# Why All Exlar SLM Servomotors Have a 50°C "Hot Spot" Temperature Safety Margin

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## Introduction

In today's demanding world of motion control, systems designers and applications engineers constantly search for the highest possible performance, smallest size yet least costly servomotors that provide the "Most Bang for Least Buck". Ask any systems designer or applications engineer to define their "ideal" servomotor and they often respond by saying the motor should have;

- ✓ **Zero Size**
- ✓ **Zero Cost**
- ✓ **Infinite Torque Output**
- ✓ **100% Efficiency**
- ✓ **No Temperature Limit**

Although this "ideal" servomotor doesn't exist, in attempting to obtain the highest possible system performance the servomotor(s) is often commanded to output its maximum "Peak" torque for the longest possible time. However, during times of "Peak" torque output a servomotor's electrical winding can quickly overheat and even burn-up! Therefore, the focus of this paper is to show you graphically why all Exlar T-Lam servomotors use the highest possible 50°C "Hot Spot" temperature Safety Margin that's defined as the difference between the winding's maximum allowable Hot Spot temperature minus the Maximum Continuous Winding Temperature and stated mathematically as;

***Hot Spot Temp Safety Margin = (Max Hot Spot Temp) – (Max Continuous Winding Temp)***

## Maximum Continuous Winding Temperature and Torque Output

After consulting numerous data sheets for both Brush and Brushless DC (BLDC) servomotors one finds manufacturers normally publish the value for each motor's maximum continuous winding temperature plus the corresponding maximum continuous current input and torque output along with the "total ambient condition" (i.e., Drive electronics, Ambient temperature, heat sink…etc.) that applies to these values [1, 2, 3, 4, 5, & 6]. So long as the 1X maximum continuous current is not exceeded at any time and so long as the total ambient condition is "equivalent" to the one specified by the manufacturer then the motor's maximum continuous winding temperature can not be exceeded and the rest of this paper is unnecessary. However, that's not the way a servomotor typically operates. Instead, servomotors are often commanded to provide a dynamic motion profile containing one or more time periods during which the motor outputs "Peak" torque greater than its 1X maximum continuous value. Hence, the manufacturer also specifies a "Peak" torque for each motor and depending on the manufacturer and model the motor's Peak to Continuous torque ratio typically ranges between 2:1 and 7:1 [1, 2, 3, 4, & 5].

Although it's normal for a servomotor to output "Peak" torque in excess of its 1X maximum continuous value, if the time duration is too long then the motor's electrical winding will overheat and quite possibly even burn up! Hence, during times of "Peak" torque output the motor's "Duty Cycle" must be limited to less than 100% and the higher the "Peak" torque is above the 1X maximum continuous value the lower the percent Duty Cycle must be [6].

## Motor's Two-Parameter Thermal Model

For over 50-years servomotors have been characterized thermally by what's generally called the two-parameter thermal model [7]. Again, consulting the data sheets for both Brush and BLDC servomotors one generally finds each manufacturer publishing a value for the motor's winding to ambient thermal resistance, $R_{th}$ (°C/watt), plus the corresponding thermal time constant, $\tau$ (second), and this allows you to calculate the motor's thermal capacitance, $C_{th}$ (joule/°C) using the following equation thereby completing the two-parameter model;

$$C_{th} = \frac{\tau}{R_{th}} . \tag{1}$$

Using this two-parameter thermal model, both manufacturers and motor users attempt to "size" and select the "optimum" motor for each application. Many manufacturers have developed motor sizing programs whereby the user supplies all the necessary application data for the system and the manufacturer determines which of their motors is optimal for your application. However, I have not yet found a single manufacturer willing to size and recommend a competitor's motor and will only tell you which of their motor's is best suited for your application. Hence, to make a competitive comparison between different manufacturers and find out which servomotor provides the "Most Bang for Least Buck" the motor user generally has to size and compare the available servomotors themselves.

Both the Electro-Craft Engineering Handbook [7] and the often cited 1972 paper by Noodleman and Patel [8] teach us how to "size" a servomotor for each application along with making the required Duty Cycle calculations for a dynamic motion profile to make sure the motor won't overheat when performing the profile. We are told in the Electro-Craft Handbook the first step in this sizing process is to accurately specify the dynamic motion profile, such as the one shown in Figure 1, along with the "total ambient condition" (i.e. ambient temperature, heat sink, forced cooling,…etc?) in which the motor will operate.

