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Comparing Peak Torque: ECM and a Typical Robot Actuator Motor

ABSTRACT

The selection of a motor for actuator and robotics applications is often reduced to a comparison of key parameters, such as the specific torque, or specific peak torque. This reductionist approach is appealing, but comparison of the capabilities and limitations of motors with fundamentally different physics is more involved. Key parameters do not always translate meaningfully across motors of different sizes, construction, or application.

This note compares limits and ratings for typical iron-core servomotors versus ECM's air-core axial-flux motors. The comparison focuses on the TQ ILK-E50x14, and the ECM small servo (SSM), and the peak torque ratings that are important to many dynamic actuation and robotics motor design opportunities. The note concludes with a discussion of results and actuator design in the ECM PCB stator environment.

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1 Introduction

Motors for robotic joints are often sized from datasheet torque numbers, particularly nominal and peak torque. These numbers are derived by the manufacturers based on various physical limits, and are a reasonable basis of comparison between motors when the same physical limits and assumptions apply equally, i.e., when the motors are of similar construction. When magnetic circuit behavior, nonlinear torque/current behavior, or thermal limits that depend on duty cycle and mounting are significantly different, the comparison is necessarily more nuanced.

ECM builds PCB-based axial-flux motors for applications where motion quality and packaging matter, including robotics. Designs are tunable, so comparisons should ask what limits torque for your use case, not which number is larger. There is no single canonical ECM motor on one datasheet but rather a range of options that can be tailored to the application.

ECM's motors use an air-core winding, with little conventional armature reaction. That results in a torque-current curve that stays linear to higher currents than many servomotors, where "peak" is often defined by departure from small-signal torque/current relations. For robots, that matters for current control, waveform fidelity, and how much peak current a maneuver needs. Waveform distortion may require higher peak current delivery from the controller.

When linearity is not the limit, short bursts of torque are often bounded by how much loss the winding and magnets can tolerate, and for how long. ECM motors can deliver very high pulse torque for brief intervals, with the practical ceiling set by time-limited thermal ratings rather than a linearity point.

This note separates linearity-limited peaks and thermal limits, and explains why an "apples-to-apples" comparison is difficult to achieve when motors exhibit different behaviors with respect to those limits.

2 Physical Considerations on Peak Torque

Peak torque is a common robot actuator metric. All other things being equal, a higher peak torque usually means greater dynamic performance. Peak specific torque, or the ratio of peak torque to actuator mass, promises to give some sense of performance that is less dependent on motor mass and torque rating. Torque density, or the ratio of torque capability to volume, might also be useful. These metrics, however, are not intrinsic constants of a "motor technology." They depend on magnetic design, winding, cooling path, and how the vendor defines "peak."

Axial flux motors, such as those produced by ECM, generally require a smaller axial length but a larger diameter than radial flux motors. It is generally not the case that an ECM motor will fit in the space allocated for a radial flux machine. However, where axial length is constrained, the form factor can provide significant advantages.

All of these metrics require consideration of how to rate torque and peak torque. This is where the physics of ECM motors versus conventional options must be considered. Mechanisms that limit torque in conventional robot motors include thermal, linearity, and armature reaction.

2.1 Peak Torque

Armature reaction refers to the effect that the magnetic field produced by the armature (or stator) has on the main magnetic field produced by the permanent magnets in the rotor. It suggests the possibility that the plot of torque as a function of current has a well-defined maximum. At zero speed and under a presumed thermal condition, this number can be calculated as a function of the magnetic materials and configuration of the machine, making it a good candidate for the datasheet. It might be possible to achieve this number in a short time under ideal conditions, but it is generally not possible to maintain a constant temperature in the machine under operation.

