Why Servomotor Temperature Sensors Can Give Misleading Readings

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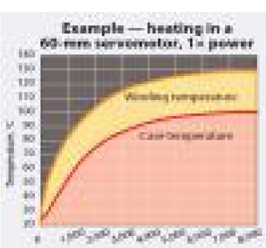
Conventional thermal models can be inaccurate enough to cause trouble when servomotors get pushed to their limits.

Key points

- The thermal models that servomotor manufacturers provide may not hold for brief periods of super high torque.
- More accurate thermal models for periods of high performance use equations with more terms.

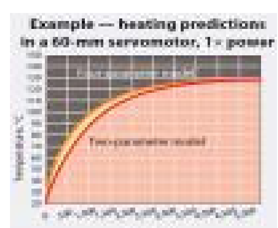
Consult the data sheet for a typical brushless-dc servomotor and one normally finds torque-speed curves for both a continuous or safe-operating area (SOAC) and for times of intermittent peak power. The correct interpretation for the SOAC is this: It defines a torque-speed boundary within which the motor can operate safely and indefinitely without exceeding its maximum continuous operating temperature when powered by a specified drive and subjected to a specific ambient condition.



Regarding the peak torque-speed curve, most servomotor manufacturers specify at least 2:1 peak-to-continuous torque ratio. Some allow an even higher 4:1 or 5:1 ratio. However, a servomotor commanded to an output peak torque exceeding its maximum continuous value for too long a time will definitely overheat. For example, 4× peak torque corresponds to 16× power dissipation in the motor's electrical winding. That's because torque output rises linearly with current while power dissipation from winding resistance (I2R) rises with the square of motor current.

Hence, commanding a servomotor to put out peak torque is normal and allowed. But the duty cycle must be kept below 100% or the motor winding can overheat and possibly even burn up!

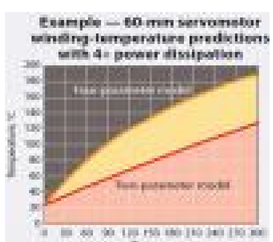
Manufacturers try to prevent servomotor windings from overheating by placing a temperature sensor inside the motor and, space permitting, attaching this sensor directly to the winding. The main purpose of this temperature sensor is to inform the drive when the winding's dynamic temperature reaches its maximum allowable value. The drive is then supposed to shut off the power to the motor.



In some multiphase motors, the manufacturer goes so far as to place a temperature switch in series with each phase of the motor winding in compliance with the UL 2111 overheating protection standard. However, after extensive research I've determined that even a temperature sensor attached directly to servomotor winding won't always protect the motor from overheating. It can be shown graphically why this can happen in the real world of servomotor operation.

Electric motors have long been thermally characterized using what's generally called the two-parameter thermal model. The two-parameter thermal model assumes the motor has one dynamic operating temperature and one value for its winding-to-ambient thermal resistance, Rth (°C/W) in parallel with its thermal capacitance, Cth (j/°C) analogous to a simple R-C electrical circuit. Solving this two-parameter thermal model for both constant power-dissipation heat-up and zero power-dissipation cool down, one finds the motor both heats and cools off in a well-known exponential manner with a thermal time constant τ(sec) such that τ = RthCth (also analogous to the R-C circuit).

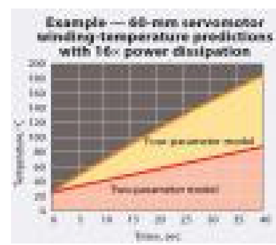
Hence, one generally finds from the servomotor data sheet that the manufacturer specifies values for both Rth and τ. This lets you calculate the motor's thermal capacitance and thus complete the two-parameter thermal model. This two-parameter thermal model is still used extensively to calculate dynamic winding temperature, but experimental measurement shows it doesn't accurately predict winding temperature when the motor draws more than 1× continuous current. Hence, a much more accurate four-parameter thermal model has been developed to overcome this inaccuracy.



