The Theory Behind 6 CIM vs. 4 CIM Drives

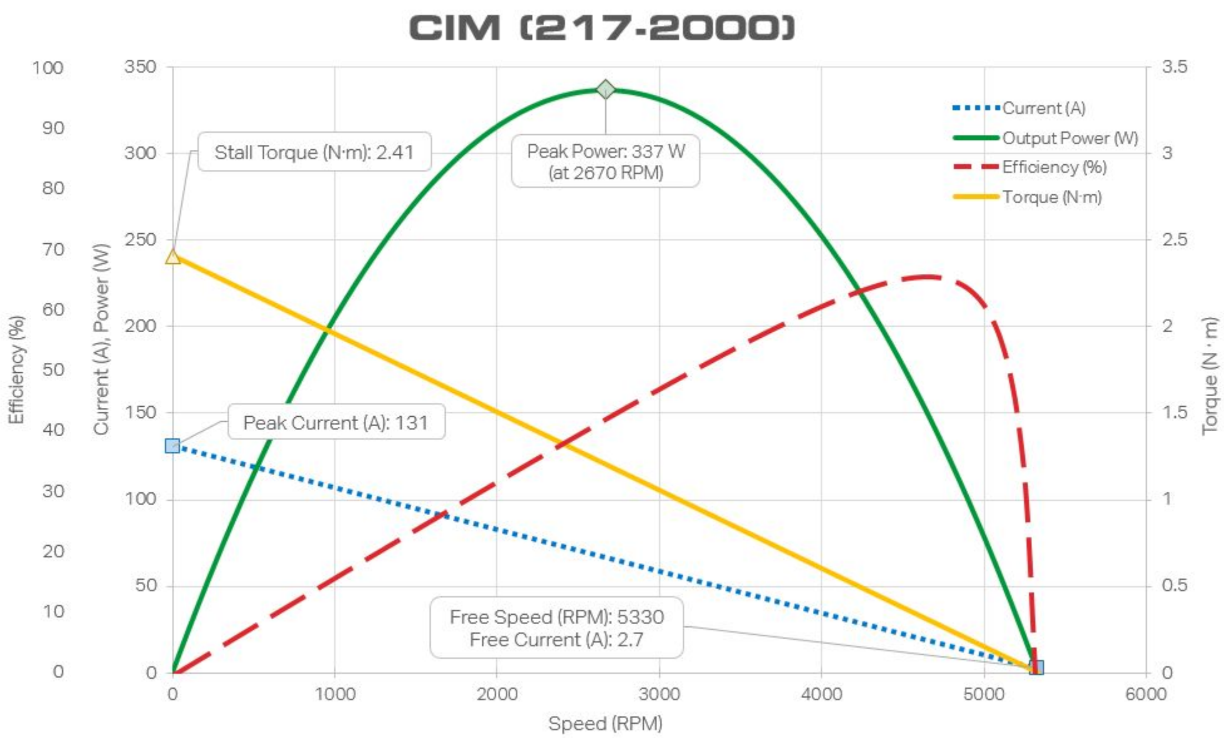
By Anand Rajamani

So for two years I thought that 6 CIM drives would die with the lower current threshold for brownouts on the RoboRIO. A 6 CIM drive can draw more amps, so it can accelerate faster if you draw 40 amps from each motor compared to a 4 CIM drive. But with the brownouts, you can no longer take advantage of the extra current drawing capabilities, and thus the extra pushing power and torque advantage of the 6 CIM drive, so it's useless now, right? After all, you can only draw so many amps with either a 4 CIM or a 6 CIM drive...
Wrong?

In the following paragraphs I'll explain how a 6 CIM drive achieves greater output power and thus faster acceleration in a drivetrain, and don't need to cause brownouts from current draw to be useful.

Section A: DC Motor Basics

First of all, I'll need to explain a few basics of electric motors. Let's take a look at a typical DC brushed electric motor curve:



Courtesy of http://motors.vex.com/cim-motor

There are a few basic rules of a DC brushed electric motor (I'll just type "motor" from now on). The first is that **the electric current (Amps) and the speed (RPM) of the motor maintain an *inverse relationship***. This means that as the speed goes down, the current goes up. If the speed goes down by 1/10th of the max speed, the current will go up by 1/10th the difference between free current and stall current. The curve above shows how as the RPM increases (from left to right) the current decreases. Once the speed hits the "free speed" of the motor (the max speed) that's when the current hits 0 amps.