2.2 Linearity Limits

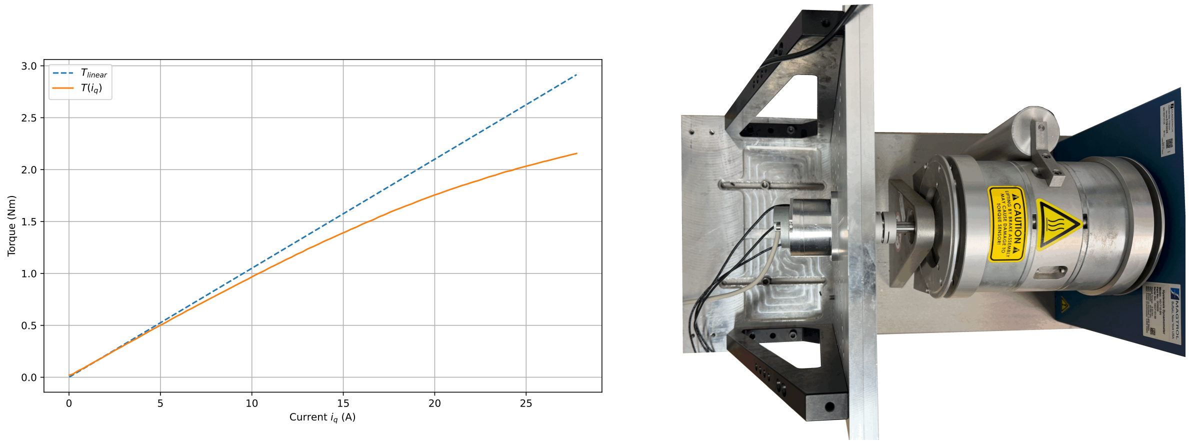


Figure 1: A nonlinear torque response to current for a machine with an armature core (TQ ILK-E50x14) and the same machine on ECM's motor performance test stand. ECM provided a case and shaft for the frameless TQ for purposes of test. This has a significant impact on thermal conditions.

Linearity limits tend to be more conservative measures of peak torque. In this scenario, a machine is rated with a peak torque corresponding to the point on the torque/current relationship where the torque produced by the machine drops a certain percentage from the linear, small-signal model. To first order, a permanent magnet machine produces torque proportional to current, so this departure from expectations means that nonlinear behavior is important, and has practical implications.

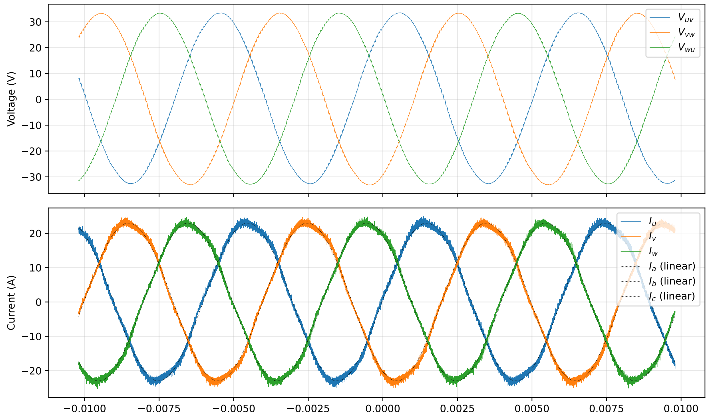


Figure 2: Voltage and current waveforms for a machine with an armature core (TQ ILK-E50x14). The current waveforms are distorted due to the nonlinearity of the motor.

Current waveforms under operation may become distorted and current control loops may require more conservative compensation strategies to remain stable. These conditions increase costs and decrease performance if the motor is regularly operated in these regimes. Harmonics in the current waveform can also cause torque ripple and additional losses in the motor, increasing the temperature of the machine.

ECM machines maintain a high degree of linearity in the torque/current relationship, especially under instan-

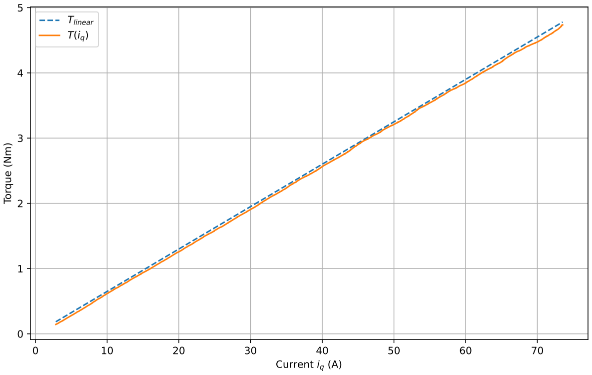


Figure 3: Torque as a function of current for an ECM motor. The torque remains linear well past the nominal torque rating of the machine.

