Why the Exlar T-LAM™ Servo Motors have Become the New Standard of Comparison for Maximum Torque Density and Power Efficiency

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Introduction

According to the U.S. Department of Energy (DOE) 63-65% of a typical manufacturing plant's monthly electric bill goes to pay for all the electricity consumed by the electric motors operating in the plant. Hence, with a steady rise in electricity cost along with constant pressure to lower manufacturing cost, if you ask plant managers to describe the three most important words associated with electric motors they quickly respond by saying its "efficiency", "efficiency" and "efficiency". As you can see, no matter how you arrange these three words "efficiency" is always at the top of your list. Furthermore, systems and design engineers who build equipment used in manufacturing plants constantly search for electric motors that provide the "most bang for least buck". Therefore, producing electric motors that have the highest obtainable torque density (i.e., continuous torque output per motor volume) along with maximum power efficiency has become a real challenge for all motor manufacturers. To meet this challenge for both high torque density and maximum power efficiency, Exlar has developed its T-LAM™ stator that's now being used in all SLM and SLG brushless DC servo motors and in all GSX and GSM rotary actuators [1]. Hence, the focus of this paper is to show you graphically why the T-LAM servo motor has become the new standard of comparison for torque density and power efficiency.

Solid Core Stator

For well over 100-years motor manufacturers have and continue to design and manufacture AC induction, variable reluctance (V-R), and brushless DC (BLDC) servo motors using what's generally called the Solid Core stator design that uses multiple, single-piece laminations to construct the stator's magnetic core structure [2,3]. Figure 1 shows two cross-sections of typical Solid Core stators for BLDC servomotors and as you can see the permanent magnet rotor can have either inner or outer rotation.

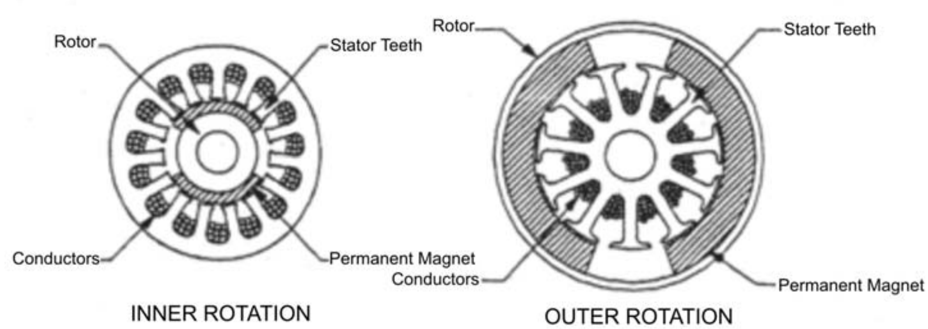


Figure 1 – Cross Sections of BLDC Stators – Inner and Outer Rotation

As also shown in Figure 1, the single-piece laminations contain numerous teeth and the multi-phase electrical winding is inserted into the slots in between these teeth.

Below in Figure 2 is the cross-section of a specific 4-pole, 12-tooth Solid Core stator along with the slot locations for each phase of its 3-phase electrical winding.