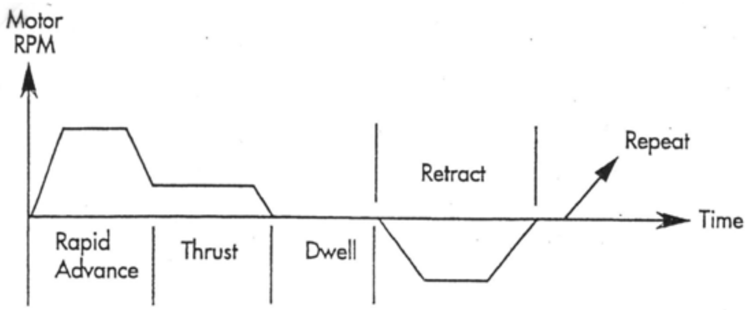


**Figure 1, Repetitive Motion Profile for a typical Machining Operation**

Next, in combination with the motor's engineering specifications one determines the "Peak" torque and velocity the motor must provide during the most demanding time period in the dynamic motion profile (Figure 1) and enter this "Peak Operation Point" onto the motor's combined "Intermittent" and "Continuous" Torque-Speed curves as shown in Figure 2.

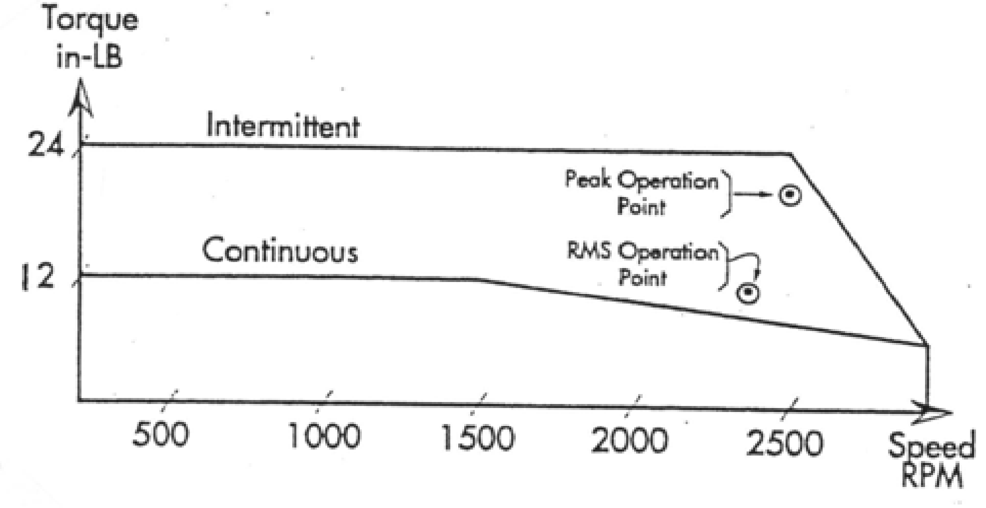


**Figure 2, Motor's Intermittent and Continuous Torque-Speed Curves**

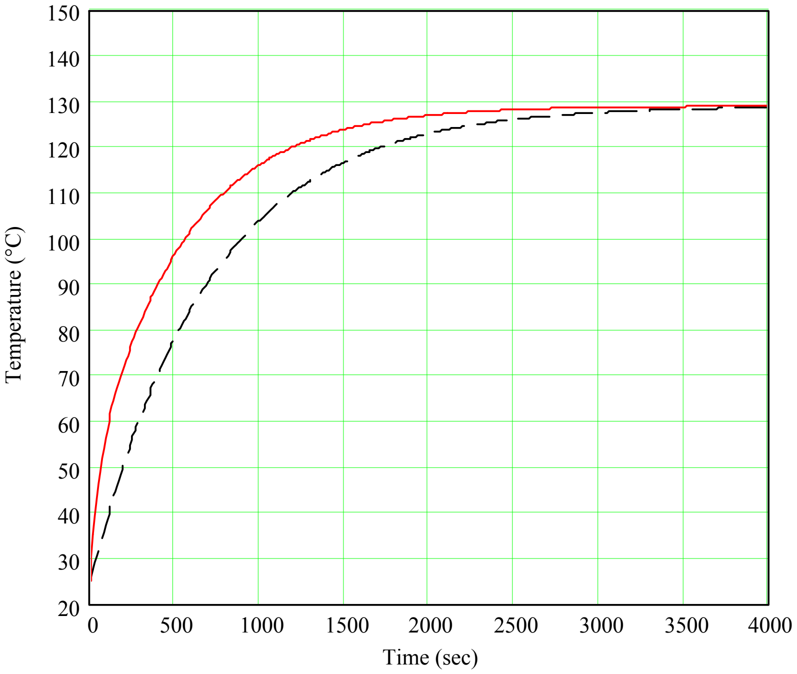
We are told a necessary requirement is the "Peak Operation Point" must lie within the boundary of the Intermittent Torque-Speed curve or this particular motor-drive combination doesn't have enough torque, velocity, and/or power for the application and you must select a different motor.

