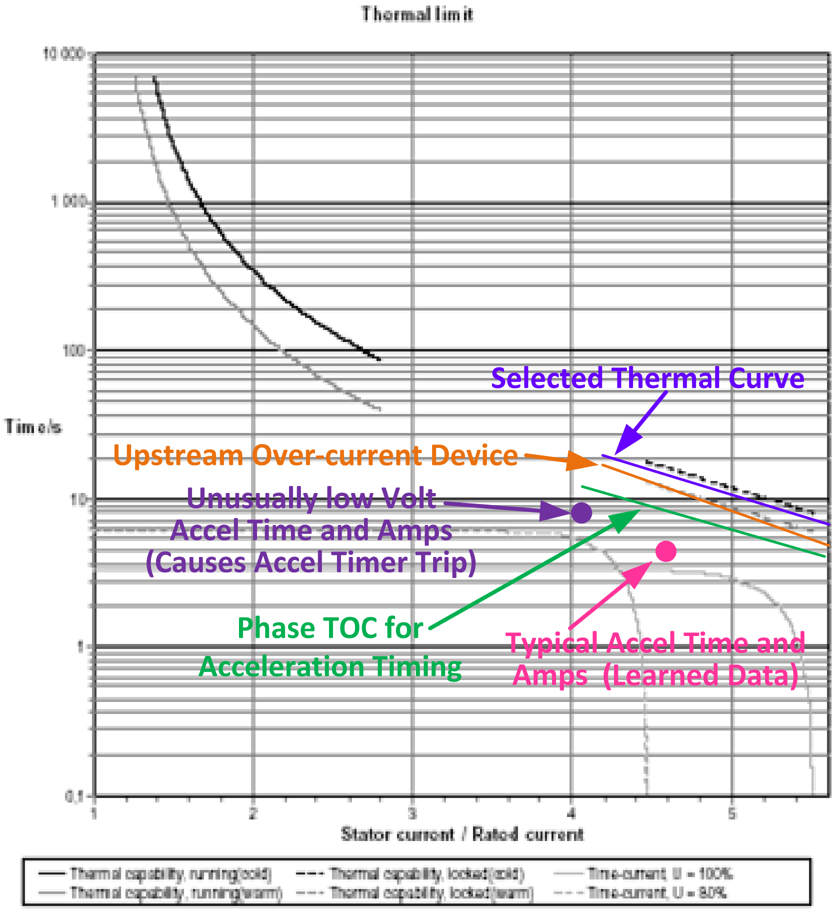
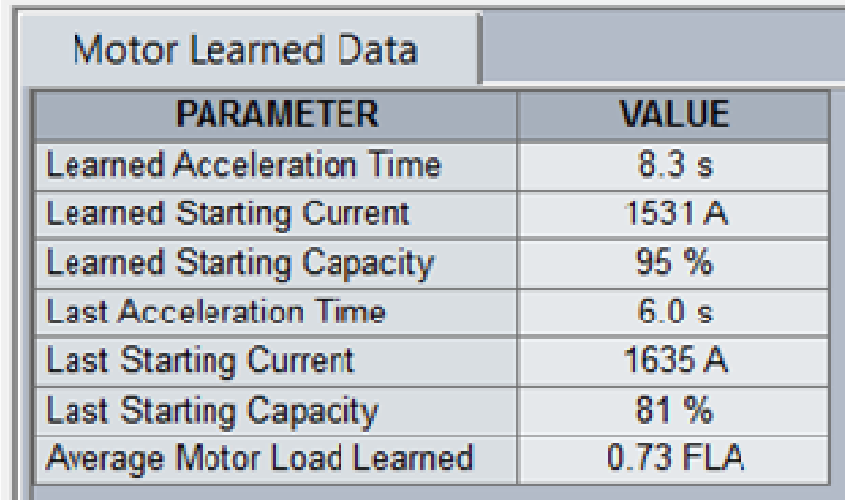


Figure 4: Thermal curve with fast upstream device and Phase TOC used for acceleration timing