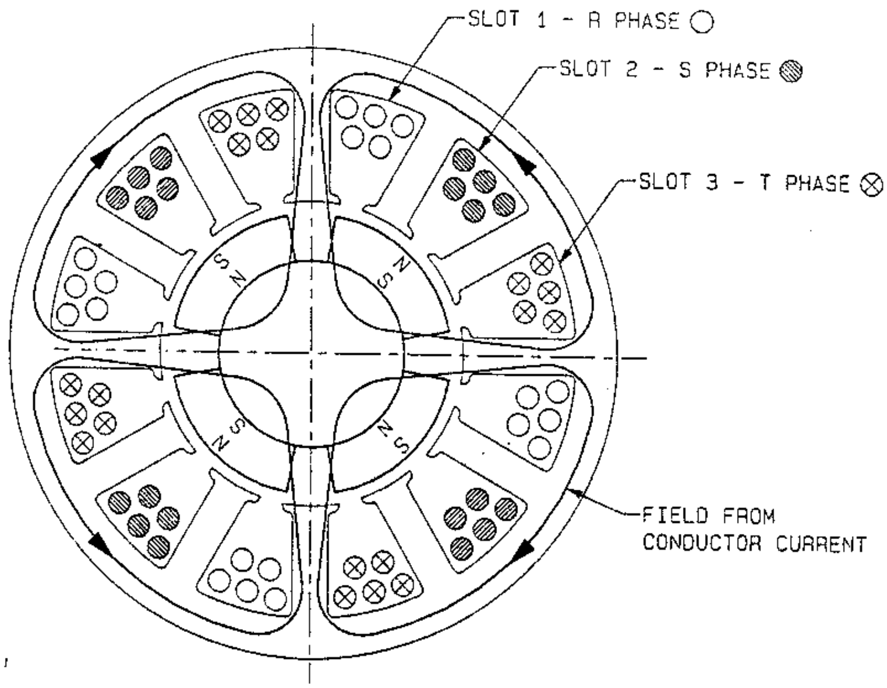
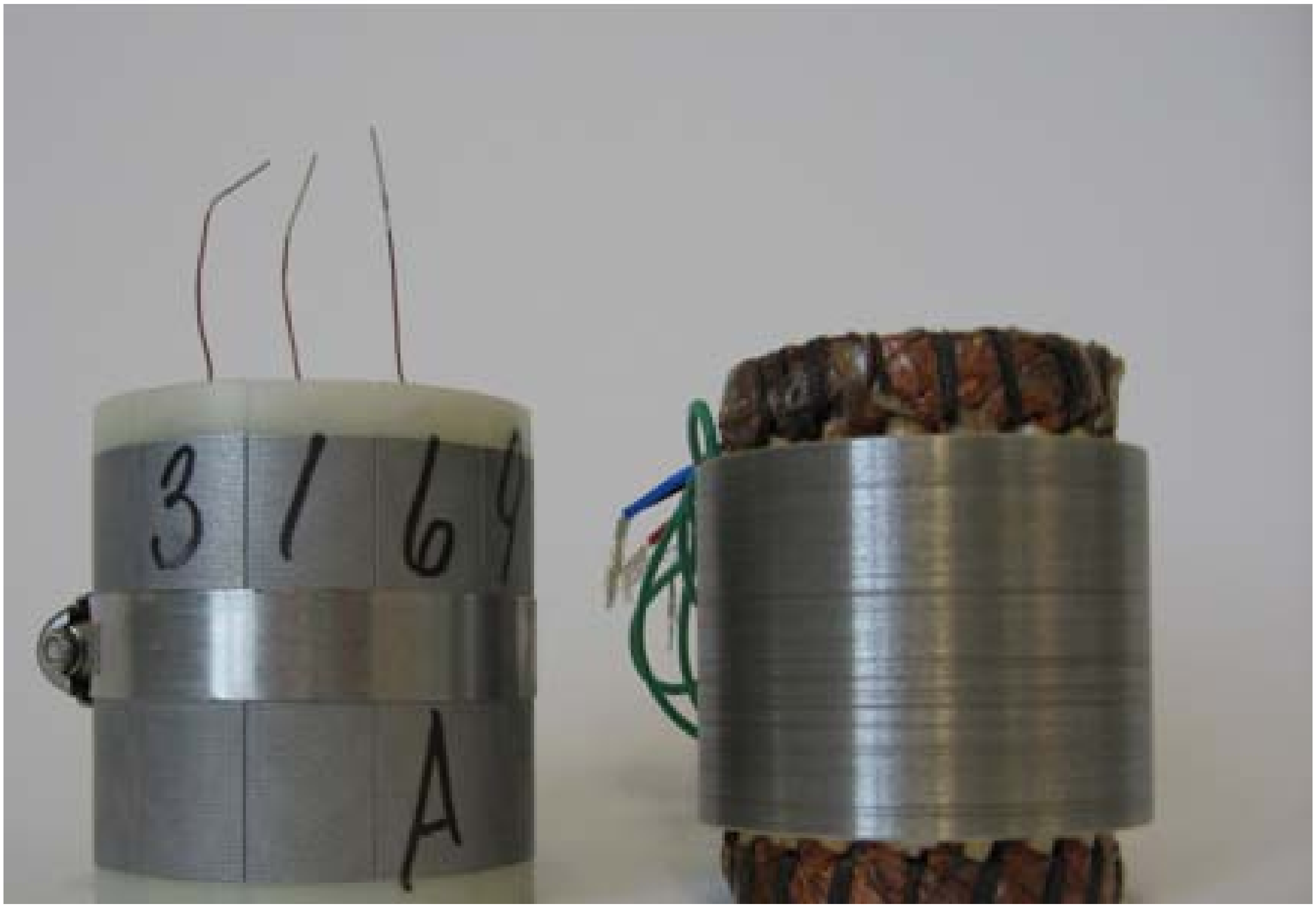


Figure 2, Cross Section of a 3-phase, 4-pole and 12-tooth stator

Notice in Figure 2 that "R-phase" is inserted into slots 1-4-7-10, "S-phase" into slots 2-5-8-11, and "T-phase" into slots 3-6-9-12 and this winding configuration is called a distributed winding and Figure 3 shows a wound Solid Core stator sub-assembly on the right hand side. Also notice in Figure 3 with a distributed winding there is significant portions of the winding that extend beyond both ends of the stators' magnetic core structure and these portions are called the end turns. End turns complete the electrical path within the winding that add to the winding's total electrical resistance but do not contribute to the motors' continuous torque output as this is obtained only from that section of the winding lying entirely within the body of the magnetic core structure [4]. Hence, we later show how end turn length along with the percent slot fill both affect continuous torque and power density along with power efficiency [5].



T-LAM Stator **Solid Core Stator**

Figure 3 – Same Volume Stators T-LAM (left) and Solid Core (right)

The Solid Core distributed winding can be wound and inserted either by hand or by using automated winding and insertion equipment [5, 6, 7, and 8]. Hand winding and insertion is often limited to prototypes, low volume production and/or motor rewind/rebuild. For high volume production, manufacturers typically use automated winding and insertion equipment along with the necessary blocking and lacing machines that form and secure the end turns [6, 7, and 8]. In addition, a "trickle" machine is often used to impregnate the winding with a varnish that rigidly secures the wires in place thereby preventing them from moving and rubbing against each other and causing premature winding failure [8]. Besides holding the wires in place the varnish also improves heat transfer within the winding itself and between the winding and the surrounding core structure. In turn, better heat transfer between the winding and the ambient environment increases the motors' continuous torque and power density [9]. As mentioned earlier, the Solid Core stator design has been used extensively for well over 100 years in most AC induction, V-R, and BLDC Servomotors and was also used by Exlar for all their original servomotor designs. Hence, the continuous torque and power density along with power efficiency for all the original Exlar servomotors serves as our basis of comparison against their new T-LAM motors.

