PSA: Your Motor Curves Are Wrong

This is a short PSA about motor curves, and how they change drastically once you limit current.

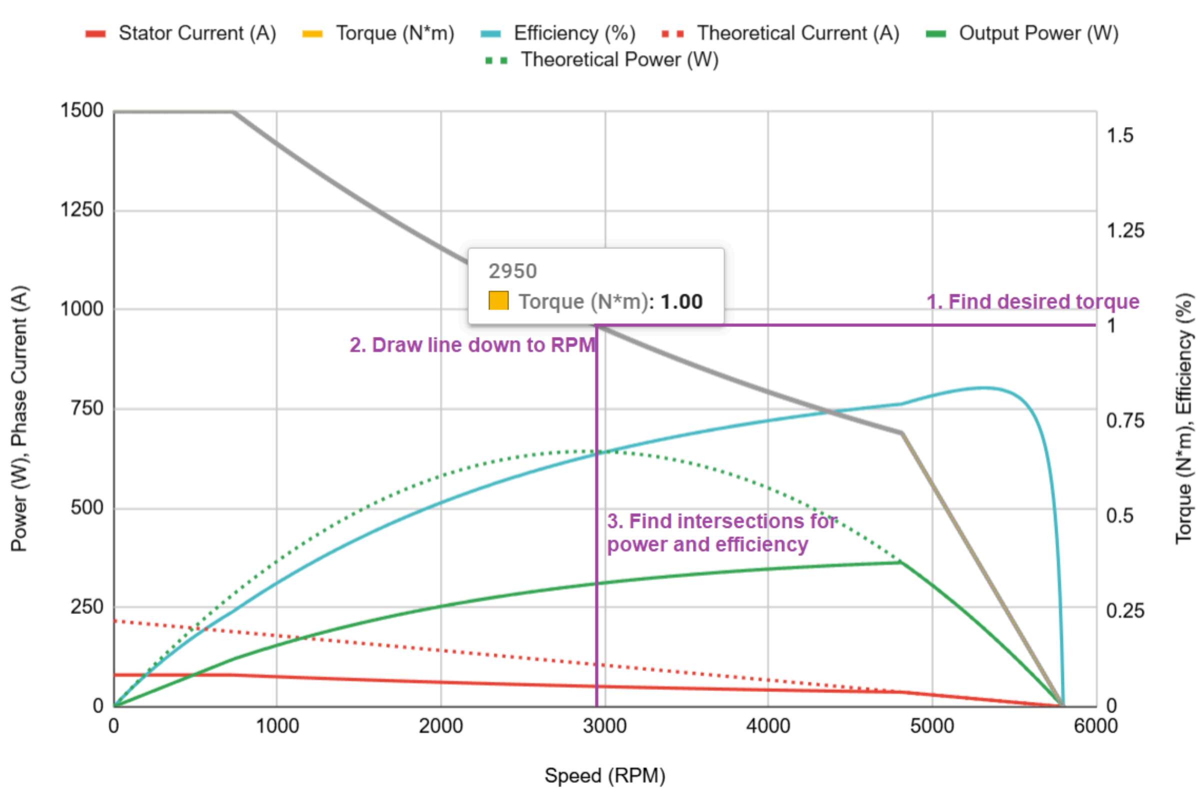
A lot of manufacturers like to publish “theoretical” motor curves. However, not only are these limited by battery supply current, they are also very strongly limited by stator current. I’m going to show what a “Limited” motor curve looks like for brushless motors once you incorporate current limits.

I have omitted brushed motors from the dataset due to their terrible linearity - brushed motors rapidly lose torque output once any amount of heat builds up, and their torque often does not vary linearly with current as one would expect. As a result, any theoretical motor curve for a brushed motor falls apart very quickly.

Reading Motor Curves

For information on how to read the charts in this doc, refer to the tutorial here: https://motors.vex.com/introduction

TL;DR: Set up your current limits, motor, gear ratio, and supply voltage. Find your desired torque output. Then, follow the torque curve down until you hit that desired torque. Draw a straight line down to the X-axis to find your speed, power, and efficiency at that torque.