Case Study 1: 3250 HP compressor with fast upstream device

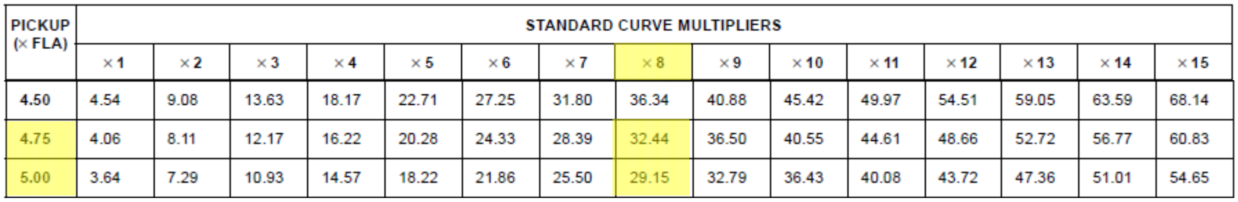
According to the relay's records, the Thermal Capacity used for a successful start on this motor was 80 – 90% (see Figure 8). As a result, the motor tripped occasionally on thermal overload during starting and a second start attempt was blocked by the relay. A look at the motor data sheet and the Thermal Capability curves indicates a Motor Hot Safe Stall Time of 28 seconds and a Motor Cold Safe Stall Time of 33 seconds at 483% of FLA. Typically, the locked rotor overload curve should be selected such that it is faster than the Cold Safe Stall Time and slower than the Hot Safe Stall Time which would indicate a cold operate time of 30-31 seconds at 483%. A look at the motor relay's Standard Overload curve multipliers shown in Table 1 indicates a good fit for curve 8:



Motor Learned Data

PARAMETER	VALUE
Learned Acceleration Time	8.3 s
Learned Starting Current	1531 A
Learned Starting Capacity	95 %
Last Acceleration Time	6.0 s
Last Starting Current	1635 A
Last Starting Capacity	81 %
Average Motor Load Learned	0.73 FLA

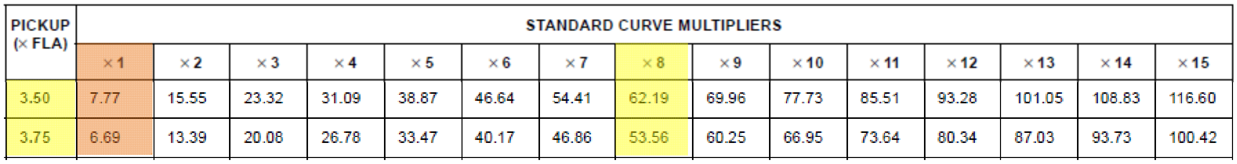
Figure 5: Motor relay's learned data.



PICKUP (× FLA)	STANDARD CURVE MULTIPLIERS														
	× 1	× 2	× 3	× 4	× 5	× 6	× 7	× 8	× 9	× 10	× 11	× 12	× 13	× 14	× 15
4.50	4.54	9.08	13.63	18.17	22.71	27.25	31.80	36.34	40.88	45.42	49.97	54.51	59.05	63.59	68.14
4.75	4.06	8.11	12.17	16.22	20.28	24.33	28.39	32.44	36.50	40.55	44.61	48.66	52.72	56.77	60.83
5.00	3.64	7.29	10.93	14.57	18.22	21.86	25.50	29.15	32.79	36.43	40.08	43.72	47.36	51.01	54.65

Table 1: Standard Overload curve multipliers at I_{LR}

This motor uses a solid state reduced voltage starter which accounts for the low locked rotor current shown in the learned data (Figure 5) of around 360% of FLA. The Standard Overload curve multipliers for this starting current shown in Table 2 indicates that curve 8 would allow around 55 seconds for a cold start:



PICKUP (× FLA)	STANDARD CURVE MULTIPLIERS														
	× 1	× 2	× 3	× 4	× 5	× 6	× 7	× 8	× 9	× 10	× 11	× 12	× 13	× 14	× 15
3.50	7.77	15.55	23.32	31.09	38.87	46.64	54.41	62.19	69.96	77.73	85.51	93.28	101.05	108.83	116.60
3.75	6.69	13.39	20.08	26.78	33.47	40.17	46.86	53.56	60.25	66.95	73.64	80.34	87.03	93.73	100.42

Table 2: Standard Overload curve multipliers around 3.6 X FLI.