T-LAM Stator Has 40% Lower Winding Resistance

During the mid 1980's when Exlar first began producing servomotors and actuators they started out by using the Solid Core stator design just like most other motor manufacturers still use. However, in response to customer requests for higher torque and power density along with improved power efficiency, Exlar developed its T-LAM stator and Figure 4 shows a 3-D view of the core structure. As you can see, instead of using several one-piece laminations to construct the stators' solid core a T-LAM core contains individual T-shaped segments that are mechanically held together to construct its segmented core structure. In turn, each T-LAM core segment is wound using a bobbin winder to obtain the typical 78-80% slot fill and then these wound segments are combined and held together to complete the stator sub-assembly shown on the left hand side in Figure 3, 5 and 6.

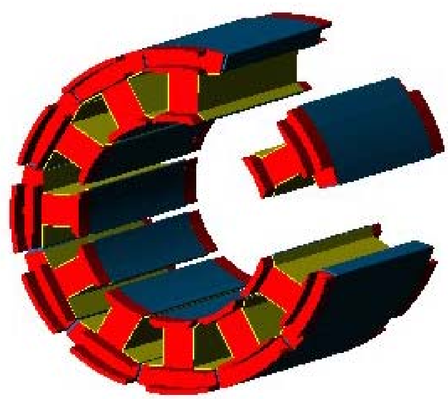
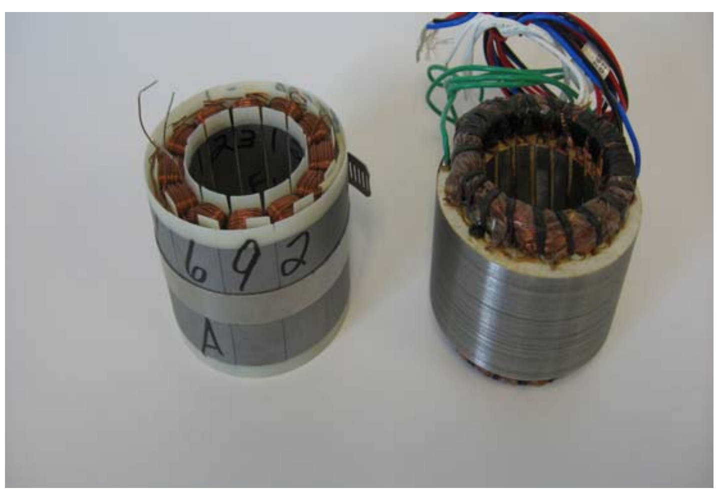
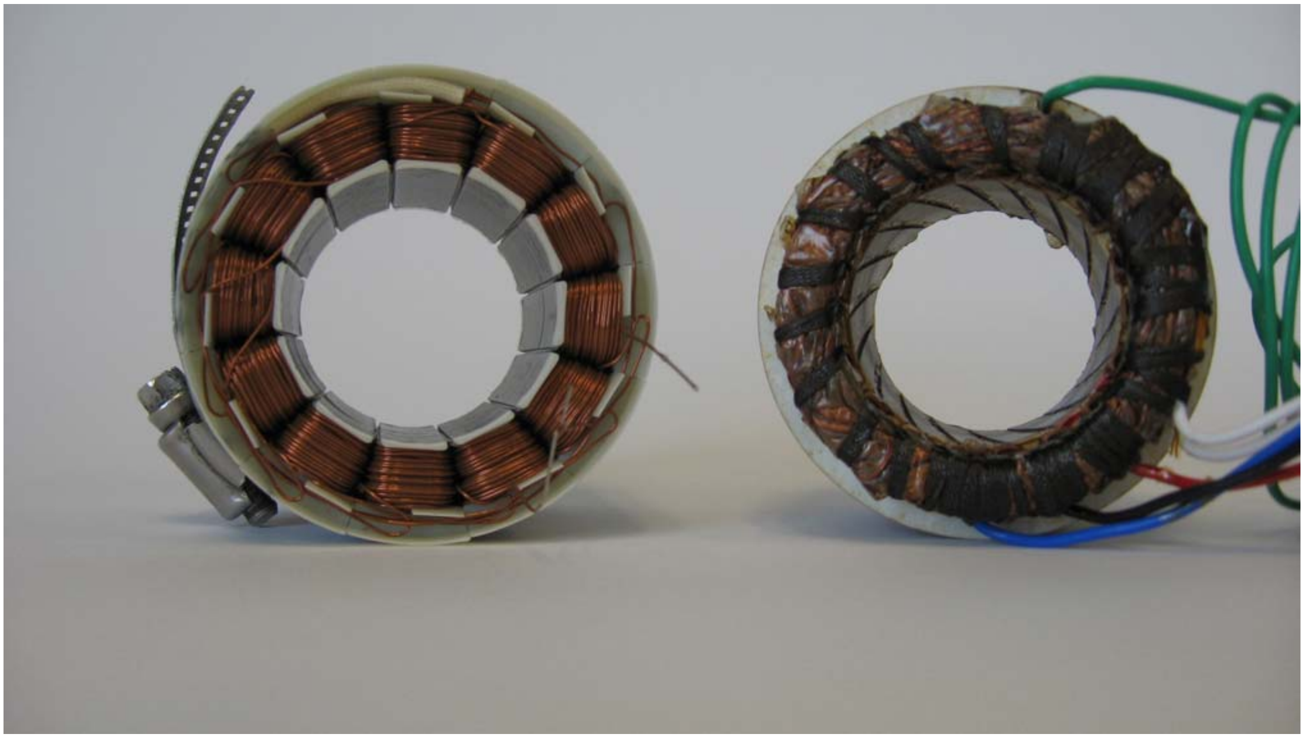