Constraints Used

Because stator current is proportional to torque in motors, there is a maximum stator current you can push in a drivetrain before you start slipping your wheels. Plus, FRC motor controllers are only capable of doing ~100-150A peak current (100A for a Spark MAX, 150A for a Talon FX), which is nowhere near the 200A+ stall current of some of these motors.

A fairly aggressive example is a 150lb robot geared for 18.4fps (5.5:1 on an X60 with 4" wheels) with a wheel friction CoF of 1.1, needing around 85A to slip the wheels. **I'll pick a generous stator current limit of 90A as the upper bound.**

Supply current limits will be checked at 60A and 40A. I would recommend running a drivetrain closer to 60A to exploit the 40A breaker curve as much as possible, but 40A is just fine for many mechanisms.

In general, stator current limits protect the controller, the motor, and slippage. Supply current limits limit total power draw and protect breakers. The square of stator current is proportional to heat generated by the motor (losses).

Data Sources and Calculation Details

Data was taken from the following sources, though only CTRE data was used in the final comparison:

- REV (https://docs.revrobotics.com/brushless/neo/compare)
- Vex (https://motors.vex.com/)
- CTRE (https://ctre.download/files/datasheet/Motor%20Performance%20Analysis%20Report.pdf)
- WCP (https://docs.wcproducts.com/kraken-x60/kraken-x60-motor/overview-and-features/motor-performance)

When possible I prefer to use CTRE data, as it seems to match up most closely with my measurement of stator resistances and theoretical values[1]. All comparisons shown below are done with CTRE data, but you can copy the calculation spreadsheet here and try it out for yourself if you want to play around:
https://docs.google.com/spreadsheets/d/1SNRdN0A11YOomOI4o7zAs0QHjqGI9kASutMxyUvZtrY/edit?gid=567574955#gid=567574955

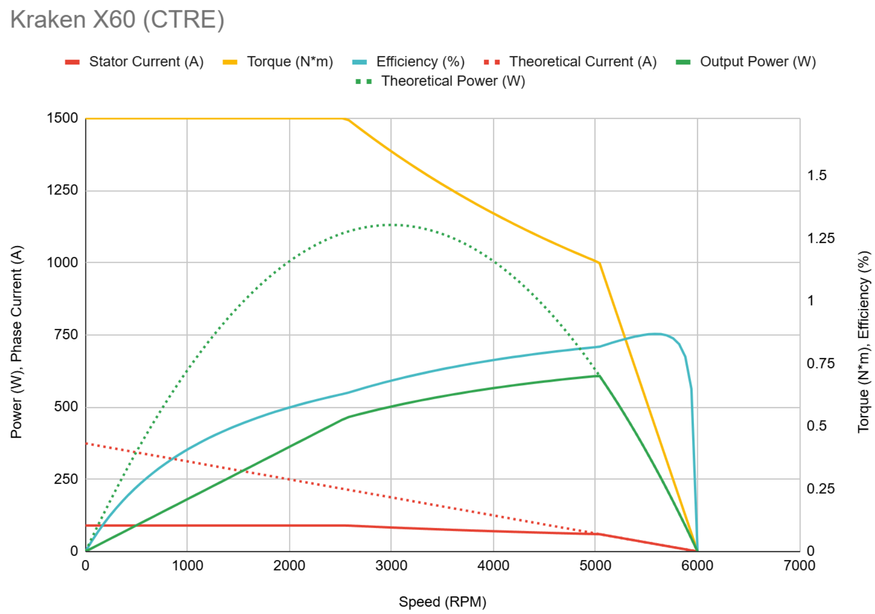
[1] In general, if you measure the stator resistance of a motor from phase to phase, you can find the stall current to be equal to 12V / (sqrt(3) * phase-phase resistance) in 6-step (trapezoidal) commutation. In FOC, the stall current will increase by up to 33% depending on how well the firmware is made. CTRE's data matches up with these observations. CTRE also has the most consistent kV*kT for each motor, which is expected to be a constant for all motors.