Initially the motor relay's thermal curve was set to curve 1 due to a coordination concern with the upstream relay. Table 2 shows that curve 1 will only allow about 7 seconds for acceleration with a current of 3.6 X FLA. Looking again at the learned data in figure 5, the last start had 1635 A (3.7 X FLA) and took 6 seconds. This is just a bit below the trip point of curve 1 which explains why the relay calculated 81% Thermal Capacity used during the start. It also explains why the motor would not have been able to be restarted had it tripped with only 19% Thermal Capacity available.

One question that was raised during this investigation was: "How does the relay know that there is a reduced voltage starter?" The answer is: "It does not know or care how the motor is started." It simply calculates the Thermal Capacity used based on the selected curve and the locked rotor current. The reduced voltage starting causes a lower locked rotor current which the relay uses to calculate Thermal Capacity used.

So what curve should we use to protect the motor and how should we deal with the upstream device? To determine the best curve, we need to look at the motor Thermal Capability curves in Figure 6. The red squares are the data points for curve 1 and the purple round data points are for curve 8. Curve 8 fits the motor Thermal Capability curve closely. Ideally, the selected curve should fall between the hot and cold starting curves and slightly above the hot running curve (since only one running curve is provided, assume the it is the hot curve). Curve 8 is slightly faster than desired during loading up to 200%. While not ideal, this should not cause any significant errors in Thermal Capacity used in this loading range. Beyond 200% curve 8 is nearly ideal. In this case curve 8 should be selected. While curve 1 is above the manufacturer's acceleration curves it is very close to the learned data starting amps and time (green diamond data point) and it is substantially below the motor Thermal Capability curves. Selecting curve 1 resulted in significant errors in starting Thermal Capacity used and caused occasional tripping during acceleration.