Figure 4 – T-LAM Core Structure



T-LAM **Solid Core**

Figure 5 – Top View of T-LAM versus Solid Core Stator



T-LAM Stator **Solid Core Stator**

Figure 6 – End View of T-LAM versus Solid Core Stator

The first feature to notice in Figure 3 and 5 is the significant reduction in the windings' end turn length. Depending on core length, ends turns in a Solid Core stator can be 30-60% of the total wire used to construct its distributed winding thereby adding 30-60% to the winding's electrical resistance. Hence, end turns are essentially a waste in terms of not contributing to the motor's torque and power output but wasting input electrical power thereby lowering torque density and power efficiency. In contrast, end turns in a T-LAM stator typically amount to only 5-7% of the wire used to construct its concentrated winding thereby requiring less wire length for the same number of turns that in turn lowers the windings' electrical resistance. Furthermore, if you also look carefully at Figure 3 you can see that for a given overall stator length the magnetic core length can be increased by 3-5% allowing you to add more magnet length to the rotor because there is less end turn length. Hence, winding both the T-LAM and the Solid Core stator with the same number of turns allows use of one wire gauge larger diameter wire in all T-LAM stators since Exlar consistently obtains 78-81% slot fill in all their T-LAM stators compared to 55-60% slot fill with Solid Core stators. Consulting a wire table for copper magnet wire you see that for every change in wire gauge the wire's electrical resistance per foot changes by 26%. Therefore, with all motors ranging in diameter from 40 mm up to 180 mm the T-LAM motor has 40-45% lower winding resistance compared to the same volume Solid Core motor that Exlar originally produced.

To better understand the significance of reduced winding resistance consider the expression for the maximum continuous torque a BLDC servomotor can safely output without overheating that amounts to [9,10],

$$T_L(\omega) = \frac{K_T(\mathrm{T}_R)}{\sqrt{R(\mathrm{T}_R)}}\left[\sqrt{\frac{(\mathrm{T}_R - \mathrm{T}_0)}{R_{th}} - D_M\omega^2 - F_M\omega}\right] - D_M\omega - F_M \quad \textbf{(1)}$$

In equation (1) the parameter values are defined by,

T_R = Rated winding temperature (°C)
T_0 = Ambient temperature (°C)
R_{th} = Winding to Ambient thermal resistance (°C/watt)
ω = Motor's angular velocity (radian/second)
D_M = Motor's viscous damping (Nm/radian/second)
F_M = Motor's friction (Nm)
$K_T(T_R)$ = Motor's total torque function @T_R (Nm/amp)
$R(T_R)$ = Winding's electrical resistance @T_R (ohm)
$T_L(\omega)$ = Maximum continuous torque motor can deliver to its load at each velocity

Next, consider the expression for the motor's maximum continuous power output at each velocity, P(ω), that amounts to,

$$P(\omega) = \omega T_L(\omega) \quad \textbf{(2)}$$

Finally, consider the expression for the motor's % power efficiency when the motor operates at the rated winding temperature, T_R [11],

$$\%E(\omega, T_R) = \frac{\omega T_L(\omega, T_R)}{\left[\dfrac{T_R - T_o}{R_{th}}\right] + \omega T_L(\omega, T_R)} x100 \quad \textbf{(3)}$$

The first feature to notice in equation (1) (2) and (3) is by lowering winding resistance, keeping all other parameter values the same, allows a T-LAM motor to output more continuous torque and power for the same temperature rise and improves the motor's power efficiency for a fixed power dissipation inside the motor. To graphically see the affect of lowering winding resistance by 40%, Figure 7 and 8 show the continuous torque and power output curves for the Exlar SLM90-238 (90mm diameter, 2.0" core length) T-LAM motor in direct comparison with their original Solid Core motor while Figure 9 shows the power efficiency curve.