Just twiddle the “Motor Playground” tab to see the effects of different current limits and voltage compensation settings.

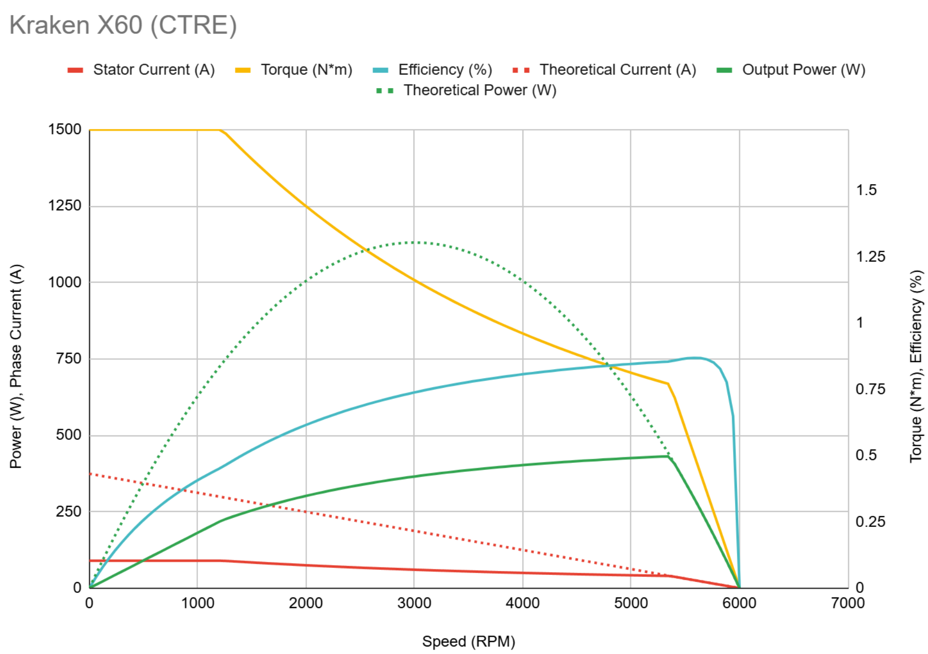
There is a small bug in the calculation of supply current limits that causes it to be < 1A off. I have not tracked the source of this down yet, and as it does not dramatically change the curves and is similarly off between motors, I have no reason to fix it right now. If you find the source of the bug, or any other bugs, please let me know. It’s probably related to free current handling and kV*kT imperfection.

Limited Motor Curves

Anyway, here's what a Kraken X60 in trapezoidal mode does with a 90A stator limit and a 60A supply limit. Pay attention to the solid green line - that's the actual output power of the motor at each speed with a 100% command at 12V. The dotted green line is the theoretical power from CTRE.