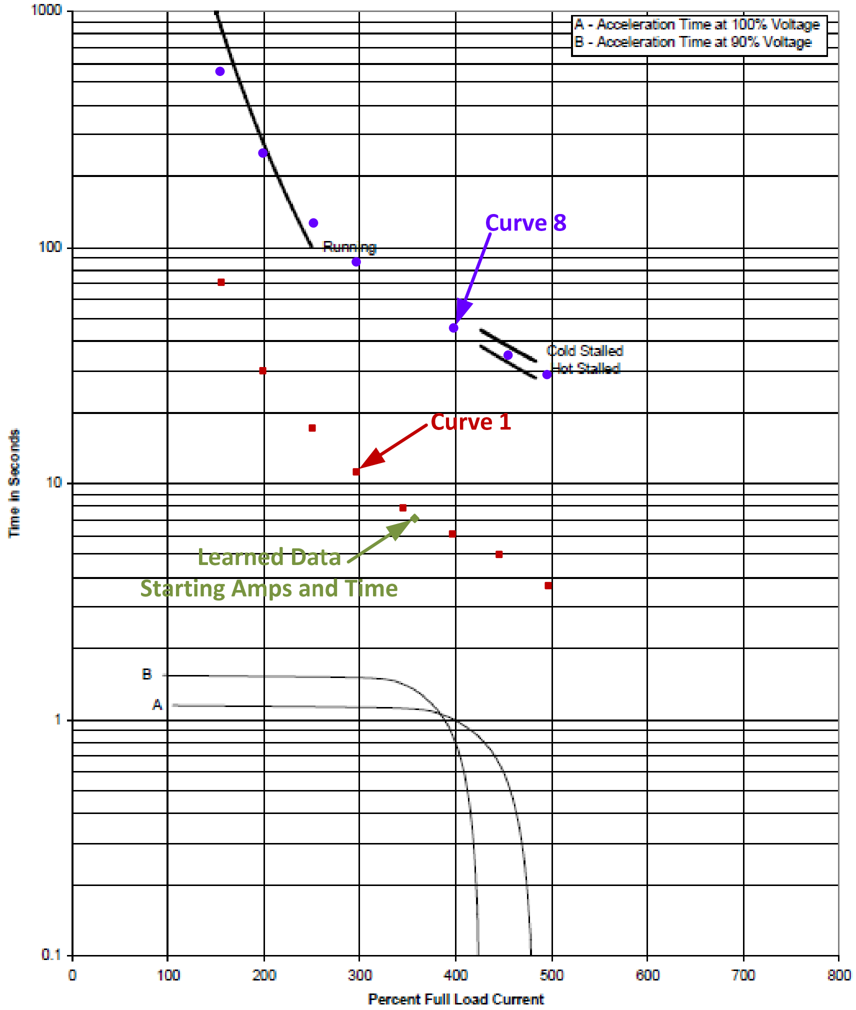


Figure 6: 3250 HP motor Thermal Capability curves.

We still need to deal with the upstream device coordination during a cold start. Figure 7 shows the time-coordination curves for this motor circuit with Thermal Overload curves 1 and 8. As we saw in figure 9, the learned data starting point is very close to curve 1. Curve 8 (orange) crosses the upstream devices (primary and backup) at around 2000 A, indicating that a full voltage cold start could cause the upstream device to operate before the thermal curve. As discussed earlier in this paper, this is only a concern for the starting portion of the Motor Capability curves where the time to trip will be the same as the plotted curve if the motor is starting cold. Adding an Acceleration Timer (trips if the acceleration time lasts longer than the setting) set for 15 seconds assures that the motor relay will trip before the upstream devices for a cold locked rotor start.