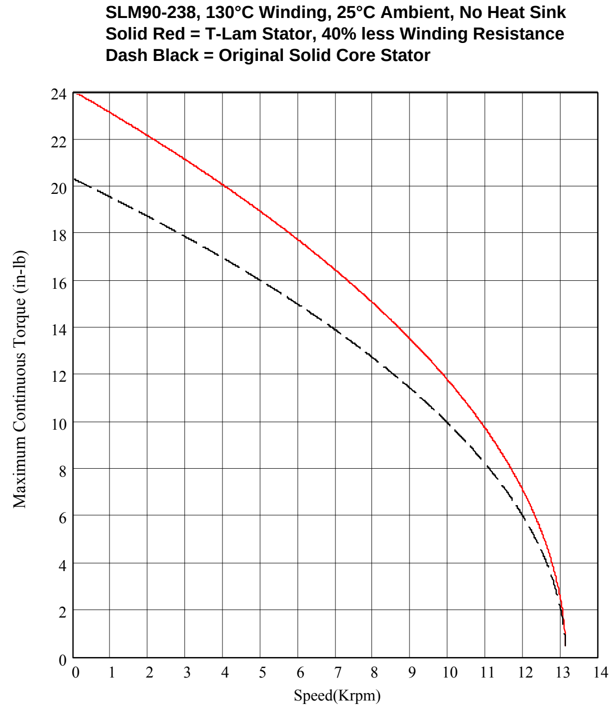


Figure 7 – SLM90-238 Continuous Torque-Speed Curve

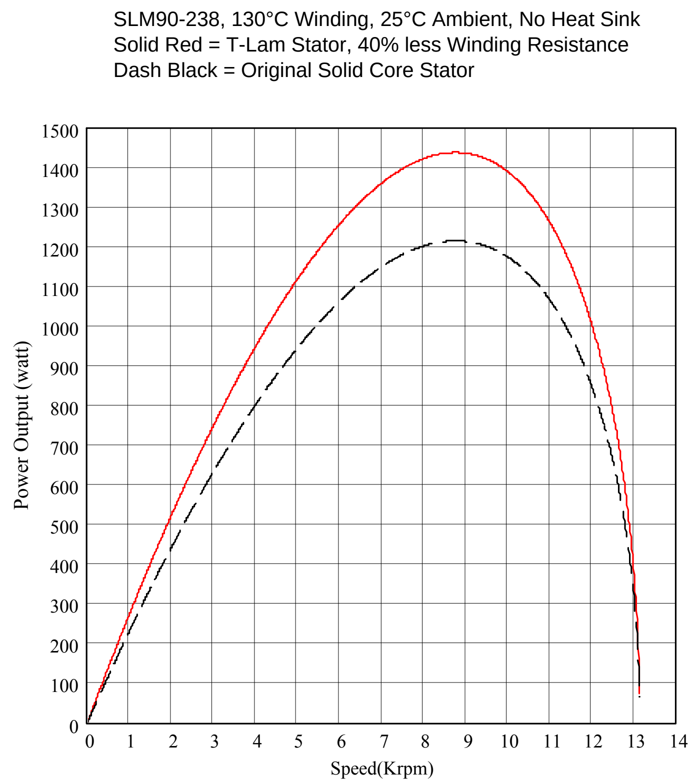


Figure 8 – SLM90-238 Continuous Power-Speed Curve

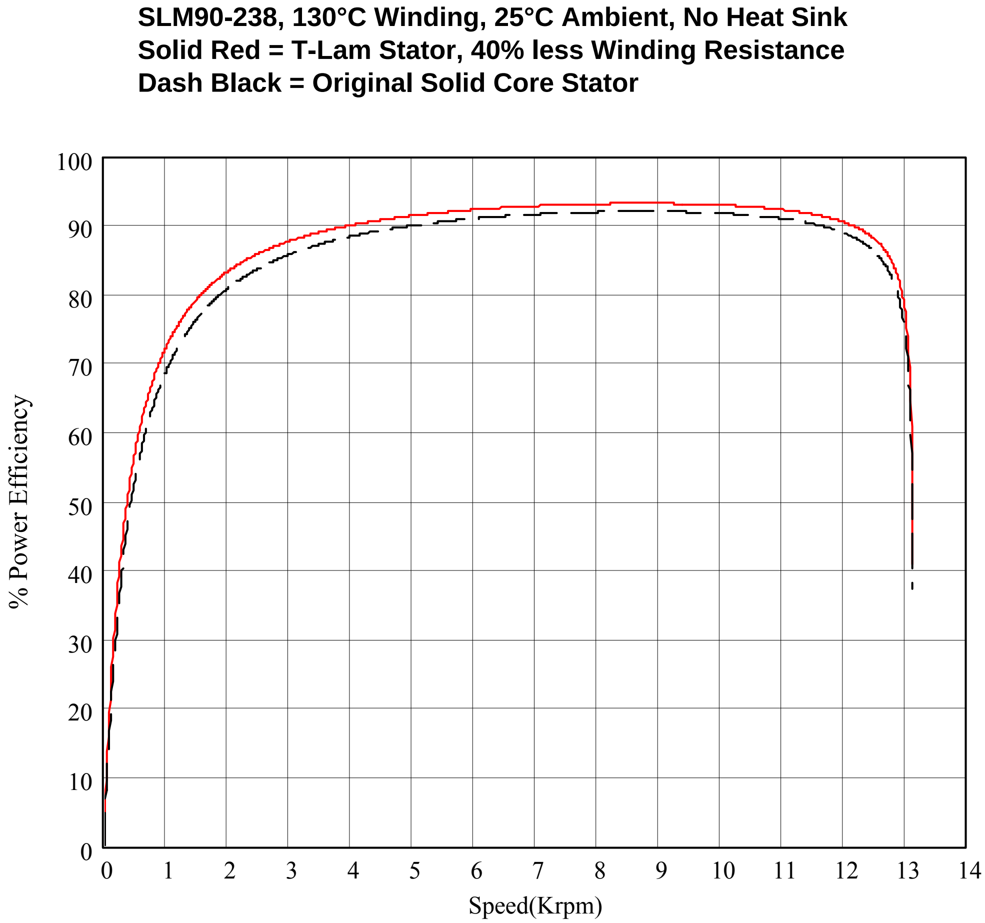


Figure 9 – SLM90-238 Continuous Power Efficiency-Speed Curve

As shown in Figure 7, 8, and 9 lowering winding resistance by 40% allows the same volume T-LAM motor to output 17% higher continuous stall torque and power with a maximum 2% higher power efficiency compared to the original Solid Core motor when both motors are operated with the same 130°C winding and 25°C ambient temperature and with no heat sink. Furthermore, it is later shown if you operate the T-LAM motor with less than maximum allowable continuous Torque-Speed and Power-Speed then it provides up to 5% higher power efficiency compared to the original Solid Core motor because the winding now operates at less than its 130°C rated temperature and the winding's resistance is even lower. Hence, 40% lower winding resistance allows the T-LAM motor to have measurably higher torque and power density along with higher power efficiency compared to the same volume Solid Core motor.