The second basic rule about motors (still talking about brushed DC motors here) is that **current is directly proportional to torque**. That means that at 0 amps, you get 0 torque (N*m). At *stall current* (the maximum current of the motor) you will get the maximum torque out of the motor. In the graph above, the two downward sloping lines represent the current and torque of the motor.

Finally, the last basic rule of motors (those would be DC brushed motors, mind you) is that **the mechanical output power is equal to the speed times the torque**. This is *not* the same as electrical power! Electrical power is current times voltage. If you again direct your attention to the graph above, you'll see that at maximum electrical power (far left of the graph, at 131 amps and 12v) generates a massive *0W of mechanical power*. Why? Because there's no speed! The rpm is 0, so 0 rpm * 2.41 N*m = 0W! That might not make a lot of sense, but consider this: If you put a giant steel block on a CIM shaft and hold it still, then nothing is moving. The CIM isn't doing anything for us; it's not moving a chassis or accelerating a mass, so the output *mechanical* power is 0W. **For the rest of this document, whenever I mention power, I am talking about mechanical power, not electrical, unless stated otherwise.**

Section B: 4-CIM vs. 6-CIM Idealized Calculations

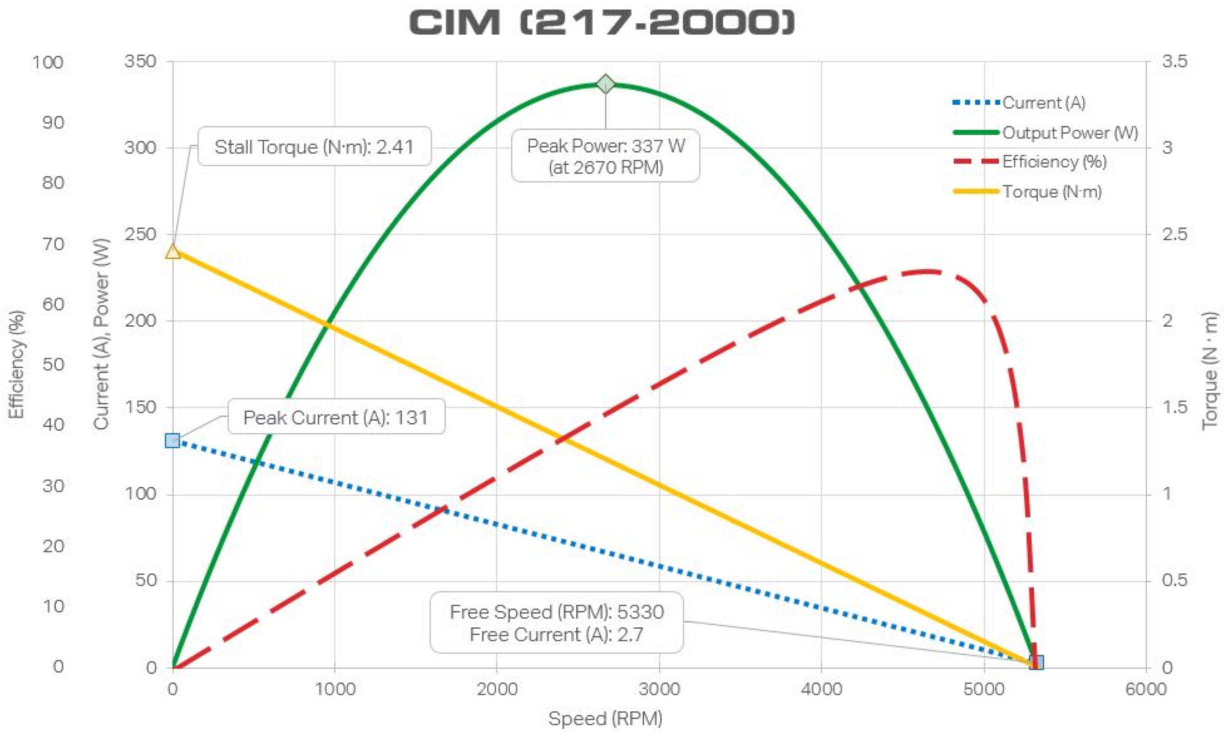
Now that all that's out of the way, let's look at how a 4 CIM drive and a 6 CIM drive stack up to each other.