Finally, using the two-parameter thermal model in combination with the "time averaged" power dissipation technique one calculates the Root-Mean-Square (RMS) torque and velocity for the entire motion profile and enters this RMS Operation Point onto the combined torque-speed curves shown in Figure 2 [6, 7, & 8]. If, as shown, this RMS Operation Point lies outside the boundary of the "Continuous" torque-speed curve then we are told with absolute certainty the motor will overheat in the application and again we must select a different motor [6 & 7]. Conversely, we are also told that so long as the RMS Operation Point lies within the boundary of the "Continuous" torque-speed curve then it's OK to select this particular motor as it will not overheat in the application [7 & 8]. However, my extensive research has proven this last statement is NOT always true since in the "real world" of servomotors it's entirely possible the winding's maximum allowable "Hot Spot" temperature is actually being exceeded in direct violation of UL 1446 and you don't even know its happening because you are still using the over simplified the two-parameter thermal model for all your winding temperature calculations [6]!

## Four-Parameter Thermal Model

Even though this simple, two-parameter thermal model is still being used to calculate dynamic winding temperature during all possible modes of servomotor operation, experimental measurement shows it's NOT very accurate when greater than 1X maximum continuous current value is supplied to the motor. Hence, to overcome this inaccuracy the much more accurate four-parameter thermal model has been developed [6]. The basic problem with the two-parameter model is it assumes the entire motor has one value for its dynamic operating temperature (including the winding) while actual measurement shows this isn't true. In fact, measurement proves that within the motor, and even within the winding itself, there can be measurable temperature differences and the two-parameter model simply doesn't account for any of these differences. Furthermore, depending on motor size and operating temperature there can be as much as a 30°C to 50°C temperature difference between the motor's winding and its outermost exposed surface area and this difference simply can't be ignored. Therefore, after extensive research I concluded a higher order [i.e., 4, 6, 8,… parameter] thermal model was needed and this higher order model must allow the motor's winding to have its own dynamic operating temperature along with its own thermal resistance and thermal time constant that differs from the rest of the motor. Ultimately, after more research I concluded the four-parameter thermal model provides sufficient accuracy to explain all the measured temperature data plus it's fairly easy to obtain the four different parameter values [6].

Using both the four-parameter and two-parameter models along with the measured parameter values for the Exlar SLM 40 (40mm diameter) servomotor, Figure 3 shows the dynamic winding temperature difference between the two models during 1X constant power dissipation heat-up.



**SLM 40 Motor, Winding Heat-Up with 1X Constant Power Dissipation**
**Solid Red = Four-Parameter Model**
**Dash Black = Two-Parameter Model**

**Figure 3**

As shown in Figure 3 , the winding temperature calculated by the four-parameter model rises faster (solid Red line) compared to the two-parameter model (dash Black line). However, as you can also see, both curves converge at the rated 130°C maximum continuous winding temperature and this feature is consistent between these two models with 1X continuous power dissipation.

Next, we again compare the winding temperature rise between the two models for the same SLM 40 servomotor but this time the motor is producing 4X “Peak” torque output corresponding to 16X power dissipation in the winding since the torque output for a permanent magnet servomotor increases linearly with input current while the electric resistance power dissipation in the winding increases as current squared, $I^2$ R.

**SLM 40 Motor, Winding Heat-Up with 4X Peak Torque Output**
**Solid Red = Four-Parameter Model**
**Dash Black = Two-Parameter Model**