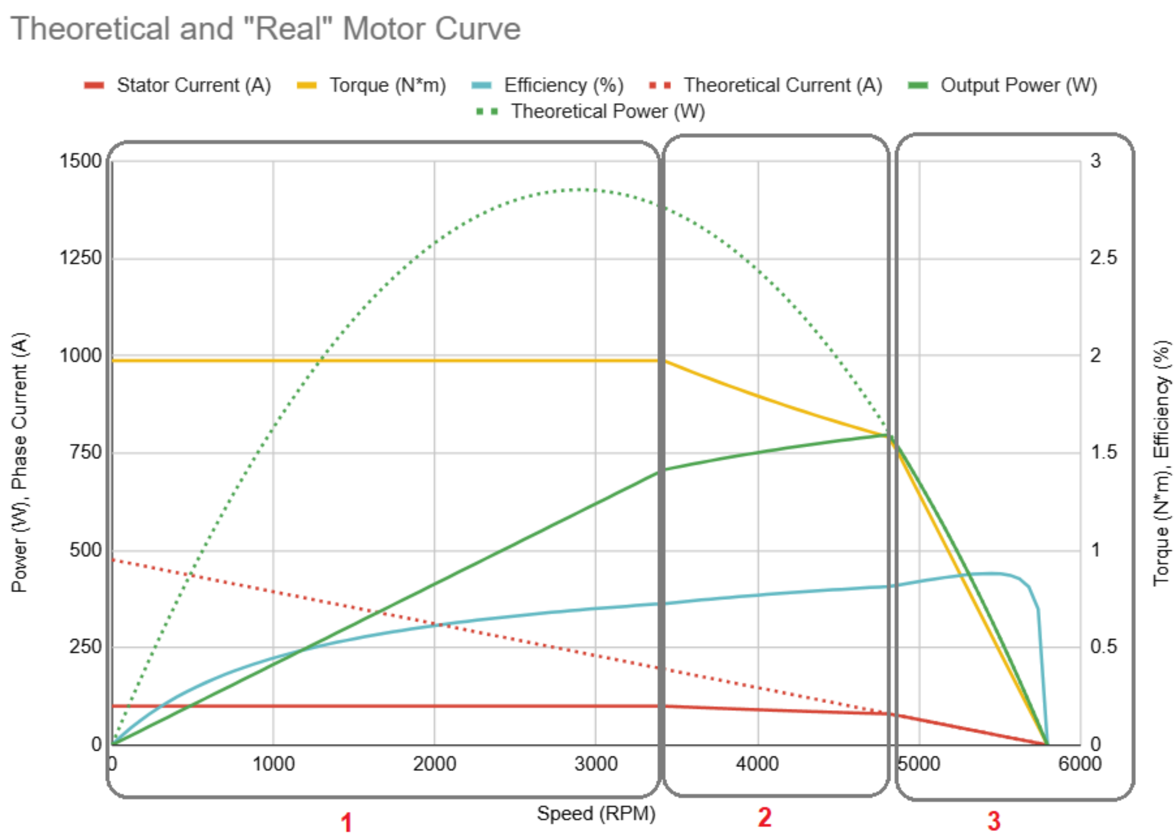


And with a 90A stator limit and 40A supply limit:



Why Does The Motor Curve Look So Weird?

Let's dig into the parts of the Limited motor curve to understand it better. I've labeled the three regions of interest as 1, 2, and 3 in the image below. This image shows a Kraken X60 with a 90A stator current limit and an 80A supply current limit.



Region 1

During the linear rise in power (the region labeled "1"), the torque is constant, as stator current is kept constant. **Stator current is directly proportional to torque.** The supply current is below the limit due to lower voltage across the phases and low total power output. The motor dissipates heat equal to the stator limit squared times the stator resistance, which in the X60 example above, is around 250W - very hot!

Region 2

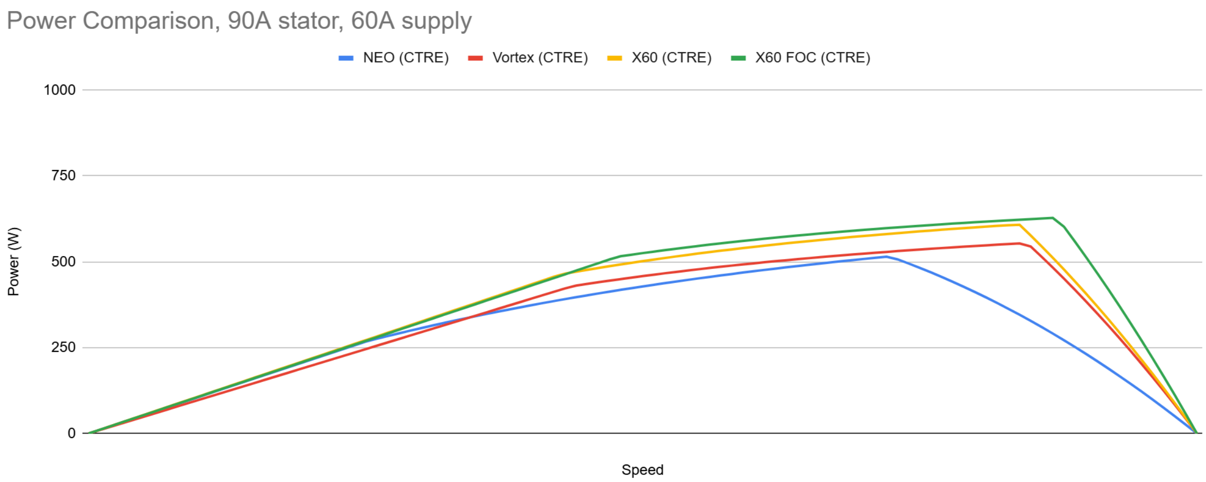
As back-EMF rises from the motor spinning faster, voltage across the phases rises, power output rises, and the supply current limit kicks in to limit total power draw. This is region "2", where we are limited by the power allowed to the controller. In the above case, 80A @ 12V is 960W, so the sum of losses and output power is 960W in this region.