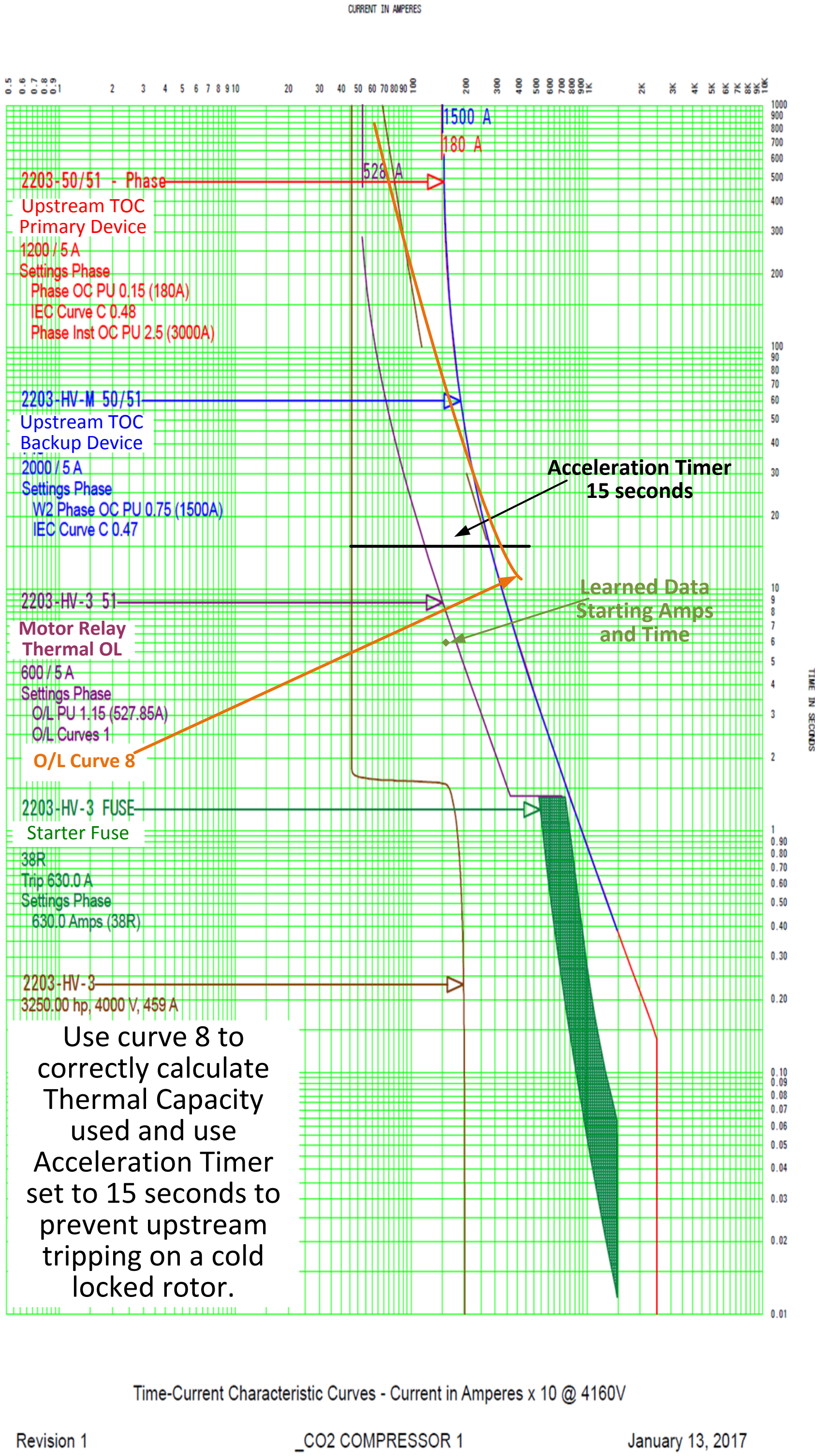


Figure 7: TCC curves showing Thermal Overload curve 8 and Acceleration Timer.

The motor data sheet indicates that this motor can have 2 consecutive cold starts and 1 hot start based on a minimum starting voltage of 90% and that the acceleration time is no longer than what is indicated on the Thermal Capability curves. Since this motor is started with reduced voltage (estimated at 75% based on the locked rotor current) and the acceleration time is considerably longer than allowed for 90% voltage, the second hot start might require some cool-down time depending on the Thermal Capacity used on the first start, even with curve 8 selected.

Switching the Thermal Over-load protection on this motor to curve 8 and adding a 15 second acceleration timer should allow the relay to correctly calculate the Thermal Capacity used and allow the motor to start without false trips.

Case Study 2: 2500 HP CO_2 compressor

The shape of this 2500 HP CO_2 compressor's Thermal Overload curves do not match the shape of the motor Thermal Capability curves well over the entire range of running and starting. The owner selected a properly matched curve for the starting curves that was substantially too fast for the running curves. As a result, the relay calculated too much Thermal Capacity used during overloads, preventing an immediate hot restart following and over-load trip.

Figure 8 shows the motor's Thermal Capability curves with relay Thermal curves. Note that relay Thermal Overload curve 9 (red square data points) matches the running portion well but is significantly too slow for the starting portion. Curve 5 (blue circle data points) matches the starting portion nicely but is too slow for the running. To provide a curve that correctly protects this motor during starting and running requires either a custom curve or the use of 2 separate curves for running and starting. In the latter case, curve 9 would be used for running and curve 5 for starting. The relay assigns 3 states to the motor: stopped, starting and running. These states can be used to switch curves by changing setting groups such that group 1 will be active while running using curve 9 and group 2 will be active while stopped or starting using curve 5.