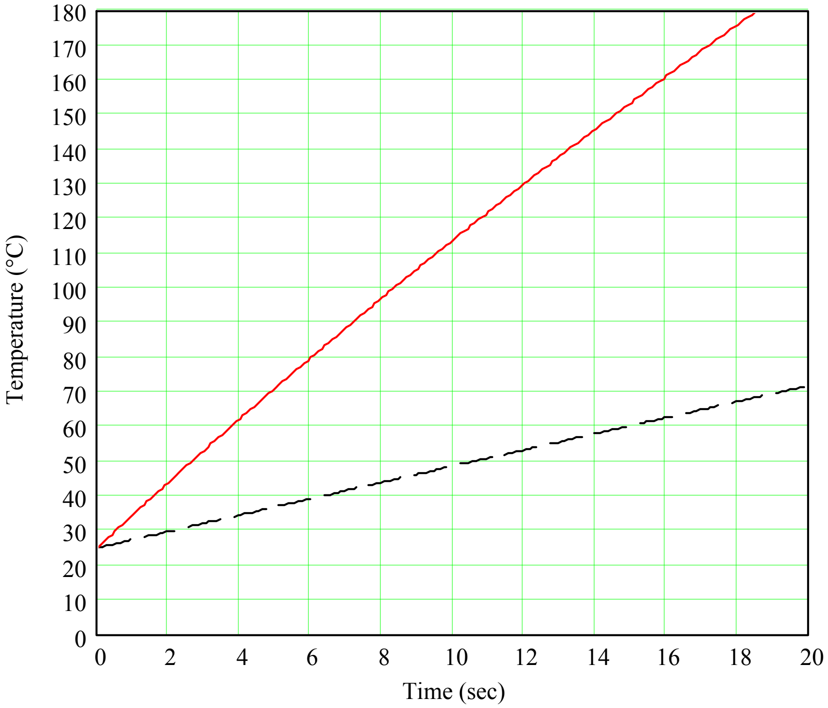


**Figure 4**

As shown in Figure 4 with 4X Peak torque output, specified for many servomotors, the four-parameter model shows the winding temperature rises from its initial 25°C to the 130°C rated value in only 12-seconds while during this same time the two-parameter model lags behind and shows the winding temperature should be less than 55°C which is very significant and a totally unacceptable temperature difference that I verified experimentally on this particular motor.

Hence, continuing to use the two-parameter thermal model to calculate dynamic winding temperature during times of Peak torque output greater than the 1X maximum continuous value provides significant temperature error that is totally unacceptable!

## Maximum Allowable Hot Spot Temperature

After reviewing the advertisements from several different manufacturers I find many of them proudly announcing their motors are Underwriters Laboratories (UL) and/or Canadian Standards Authority (CSA) recognized under the UL 1004 and/or CSA 22.2/100 standards and this includes the Exlar SLM servomotors [1]. As part of the UL/CSA recognition process, the insulation system used to construct the motor's electrical winding must comply with the UL 1446 Insulation System standard [9]. As specified in Section 4 and shown in Table 4.1 of UL 1446, the maximum "Hot Spot" temperature, occurring at any time and at any point in the winding, is determined by the "Class" of the insulation system used to construct the winding. Hence, to be compliant with UL 1446 the winding must at least have a "Hot Spot" temperature rating that's equal to or greater than the maximum continuous winding temperature. Furthermore, in attempting to make sure the motor always remains compliant with UL 1446 and to make sure the winding can't possibly overheat; many manufacturers often place a temperature sensor/switch inside the motor [11]. The sole purpose of this temperature sensor/switch is to inform the Drive when the winding is approaching its maximum allowable Hot Spot temperature and in turn the Drive is supposed to shut off the power being supplied to the motor and keep its winding from overheating in direct violation of UL 1446. However, there are at least three practical reasons why this temperature sensor protection scenario doesn't always work the way it should with the end result being the motor's maximum allowable Hot Spot temperature is exceeded thereby violating UL 1446 and even worse yet the winding can burn up [10]!

## Why a Servomotor Needs a Hot Spot Temperature Safety Margin

As discussed earlier the two-parameter model is still used extensively by both servomotor manufacturers and motor users to thermally characterize each motor but it isn't accurate enough in calculating dynamic winding temperature when greater than the 1X maximum continuous current value is being supplied to the motor. As also discussed, the basic problem with the two-parameter model is it assumes the entire motor, including the winding, has one dynamic temperature value while actual measurement shows this isn't generally true. Therefore, the much more accurate four-parameter thermal model has been developed [6] and using this model I have already shown graphically how the motor's winding heats up much faster than is calculated by the two-parameter model. However, even this four-parameter model isn't perfect and even though it allows the winding to have its own dynamic operating temperature, different from the rest of the motor, the entire winding is still assumed to have one uniform temperature value and this too is not always accurate as verified by actual measurement at different locations in the winding. Although, despite this one winding temperature assumption, the four-parameter model still provides much better accuracy that allows me to prove conclusively why a servomotor must have a Hot Spot temperature "Safety Margin" during times of "Peak" torque output.