taneous conditions. Optimization choices can influence this, but the linear range often extends significantly beyond the steady-state rating. Operating temperature is also important when considering linearity, as constant or room temperature conditions are not realistic for a machine operating in steady-state at the limits of its performance. Again, the argument can be made that for short excursions, the thermal condition may be approximately constant.

2.3 Thermal Limits

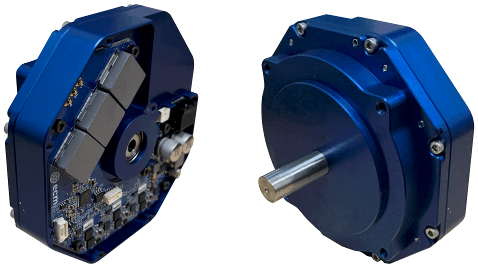
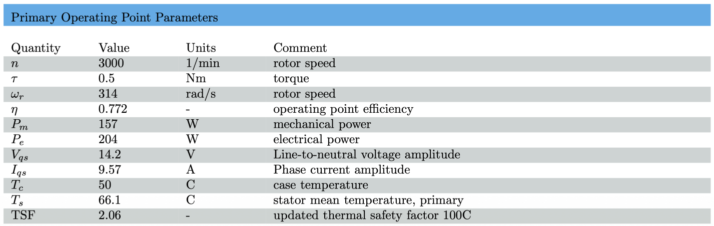


Figure 4: ECM's small servo motor with integrated absolute encoder and controller.

Thermal considerations apply to all machine types, and can be the controlling bound for any machine if the steady-state rating is important. The difficulty with thermal, and perhaps why thermally simplifying conditions appear on datasheets, is that the thermal condition of the machine is highly dependent on the use case and the manner in which the machine is installed. Temperature rise will impact magnet operating point, insulation, copper resistance, and generally lower the torque as a function of current curve.

ECM machines are generally quite linear in terms of the torque/current relationship. The steady-state rating is determined with a thermal model that treats the case temperature as a boundary condition, often selected as a worst-case temperature. In many practical cases, an ECM motor's maximum torque is determined more by controller limits than the maximum torque of the machine, especially when the controller has been selected with the nominal torque specification in mind. The absolute instantaneous peak torque can be estimated based on an internal thermal hotspot model and the properties of the materials.

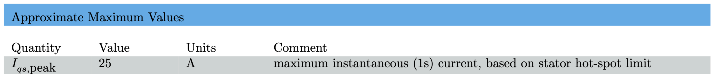
For example, consider the snippets of the datasheet for the ECM small servo below:



Primary Operating Point Parameters

Quantity	Value	Units	Comment
n	3000	1/min	rotor speed
τ	0.5	Nm	torque
ω_r	314	rad/s	rotor speed
η	0.772	-	operating point efficiency
P_m	157	W	mechanical power
P_e	204	W	electrical power
V_{qs}	14.2	V	Line-to-neutral voltage amplitude
I_{qs}	9.57	A	Phase current amplitude
T_c	50	C	case temperature
T_s	66.1	C	stator mean temperature, primary
TSF	2.06	-	updated thermal safety factor 100C

Figure 5: The design operating point for ECM's small servo motor.



Approximate Maximum Values

Quantity	Value	Units	Comment
$I_{qs,\text{peak}}$	25	A	maximum instantaneous (1s) current, based on stator hot-spot limit

Figure 6: The datasheet thermal hotspot current and torque limit for ECM's small servo motor.