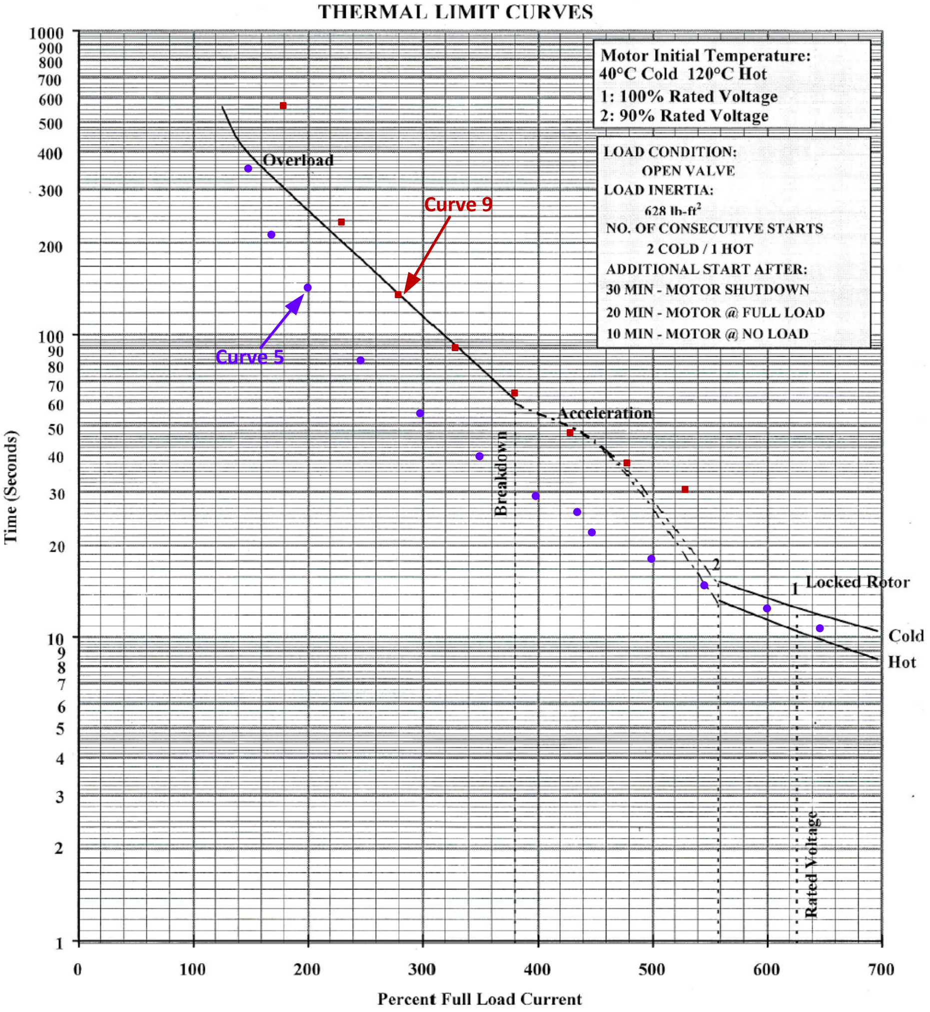


Figure 8: 2500 HP motor Thermal Capability curves.

In this case, the customer did not want to change setting groups so a custom curve was selected which will transition from curve 5 data points to curve 9 data points. Figure 9 shows the motor Thermal Capability curves with the custom curve which transitions from curve 5 to curve 9 between 450 and 525% where the composite curve uses the red, green and blue data points to form a single curve. This approach accomplished the same thing as changing curves between running and starting without changing setting groups.