The problem with the two-parameter model is that it assumes the entire motor has one value (including the winding) for its dynamic operating temperature. Actual measurement shows this isn't true. In fact, actual measurement proves that even within the winding there can be significant temperature differences for which the two-parameter model doesn't account.

Furthermore, thermodynamics teaches that for heat to flow from within the motor out towards its exposed surface area, there must be a temperature gradient both within the motor and between the motor and the ambient environment. Depending on motor size and operating temperature there can be as much as a 30 to 50°C temperature difference between the electrical winding and its exposed outermost surface area. This difference can't be ignored.

After much research I concluded servomotors need a higher-order (i.e., 4, 6, 8,… parameter) thermal model, and this model must give the motor winding its own dynamic operating temperature along with its own thermal resistance and thermal time constant. A four-parameter thermal model provides enough accuracy to explain all the measured temperature data. Plus it is end-user friendly and the four parameter values are fairly easy to find.

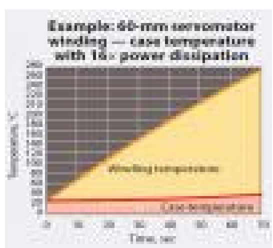


Consider an example of a 60-mm-diameter servomotor. The accompanying figure shows the dynamic temperatures of both the winding and the case (that is, rest of the motor) as temperatures rise during 1× constant power dissipation. The winding temperature begins to rise immediately. However, there is a time lag before the case temperature begins to rise. This is a key point to understand when considering why a temperature sensor won't always protect the motor from overheating.

Also notice for this example the winding temperature ultimately stabilizes at its rated 130°C maximum continuous value. The case temperature stabilizes at 100°C when surrounded by 25°C ambient air. Knowing of this 30°C winding-to-case temperature gradient, motor manufacturers must decide where to locate the motor temperature sensor and what type of sensor will protect the motor from overheating but without nuisance shutdowns.

The second accompanying figure directly compares the winding-temperature rise for this example as predicted by both the two-parameter and four-parameter thermal models. The winding temperature calculated by the four-parameter model does indeed rise faster than the temperature calculated with the two-parameter model. However, as one might expect, both curves converge at the rated 130°C maximum continuous winding temperature. This feature proves to be consistent between the two models for 1× continuous power dissipation.

The much simpler two-parameter thermal model provides reasonable accuracy in calculating dynamic winding temperature so long as the motor doesn't exceed its 1× maximum continuous value. But that's not the way a servomotor typically operates. Instead, servomotors are often commanded to produce a dynamic motion profile that typically contains time periods calling for 2× or even 4× peak torque output if motor parameters permit it.



Now consider the winding's dynamic temperature rise while assuming 2× peak torque output corresponding to 4× power dissipation in the motor winding. The four-parameter model shows the winding temperature rising to its rated 130°C value in 140 sec. The two-parameter model lags behind. It shows the winding temperature should be less than 80°C — a significant and unacceptable temperature difference. I have verified experimentally on this particular servomotor that the two-parameter model is inaccurate.

It is evident from the graphs that the two-parameter model becomes inaccurate once the power dissipation exceeds the 1× maximum continuous value. The temperature difference between what the two thermal models predict grows progressively worse with rising power dissipation. To verify this last statement, compare the dynamic winding temperature for both models while the motor produces 4× peak torque. This corresponds to 16× power dissipation in the winding.

A graph of the four-parameter model in this example shows the winding temperature reaches its rated 130°C value in only 25 sec. The two-parameter model lags behind. It predicts the winding temperature should only be 62°C, a huge temperature difference. Again, measurements on motors of different sizes show the four-parameter model predicts dynamic winding temperature accurately when the motor runs under more than 1× power dissipation.

Also consider the heating that takes place when the motor puts out 4× peak torque corresponding to 16× power dissipation. The four-parameter model for this case predicts the winding temperature rises from its initial 25°C ambient value to its 130°C rated value in only 25 sec. However, during this same time the case temperature only rises to 30°C. Thus little heat gets transferred to the case during this time period.