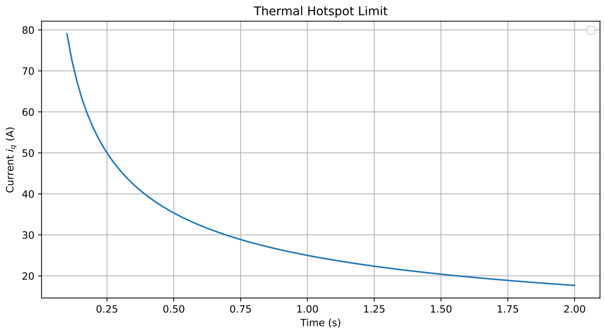


Figure 7: The thermal hotspot limit for a given time duration for ECM's small servo motor.

The primary operating point of 0.5 Nm at 3000 RPM requires a motor current of 9.57 A. The thermal hotspot current is 25 A for 1 second. The thermal hotspot limit for 0.25 seconds will be 50 A.

2.4 Comparing Torque Limits

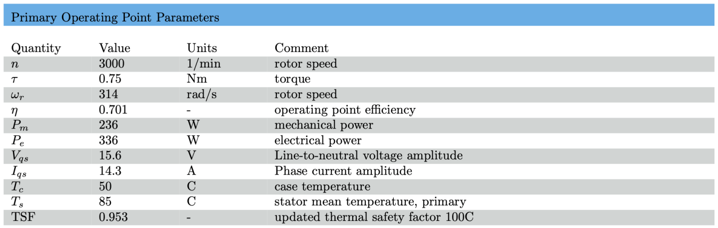
If the mechanisms and underlying assumptions around a particular rating (like peak specific torque) are the same, there is a rational basis for asserting that one machine is superior (or inferior) to another by comparing those ratings. However, this argument gets weak if the mechanisms controlling a figure of merit are fundamentally different, and is further compromised if one rating ignores effect(s) that are critical to the other. The solution might be to pick the dominant limit depending on motor type, but then the question becomes which figures of merit are actually relevant to the application.

For example, consider the TQ ILK-E50x14 frameless servomotor kit. The frameless machine has a mass of 134.75 g and has a **continuous rated torque of 0.53** N m **at a temperature of 20** °C. The peak torque is defined by a limit of 20% departure from linearity at 1.72 N m. This results in a rated specific torque of 3.93 $\mathrm{N\,m\,kg^{-1}}$ and a peak specific torque of 12.76 $\mathrm{N\,m\,kg^{-1}}$.

The ECM small servo motor (SSM) has a frameless mass of 393 g. It was not designed to maximize specific torque, and it was designed with a specific enclosure rather than for frameless application. It has a nominal continuous torque rating of 0.5 N m, based on temperature and efficiency constraints and on a presumed convective heat transfer coefficient from the case to the ambient. It is possible, in ECM's software environment, to re-rate a given design for different temperature conditions. The SSM, when re-evaluated with a fixed case temperature of 20C, can provide 1Nm in the steady-state without developing objectionable internal temperatures. In this condition, it is perhaps most comparable to the TQ datasheet, and this illustrates that the ECM SSM is not strictly comparable to the TQ ILK-E50x14. The same calculation was done with a case temperature of 50C. If the SSM is operated for 110 ms, it can conservatively produce 5.06 N m of torque which results in a specific torque density of 12.87 $\mathrm{N\,m\,kg^{-1}}$.

These results are compiled in a table, below. The comparison based on thermal performance is highlighted in the first three rows. Based on the closest available thermal comparison, which is the ECM SSM at 20°C. The continuous specific torque of the TQ machine exceeds that of the ECM SSM by roughly 50%.

Peak torque performance is shown in the last two rows of the table. In this comparison, the mechanisms of the limits are fundamentally different. The TQ ILK-E50x14 is linearity limited, and in most installations will likely have a thermal bound that is not easily quantifiable. The SSM is limited by an internal hotspot temperature and the duration of the peak. In this analysis, the peak specific torque of the motors is comparable.



Primary Operating Point Parameters

Quantity	Value	Units	Comment
n	3000	1/min	rotor speed
τ	0.75	Nm	torque
ω_r	314	rad/s	rotor speed
η	0.701	-	operating point efficiency
P_m	236	W	mechanical power
P_e	336	W	electrical power
V_{qs}	15.6	V	Line-to-neutral voltage amplitude
I_{qs}	14.3	A	Phase current amplitude
T_c	50	C	case temperature
T_s	85	C	stator mean temperature, primary
TSF	0.953	-	updated thermal safety factor 100C

Figure 8: A rerun of an elevated operating point for ECM's small servo motor.