Having reviewed the data for numerous servomotors manufactured around the world, I have thus far found only one manufacturer publishing the four-parameter thermal model values for both their Brush and BLDC motors [13]. Therefore, it's reasonable to assume most servomotor manufacturers still perform all their motor sizing and dynamic winding temperature calculations using the two-parameter thermal model. Correspondingly, since manufacturers generally publish only one value for both the motor's winding to ambient thermal resistance plus its thermal time constant, motor users have no choice but to use this two-parameter model in making all of their dynamic temperature calculations unless they measure the needed four-parameter values themselves which is rather easily done as taught in reference [6]. As shown in Figure 1, sizing and selecting the "optimum" motor for your application begins by defining the dynamic motion profile along with the total ambient condition in which the motor will operate. Next, using the two-parameter thermal model in combination with the "time averaged" power dissipation technique the candidate motor's RMS operation point is determined and entered onto its continuous torque-speed curve as shown in Figure 2. If this RMS operation point lies outside the boundary of the continuous torque-speed curve then for sure this particular motor-drive combination will over heat in the application and thus can not be used unless the motion profile is modified and/or the total ambient condition is changed. Conversely, if the RMS operation point lies within the boundary of the motor's continuous torque-speed curve then the motor manufacturer, along with the Electro-Craft Handbook [7] both claim this motor can't possibly overheat in the application while performing the specified motion profile so long as the total ambient remains "equivalent" to the one specified by the motor manufacturer.

However, as shown in both Figure 3 and Figure 4, the four-parameter model proves the winding actually heats up and attains a higher temperature much faster than the two-parameter model predicts. Hence, even though the "time averaged" power dissipation technique in combination with the two-parameter model claims the winding's maximum continuous temperature shouldn't be exceeded the four-parameter model shows and actual measurement proves that during times of "Peak" torque output the maximum continuous winding temperature can in fact be exceeded. Furthermore, even though the motor contains a temperature sensor/switch that's supposed to protect the winding from overheating this sensor/switch can't and doesn't always react fast enough to prevent this from happening as detailed in reference [10]. Therefore, if you want to obtain the "Most Bang" from a servomotor plus protect it from violating UL 1446 then the Class of the insulation system used to construct its electrical winding must have a maximum allowable Hot Spot Temperature that is greater than its maximum continuous winding temperature and the greater this Hot Spot temperature Safety Margin the better the protection! For example, all the Exlar SLM servomotors shown in reference [1] have a 130°C maximum continuous winding temperature while their winding's insulation system is rated Class H and this provides the winding with a 180°C maximum allowable Hot Spot temperature thus providing a 180°C – 130°C = 50°C Hot Spot temperature Safety Margin for all SLM motors. In addition, all SLM servomotors are specified with a 2:1 Peak to continuous torque ratio and in combination with their 50°C Hot Spot temperature Safety Margin this provides the SLM servomotors with the highest possible thermal protection during times of Peak torque output. In comparison, if you look at the published specifications for other BLDC servomotors, you find many of them have a Hot Spot temperature Safety Margin that's 15°C or less (many have ZERO margin) plus they are also being specified with Peak to Continuous torque ratios ranging between 3:1 up to 5:1.

Over time, several authors have suggested different figures of merit that one should use when selecting the “optimum” servomotor for your high performance motion control applications. Based on the findings in this paper along with those in a recently published paper [10], I‘m suggesting that from a motor users perspective the single most important “figure of merit” in selecting the optimum servomotor is “Most Bang - Least Buck”! Therefore, if you need to obtain the “Most Bang” for the longest period of time yet still remain compliant with UL 1446 then I’m saying the servomotor must have the highest possible “Hot Spot” temperature Safety Margin and so far 50°C is the highest margin I’ve been able to find [1]. Hence, when selecting the optimum servomotor for your demanding, high performance motion control application why settle for anything less than a 50°C Hot Spot temperature Safety Margin when all the Exlar SLM servomotors offer this level of thermal protection? Furthermore, in other recently published papers [14, 15 & 16] it has also been shown graphically that the T-Lam stator design provides the Exlar SLM servomotors with up to 40% more continuous torque and power density (i.e., torque and power per unit motor volume) compared to any other design currently available. As a result, not only can the SLM servomotors provide the “Most Bang” for the longest time but for a specified amount of continuous torque output they also provide the smallest size motor thereby making all SLM servomotors as close to “ideal” as physically possible using the same materials available to all motor manufactures!

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