Potting a T-LAM Stator using Thermally Conductive Epoxy

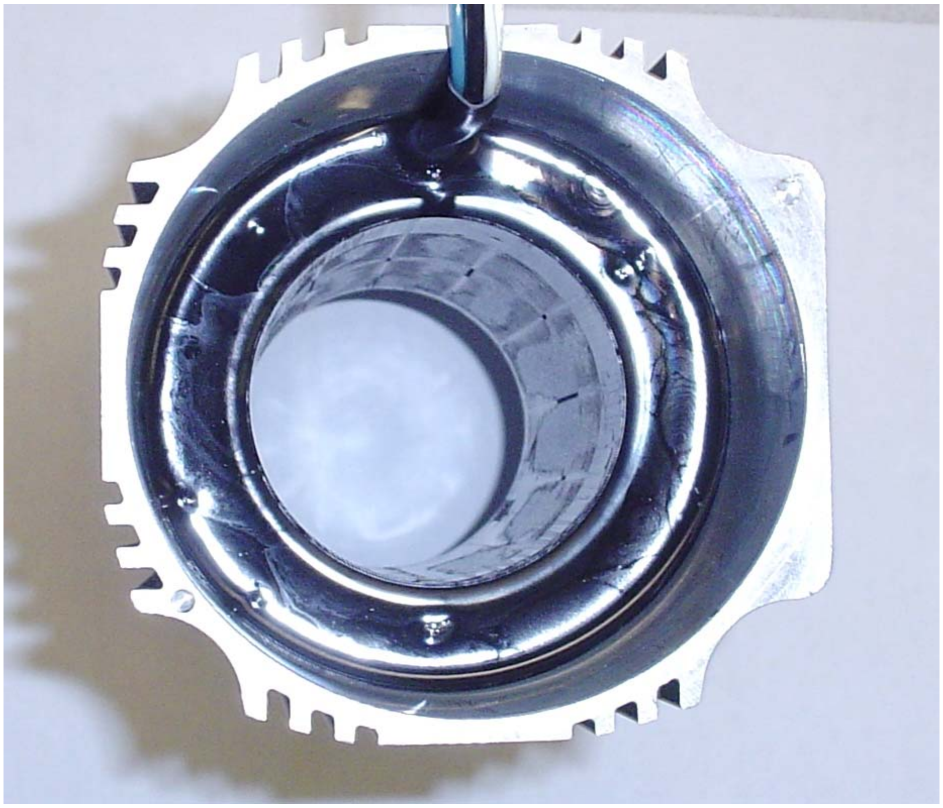


Figure 10 – T-LAM Stator Potted with Thermally Conductive Epoxy

Besides lowering the winding resistance, all Exlar T-LAM motors and actuators are potted using a thermally conductive epoxy instead of impregnating the winding using a varnish that's still typically used by most motor manufacturers. The particular epoxy used by Exlar is recognized in a UL-1446 insulation system as having a Class 180 H (180ºC) temperature rating. Actual measurement shows that potting the stator winding with a thermally conductive epoxy lowers the winding to ambient thermal resistance, R_{th}(ºC/watt), by 50% compared to impregnating the same winding with a varnish. Figure 10 shows T-LAM stator potted in its aluminum housing while Figure 11 shows a cut cross-section of the stator so you can see how the winding is completely encapsulated by the epoxy thereby improving heat transfer between the winding and the surrounding T-LAM core structure.

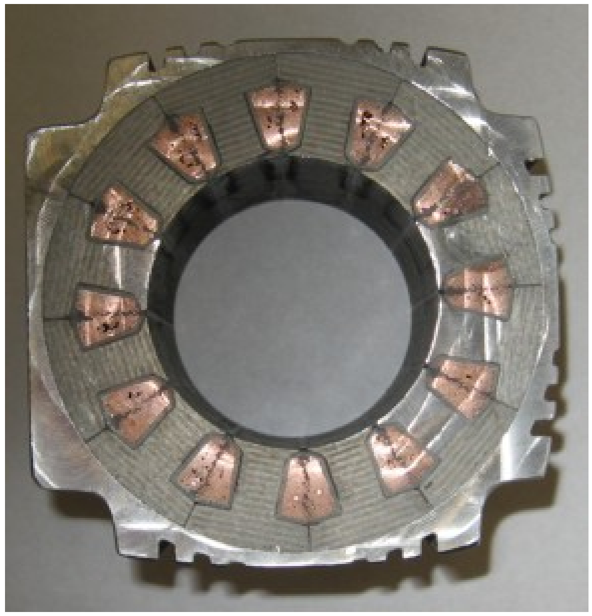


Figure 11 – Cross-Section of Potted T-LAM Stator

To see the combined affect of 40% lower winding resistance along with 50% lower thermal resistance look at Figure 12, 13 and 14. Figure 12 shows the actual, continuous torque-speed curve for the SLM90-238 while Figure 13 shows its continuous power output and Figure 14 shows its power efficiency with a free standing motor attached to no heat sink and operating at its 130°C rated winding temperature and 25°C ambient temperature.