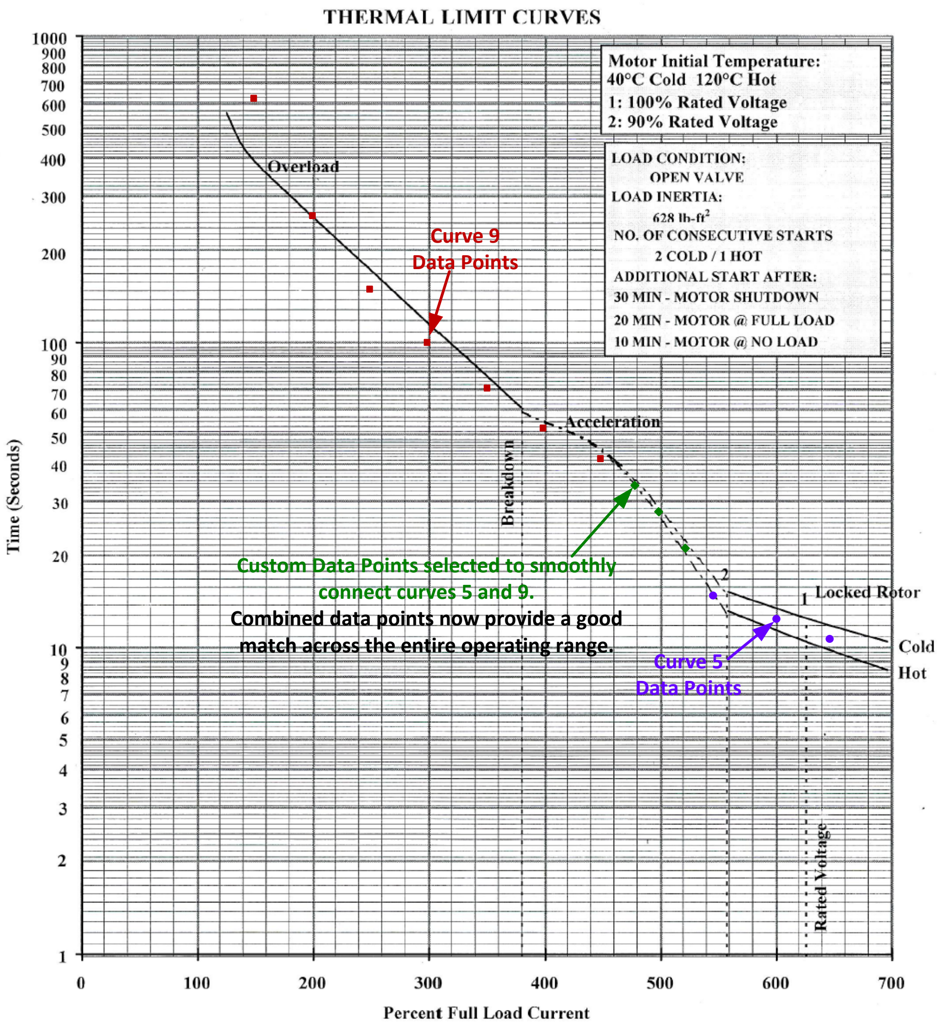


Figure 9: 2500 HP motor Thermal Capability curves with custom Thermal Over-load curve.

Conclusions

Modern micro-processor motor protection relays use the stator current to calculate the stator winding temperature. RTDs, stator current imbalances and harmonics are used to bias the temperature calculation to assure that the function trips the motor before damaging the insulation. This heat calculation is performed continuously, regardless of the motor loading. The relay uses the selected thermal overload curve to determine when the stator temperature reaches the limiting temperature of the insulation.

The starting point temperature is required to calculate the stator temperature caused by the heat energy released. As a result, thermal overload curves are three dimensional and the time to trip is a function of the current magnitude and the starting point temperature. Care must be taken when drawing the motor thermal curve on a time current coordination (TCC) diagram with other time-overcurrent devices which are 2 dimensional to avoid undo concern about the speed of upstream devices relative to the motor thermal trip time, especially in the overload portion of the curve.

Selecting overload curves that are faster than the motor Thermal Capability curves can result in the relay calculating excessively high Thermal Capacity used, causing erroneous trips during starting and unnecessarily blocking restarts. Reduced voltage starters create additional application problems. Proper curve selection, including custom curves and curve switching, in conjunction with other non-thermal functions such as acceleration timers, can generally solve the operational problems created by starting conditions and upstream device coordination. Proper curve selection allows the relay to correctly calculate Thermal Capacity used while providing the operational flexibility required by the process.

References

1) Protection and Control Reference Guide, Volume 23, GE Digital Energy, 2015.
2) Various micro-processor based motor relay instruction manuals.
3) IEEE Guide for AC Motor Protection, IEEE Std C37.96-2012 (Revision of IEEE Std C37.96-2000)