Table 1: Comparison of motor torque performance.

Motor	**Description**	**Torque** (N m)	**Specific Torque** ($\mathrm{N\,m\,kg^{-1}}$)
TQ ILK-E50x14	Continuous Rating @ 20°C	0.53	3.93
ECM SSM	Case at @ 20°C	1.0	2.56
ECM SSM	Case at @ 50°C	0.75	1.91
ECM SSM	Nominal Rating	0.5	1.28
TQ ILK-E50x14	Linearity Limit	1.72	12.76
ECM SSM	Peak for 110ms	5.06	12.87

3 Discussion

The data and analysis provided above show that datasheet specific torque and other ratings are highly dependent on the assumed circumstances.

In the thermal cases in the table above, the validity of comparison between the two motors seems strongly dependent on the rest of the system. The integration of a reduction or the actuator will determine system mass. The surface area and nature of the mounting surface will be important to thermal performance. Because the shapes of these motors are so different, the respective solutions will be difficult to compare directly.

In the peak torque cases in the table, the two motors seem relatively comparable. Yet, in this comparison, the ECM SSM is producing nearly three times the torque of the TQ. Is it appropriate to look at peak specific torque in motors that differ by a factor of three, when the limiting factors are also different?

Specific torque does have some applicability. If a conventional radial flux motor design is, for example, in the ballpark of a desired torque rating, it might be reasonable to assume that the motor can be lengthened (shortened) by adding (removing) stator and rotor laminations to achieve a new desired torque rating, all else remaining the same. The new machine might have roughly the same specific torque and other properties because mass, area, and torque scale linearly in this case. A single parameter, or slope, is sufficient. The reductionist beauty of this approach is that exact definition of the torque rating is not critical. Whatever the thermal and nonlinearity details are, they should apply in a scaled manner.

ECM motors are not confined to grow in one dimension, although they can be stacked axially. The optimizer operates in a more-than-ten-dimensional space. Among these variables, the most important is overall radius. The multiplicity of arrangements of PCB stator features grows quickly with radius, but neither mass nor torque nor thermal features scale linearly. A single parameter is neither useful nor necessary as a predictor of nearby designs in the PCB stator environment.

The problem is that the nature of torque production *is critical* to motor suitability for joint and actuator design. In many robot joint design problems, a plot of time-sampled torque and speed magnitudes under operation will show a clustering of torques and speeds close to the axes and origin. Peak torques are encountered in transient excursions that are large compared to median torques. It is not so easy to determine a nominal and peak torque motor requirement. The load is essentially a dynamic system, not a data point.

ECM can design motors to achieve specific performance criteria given *a locus of torque-speed data*. ECM (and others) can produce a model of motor performance that can accept a torque speed trajectory. Given this modern reality, ECM suggests that the motor-to-motor comparisons for complicated torque-speed requirements be addressed as follows.

1. Design (or select) motors suitable to the torque and speed dynamic requirements. This step incorporates a process and results in a design.
2. Simulate the performance of the motor(s) over the trajectories of the system (in torque, speed, and acceleration). Apply similar thermal boundary conditions.
3. Repeat steps 1 and 2 as needed.
4. Compare motor features and performance directly, using the measures that matter.

With this procedure, the impacts of motor selection, catalog spacing, and performance are taken into account, as they should, because they matter to the solution. ECM's PrintStator software shines here thanks to its fast and accurate simulation capabilities, but, in principle, the procedure is applicable to all machines.

Unsuccessful potential applications of ECM PCB generally involve form-factor, i.e., whether or not a flat motor fits in the space allocated. Successful ECM PCB stator motor applications in robotics and actuators generally benefit from some combination of form factor (flat), design appropriate to the problem, quality of motion, linear response through high peak torque, or ability to integrate advantageously with a reduction.