As you can see in Figure 12 and 13, potting the T-LAM stator using thermally conductive epoxy lowers its winding to ambient thermal resistance by 50%, and produces a motor that has 45% higher continuous stall torque and 63% higher power output compared to the original Solid Core motor. Hence, the T-LAM motor lives up to its claim of having significantly higher continuous torque and power density. However, Figure 14 is somewhat counter intuitive because we see that instead of having higher power efficiency a potted SLM90-238 motor actually has the same or only slightly higher power efficiency between 0-8Krpm compared to the original Solid Core motor. Although, above 8Krpm it has noticeably higher power efficiency such that at 13Krpm the SLM90-238 actually has 10% higher power efficiency compared to both a Solid Core and the T-LAM motor impregnated with varnish. Furthermore, between 13.3-15Krpm the potted SLM90-238 is infinitely more efficient because the velocity dependent power loss due to friction and viscous damping does not allow the varnished motor to produce continuous torque output above 13.3Krpm without exceeding its 130°C rated winding temperature. Therefore, the question becomes what prevents increased power efficiency below 8Krpm when you pot the motor with thermally conductive epoxy even though the thermal resistance is reduced by 50%?

SLM90-238, 130°C Winding, 25°C Ambient, No Heat Sink
Dash Blue = T-Lam - 40% less R, 50% less Rth
Solid Red = T-Lam - 40% less R
Dash Black = Original Solid Core

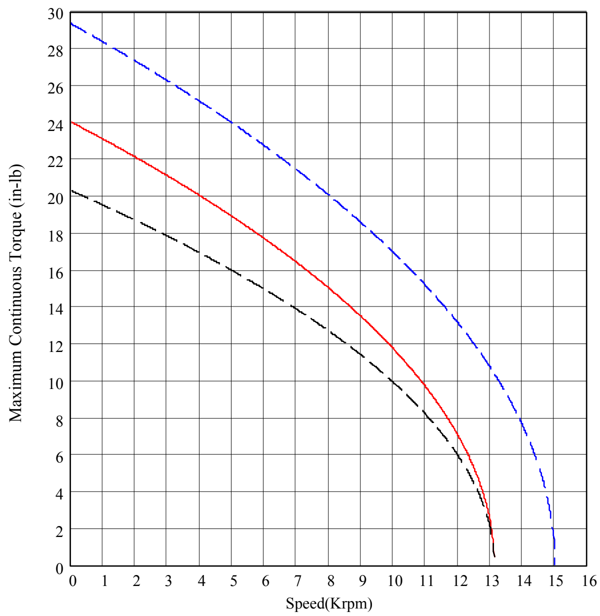


Figure 12 – SLM90-238 Continuous Torque-Speed Curve

SLM90-238, 130°C Winding, 25°C Ambient, No Heat Sink
Dash Blue = T-Lam - 40% less R, 50% less Rth
Solid Red = T-Lam - 40% less R
Dash Black = Original Solid Core