In today's FRC, the main limiting factor in the power of your drivetrain is the tendency of the RoboRIO to "brown out" under heavy current draws. This is caused by a large current draw by the motors causing the battery's voltage to drop (a characteristic of batteries) below the threshold for resetting the RoboRIO. This causes the RIO to temporarily shut down, causing the motors to stop moving and drawing current, which bring the voltage of the battery back up, which restarts the RIO, which starts the cycle all over again. **For the purposes of this discussion, we will assume the RIO will brown out at about 220 amps**, in accordance with this graph:
https://wpilib.screenstepslive.com/s/4485/m/24166/l/289498-roborio-brownout-and-understanding-current-draw
This does factor in a bit of safety. Realistically you might brown out at a bit more or less than 220 amps depending on other factors of your system.

We will also assume that other things in the robot and efficiency losses are drawing a total of 20 amps. **This means that we are reserving 200 amps for the motors. All calculations**

henceforth will assume that the *entire drivetrain*, regardless of motor combination, will draw 200 amps.

Here's the picture of the motor curve for a CIM again, because we'll need it:



So assuming we are drawing 200 amps from the drivetrain, this means that per CIM we are drawing the following currents:

4 CIM: 50 amps/CIM
6 CIM: 33 amps/CIM

If we follow the dotted blue curve on the graph down to 50/33 amps, then we get the RPMs of each CIM:

4 CIM: 3,264rpm
6 CIM: 3,937rpm
(you can also use the equation (1-i/131)*5,310 to do this, where "i" is the motor current)

Follow the rpm up to meet the power curve and you get the following output powers per CIM:

4 CIM: 320 W/CIM

6 CIM: 260 W/CIM

Multiply by the number of CIMs, and we get the output mechanical power of the drivetrain:

4 CIM: 1,280w
6 CIM: 1,540w

Holy cow! That's more than a 20% increase in power! But here's the twist: *the electrical power is the same for both drivetrains!* But why?

The key is in the difference in *efficiency*. The efficiency of an electric motor is just the mechanical power divided by the electrical power. That means that if you are getting no mechanical power out, but you are applying 12v to the CIM (and presumably drawing 131 amps) your efficiency is 0%. That's right, when your motor is trying hard but not accomplishing anything, it's 0% efficient. If you look at the motor's efficiency curve on the graph above, you'll see that the *efficiency goes up as RPM increases*, up to about 4,800rpm. Because *each motor* in a 6 CIM drivetrain draws less current (33 amps as opposed to 50 amps for a 4 CIM), the inverse relationship makes it have a higher RPM, and thus a higher efficiency.

Now to explain why we made the assumption that the drivetrain current draw is the only thing that matters.

In our example above, the 6 CIM drive ends up with a higher output RPM than the 4 CIM drive. However, the total torque is the same, because we are only drawing 200 amps total from either drivetrain. Here's a quick calculation that shows this:

6 CIMs * 33.3/131 amps * 2.41 Nm = 3.67 N*m output torque
4 CIMs * 50/131 amps * 2.41 Nm = 3.67 N*m output torque

But the RPM is 3,937 RPM for a 6 CIM and only 3,264 RPM for a 4 CIM! That means that if you stick 6 CIMs into the same gearboxes as 4 CIMs, your output speed will be different at the same total current draws, but the torque will be the same. Your free speed of the gearbox (the final attainable speed) won't change, as that's the same for both 6 CIM and 4 CIM, but your acceleration curves will end up different. Namely, at the same speed, the 6 CIM drive will require less current total than a 4 CIM drive due to the efficiency, so you can afford to run the 6 CIM drives a bit harder and accelerate to the final speed faster than a 4 CIM drive.