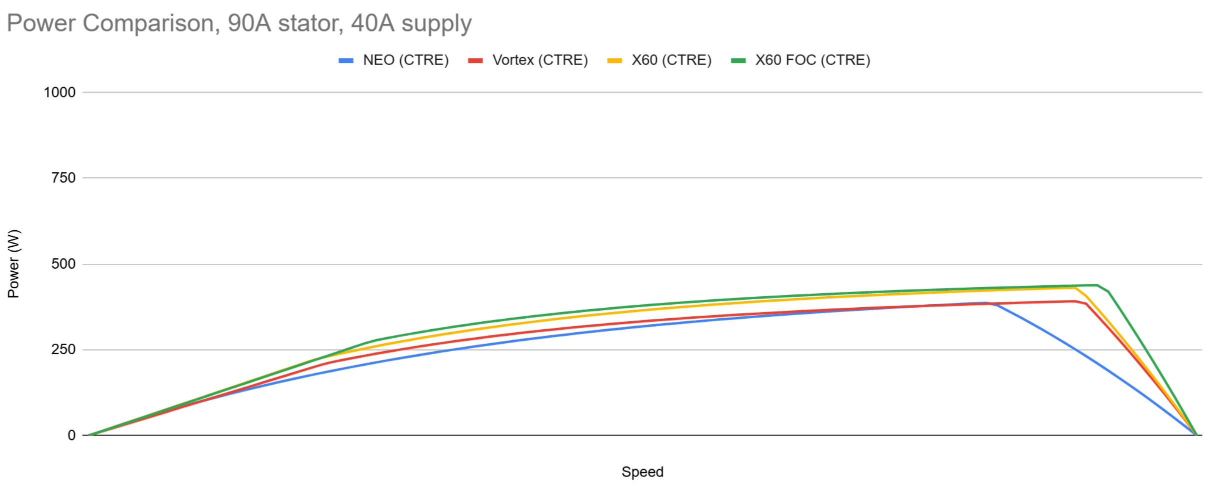
Region 3

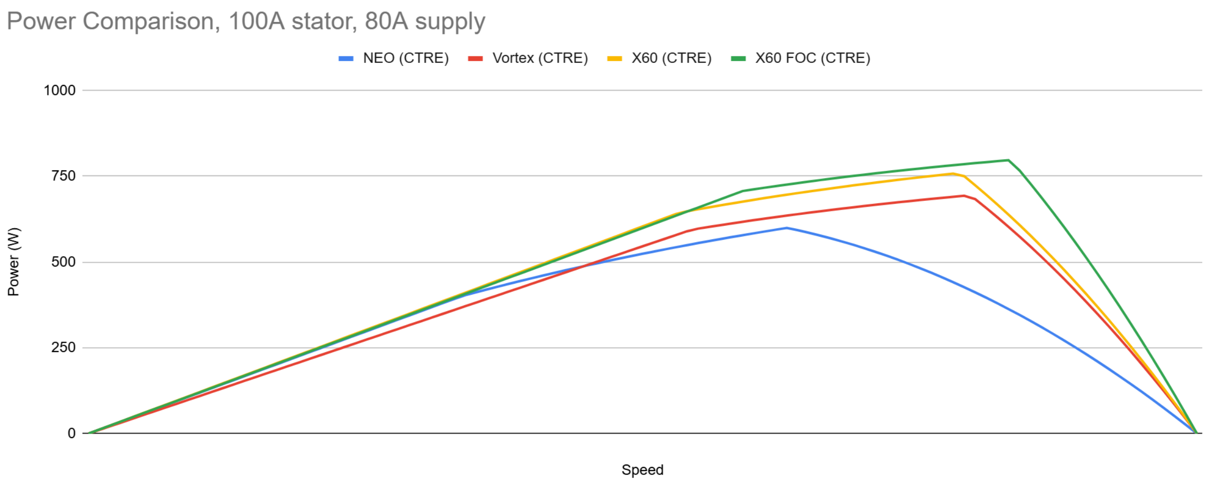
Finally, in region "3", the power output is motor-limited. Here, the motor operates below the supply and stator current maximums, and thus is limited entirely by the physical characteristics of the motor at 12V. The power output and torque rapidly fall off.