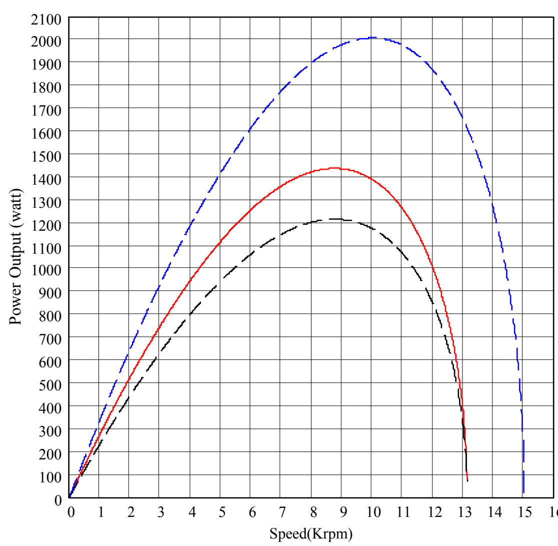


Figure 13 – SLM90-238 Continuous Power-Speed Curve

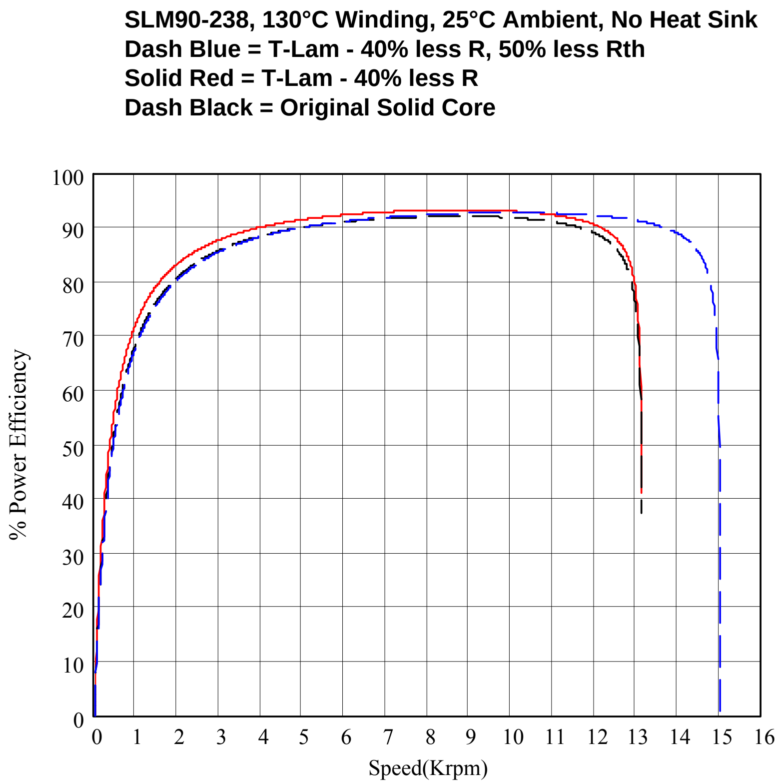


Figure 14 – SLM90-238 Continuous Power Efficiency Curve

To answer to this question look back at equation (1) and (3). Initially, the winding resistance for the T-LAM motor is 40% lower compared to the original Solid Core design due to increased slot fill and less end turn waste. Hence, at each current level, "I" amperes, there is less I^2 R power loss allowing the T-LAM motor to output higher continuous torque and power at higher efficiency because the velocity dependent viscous damping and friction power loss remains the same for both types of motor. Therefore, even though a varnished T-LAM motor can output 17% higher continuous torque and more power over its entire velocity range the 17% higher current value in combination with 40% lower winding resistance produces less I^2 R power loss and the motor has higher power efficiency shown in Figure 9. However, potting the T-LAM motor with thermally conductive epoxy lowers the winding to ambient thermal resistance by 50% and further increases the maximum allowable power dissipation inside the motor by the same 50%. Because the winding's electrical resistance remains the same the increase in current needed to produce more torque and power output results in higher I^2R power loss and the lower R_{th} does not allow for higher power efficiency until the SLM90-238 gets above 11Krpm as shown in Figure 14. Therefore, the key element to obtaining higher power efficiency over the motor's entire continuous velocity range is to lower the winding's electrical resistance which is accomplished by operating the motor at a lower winding temperature.

The electrical resistance for the copper magnet wire used to construct the motor's electrical winding depends on winding temperature and the accepted international standard for the change in a copper winding's change in resistance with temperature amounts to,

$$R(T) = R(T_0)\left(1 + .00393(T - T_0)\right) \quad \textbf{(4)}$$

In equation (4), T_0, is the reference temperature (typically 25°C) and T (°C) is the new winding temperature either above or below T_0. Using equation (1) you can calculate for a copper winding that if its electrical resistance is specified at 25°C then at 130°C its electrical resistance increases by a factor of 1.4126 or 41%. However, if the winding operates at 100°C then the increase in resistance is only 1.294 and this is 9% less than its 130°C value. Hence, if instead of operating the SLM90-238 with its maximum continuous torque (dashed blue in Figure 12) you instead operate it with the lower torque (solid red in Figure 12) then it still produces 17% higher continuous torque higher power compared to the original Solid Core motor (dashed black), but with the higher power efficiency shown in Figure 15 as the dashed brown line. The reason being the winding temperature only rises to 100°C because with 50% lower thermal resistance and with the less current needed to produce the lower torque and power values in combination with 9% lower winding resistance there is less I^2 R power loss thereby decreasing the winding temperature and this increases the motor's power efficiency.

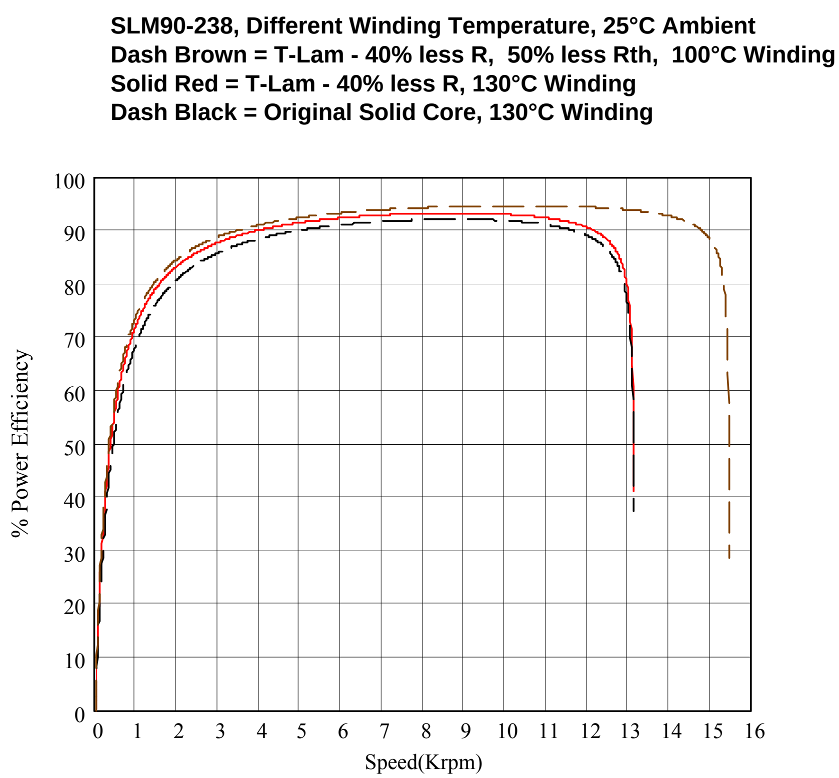


Figure 15 – Improved Power Efficiency with Lower Winding Temperature

As shown in Figure 15, decreasing the winding temperature below its 130°C rated value down to 100°C still allows the SLM90-138 T-LAM motor to produce 17% higher continuous torque and power, compared to the original Solid Core motor but with 3-10% higher power efficiency and it also allows for higher velocity operation compared to the same motor if its stator impregnated with varnish instead of potting it with thermally conductive epoxy. However, if you take full advantage of the 45% higher continuous torque and 63% higher power from the SLM90-138 then Figure 14 shows it provides 45-50% higher torque and power density along with higher power efficiency compared to the original Solid Core motor. Therefore, without question the Exlar T-LAM motor has now become the new standard of comparison for all BLDC servomotors in terms of their continuous torque and power density along with maximum power efficiency.

References

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