During the next 70 sec the winding approaches 280°C while the case has barely reached 40°C. Actual measurements confirm this behavior. In contrast, the two-parameter model (graph not shown) predicts the winding temperature is less than its 130°C rated value at 70 sec.

Temperature sensors aren't foolproof

Such thermal behavior complicates the selection of temperature sensors and decisions about where to position them in the servomotor. Further, because servomotors can only operate in combination with drives, temperature sensors must be compatible with the drive of choice.

In this regard, most modern drives use pulse-width-modulation (PWM) techniques to produce their output voltage and current. PWM drives are electrically noisy. This noise makes it difficult to measure dynamic winding temperature accurately using a thermocouple and the low-level signals it generates. Thus many servomotors contain either a temperature switch or a thermistor mounted inside the motor rather than a thermocouple.

There is also the question of where to locate the motor temperature sensor. The four-parameter thermal model would seem to indicate that the logical spot for a temperature sensor is directly on the motor windings because of the speed with which they heat up.

Furthermore, many servomotors are recognized under the UL 1004 and/or CSA 22.2 motor standards. As part of the UL/CSA recognition process, the motor's electrical-insulation system must be constructed to comply with the UL 1446 Insulation System Standard.

As displayed in Table 4.1 of UL 1446, the winding's maximum allowable hot-spot temperature at any point and at any time is determined by the Class of the insulation system on the winding. Thus to comply with UL 1446, the winding's insulation system must have a maximum hot-spot temperature at least equal to or greater than the maximum continuous-winding temperature.

All in all, it makes engineering sense to construct the winding using a higher Class insulation system such that the winding never exceeds its maximum hot-spot temperature. However, this is not the case in all servomotors. Several have the same value for both the maximum continuous and the maximum hot-spot temperature. So to ensure the servomotor stays in compliance with UL 1446, the temperature sensor should also sit at the point of the maximum hot-spot temperature. But this isn't always practical, especially in smaller 20 to 90-mm-diameter servomotors.

The physical size of a temperature switch in combination with the packing density of the motor winding often forces the manufacturer to attach the switch on the winding end turns. However, the end turn doesn't always correspond with the winding hot spot. Further, in some servomotors of this size, the temperature switch sits inside the motor but the physical size of both the switch and the winding make it impractical to attach this switch to the winding. So the winding dynamic temperatures are not measured directly.

Some servomotor manufacturers also specify their motors as having Class B (130°C) or Class F (155°C) insulation systems while correspondingly specifying 130 or 155°C as the maximum continuous-winding temperature. In addition, they also specify 4:1 or even 5:1 as the peak to continuous torque ratio. But this sort of specification doesn't provide any safety margin between the winding's maximum continuous and maximum hot-spot temperature.

One can infer from the four-parameter thermal model, and physical measurements confirm, that there are problems when there is no safety margin between the winding's maximum continuous and hot-spot temperature. Here it's extremely difficult, if not impossible, for a motor temperature sensor not attached directly on the winding to react fast enough during periods of 2× torque demand. The result can be that the motor exceeds the winding maximum hot-spot temperature in direct violation of UL 1446.

Adding to this problem is a reality that both servomotor manufacturers and motor users still use the oversimplified two-parameter thermal model to make duty-cycle calculations. (Most manufacturers publish only one value for the winding-to-ambient thermal resistance along with its thermal time constant.)

Thus users should understand that the servomotor may still overheat during a specified dynamic motion profile even when the two-parameter calculation predicts the maximum hot-spot temperature won't be exceeded. Nor will a temperature sensor necessarily prevent such problems. It may be that the temperature sensor won't detect the dynamic rise in hot-spot temperature fast enough to prevent exceeding the maximum allowable value which, again, is in direct violation of UL 1446.

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