All-Motor Comparison

A comparison of all the large motors' power outputs with a few different current limits is shown below. This chart normalizes for speed, that is, it assumes that you gear each motor to the same output speed. Comparing motors without adjusting gear ratios is basically pointless, as you should always select your gear ratio with a motor in mind to get your desired output characteristics.







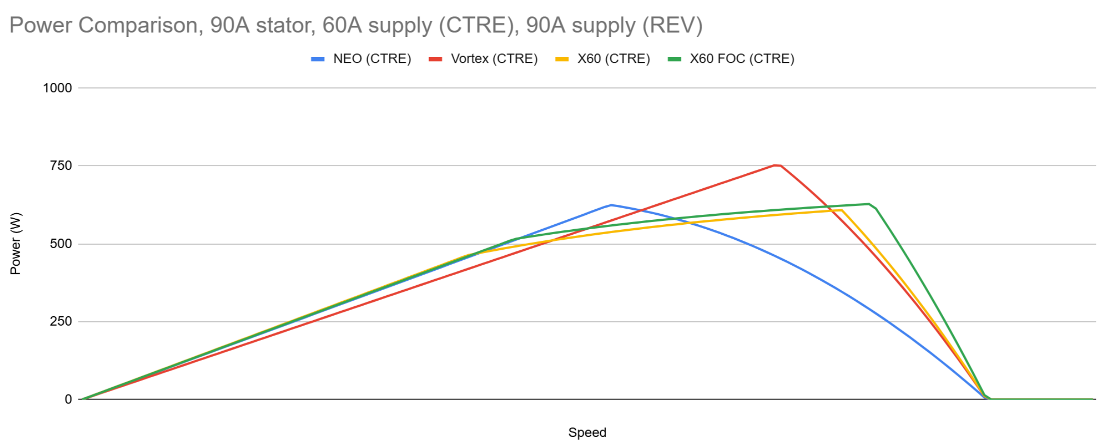
All of the motors in FRC fare similarly until you get above a certain speed to reach the 2nd region, determined by the stator limit. Supply limits affect lower power motors more than higher power ones. Overall, low current limits will make the differences between motors seem more slight. Certainly, between the Kraken X60, X60 w/ FOC, and NEO Vortex, the differences become quite small considering that you're usually running a mechanism below 50% of its free speed. If you run a 60A stator limit and a 40A supply limit, even the NEO starts punching in the same weight class under ~80% of free speed when it enters the 3rd region.

The NEO Vortex loses a bit of output power over the whole curve due to its reduced efficiency. Its free current its higher, and the product of its kT and kV is lower than that of some of the other motors on the market - including the NEO 1.1.

Setting a higher current limit on the stator will get you more power out of a motor in the 1st region. Manufacturers have not released thermal data for the Kraken X60 or the NEO Vortex at time of writing, making it difficult to compare them fairly with each other or with other motors. A motor with less theoretical power than a Kraken X60 can absolutely outperform a Kraken if it can sustain more stator current for a longer period of time!

Setting a lower current limit on the supply decreases your output power, but significantly increases your efficiency, as Region 2 is more efficient than Region 1.

A really important thing to note is that at present, **REV only supports the Smart current limit, which is similar to a Stator current limit.** This means that your supply current limit effectively does not exist (is equal to your stator limit or is infinite). This can increase output power, but at the cost of efficiency (and potentially your breakers). The effect this has on motor curves cannot be understated - below is an example of a 90A stator limit compared across CTRE and REV, with a 60A supply limit in place for CTRE.



Wacky stuff. The Kraken underperforms the output power of the NEO for a small region, and underperforms over most of the curve compared to the Vortex! Obviously this is an unfair comparison, as setting the supply limits to 90A on CTRE would make them outperform the REV motors again, but this should make you consider being careful with your stator limits with REV to protect breakers, and maybe being more liberal with your supply limits for CTRE to make the most of your investment. However…

We Need Thermal Testing

There is no way to know how long any motor will last at a given stator current without manufacturer thermal testing. And the corollary to that is that there is no way to know which motor is the “most powerful” without thermal testing. There are many methods to estimate the life of a motor, but none of them are accurate compared to manufacturer test data. REV, at least, shows that at 80A stator on a NEO (355W dissipation) the motor will fail in about 45 seconds[2]. The Kraken has similar mass and will dissipate 355W with a stator current of 105A. So it’s *probably* safe to assume that running into a 90A stator limit regularly on a Kraken X60 or NEO Vortex is fine… but we can’t be sure until we get real manufacturer data. FOC and

[2] https://www.revrobotics.com/neo-brushless-motor-locked-rotor-testing/

Trapezoidal commutation may also interpret stator current limits differently. That is to say, a 90A limit on an X60 in Trapezoidal mode might last significantly longer than the same motor with a 90A limit in FOC mode.

Thermals make a huge difference in setting the stator current limit for smaller motors like the Kraken X44, CTRE Minion, and NEO 550, which have similar stator sizes, but different power output and construction. Because brushless motor curves are mostly limited by the stator and supply current limits, and not the motor itself, lacking thermal data means that **there is no way to fairly compare the output power of these motors.**

Conclusions

All this is very cool, but what's something you can actually do with the data? Here's some things to consider:

- **Upgrading your motors is an incremental change, not a fundamental one.** Tuning current limits and gear ratios correctly matters much more than picking the most powerful motor for an application.
- **Ask manufacturers for thermal testing data.** There is no way to compare the power outputs of motors fairly without knowing the safe current limits for each one. A Kraken X44 could be "more powerful" than a REV NEO by setting the stator current limit to 100A, but that's meaningless if it can only do it for two seconds - you'll burn out before even accelerating to the motor-limited part of the curve!
- **Stator current limits should be higher than supply current limits.** Your stator current limit defines your torque near stall, so it should be set higher than your supply current limit to minimize acceleration time. A stator limit that's lower than or equal to a supply limit won't do anything, as stator current will always be higher than supply current in normal operation.
- Mechanisms like flywheels should be designed to operate close to the **"true" peak power region between 60 and 80% of free speed, not the theoretical 50%.** Your output power is maximized right at the intersection of region 2 and 3 (where input current limits meet motor limits) so your recovery time will be minimized near that area.
    - However, going *too* fast (90%+) may risk moving into the sharp power dropoff near free speed. Change your gear ratios if you're in that region often.
- **Drivetrains are mostly limited by traction, not by motor selection.** Don't pick teams for Eliminations based on their motor output power alone - many factors matter, and few teams will correctly optimize their current limits, gear ratios, and wheel traction to make the most of their motors. A swerve drive with 60A stator limits on Krakens will be beaten by a NEO drivetrain with 80A stator limits.
- **You will hit your stator current limit a lot.** The stator-limited region can occupy a large chunk of the low-speed curve, and you're likely to approach it every time you accelerate from a stop. Set it safely.
- **Lower supply limits increase efficiency.** Lowering the supply current limit extends Region 2 to lower RPMs, which significantly increases efficiency.

Give design calculators extra scrutiny to see if they implement supply and stator current limits properly. Most either choose to limit one or the other, only revealing part of the whole picture.

I encourage you to play with the spreadsheet to get a better feel for how the motor curve behaves.