The alternative to running identical gearboxes is to gear the 6 CIM drive about 20% less than the 4 CIM drive. I.E. if you are running 10:1 on a 4 CIM drive, run 8:1 on a 6 CIM drive. That will mean that you draw the same amount of current for a given output RPM, until you start nearing the maximum speed of the gearbox (AKA your motor speed goes above ~4,650 rpm and efficiency starts dropping off). The 4 CIM drive will have a lower top speed due to the more conservative gearing (10:1), but it will accelerate just as fast as the 6 CIM drive (8:1) until the efficiency starts dropping off.

In practice, it makes more sense just to run a 6 CIM drive only slightly faster than a 4 CIM drive. That way, you get a slightly higher top speed with an increased acceleration as well.

Section C: Let's Talk About Electricity

But why is a 6 CIM drivetrain easier to brown out?
(this section is courtesy of InFlight (Jim) of 3574)

First of all, it is easier to brown out a 6 CIM drivetrain, in 2 scenarios mainly: when your robot just starts moving, and when you're stuck in a pushing match. In that situation, with no voltage ramping on the drivetrain at all, the current draws are as follows in an idealized situation:

4 CIM: 131 amps * 4 = 524 amps
6 CIM: 131 amps * 6 = 786 amps

You're probably thinking "but my 4-CIM drivetrain didn't brown out when I started it at 100%!". That's because of the electrical resistance of the system actually limits the amount of current your battery can output without entering a brownout.

The RoboRIO will brown out below a voltage of 6.3v from the battery, meaning with a battery charged to 12v, is a total of 5.7v of drop. The power has to flow from the battery, through the PDP, and through wiring to motor controllers, and then to the motors. According to Jim: "You could reasonably model this situation as a 12 V voltage source with 0.05 Ohms of resistance to the power distribution board; and 0.3 Ohms of resistance through each of motor controls (Talon SRX) and wiring". Some further investigation revealed that wiring + battery was only around 0.012 ohms instead of 0.05; 0.011 ohm for the battery and 0.001 ohm for the wires.

The resistance of the motor itself is a function of stall current. We can use Ohm's Law V=I*R to find the resistance of each motor.

For a CIM: 12 = 131*R, so R = 0.092 ohm
For a MiniCIM: 12 = 89*R, so R = 0.135 ohm
For a 775pro: 12 = 134*R, so R = 0.090 ohm

Our total resistance from the battery to ground will be equal to 0.011 + the parallel resistance of all motors, speed controllers, and their wires. Parallel resistance is given by:

$$1/R = 1/r1 + 1/r2 + 1/r3 \dots + 1/rn$$

In this case, this works out to the following resistances:

4 CIM: 0.012 + 0.075 = 0.087 ohms to the battery
6 CIM: 0.012 + 0.05 = 0.062 ohms to the battery.

If we plug in V = IR one more time, we can find the maximum current the system can draw due to the resistance.
4 CIM: 12 = I*0.087, I = 137 amps
6 CIM: 12 = I*0.062, I = 193 amps

That means that a 4-CIM drive will practically never brown out, and even a 6-CIM drive will only rarely brown out, if you're only going in one direction.
There is one situation, however, that can cause a brownout in both drivetrains (although much more easily in a 6-CIM drive): reversing direction. When a motor is spinning in one direction, and the motor controller tells it to spin in the other direction, the motor does not instantly start to turn the other way. Instead, it needs to accelerate to the target speed in the opposite direction. If a motor is slammed from full forward to full reverse, it behaves like a voltage *source* instead of a voltage *sink* instead, which means the maximum current draw of the motor is increased greatly.

As an example, let's look at what happens when a robot is going at 75% of the maximum speed forward and receives a command to go in full reverse (-100%). At first, our electronics look like this:

Without any power ramping in the code, the 6 CIM drivetrain will draw way more current until it hits a certain amount of RPM. This extra current draw can cause a brownout, especially if the drivetrain will take a long time to accelerate. So one needs to limit the current draw to around 200 amps to be safe. That means that when you start up your drivetrains, you need the following motor powers:

4 CIM: 200/524 = 38%
6 CIM: 200/786 = 25%

This guarantees that you only draw 200 amps from the drivetrain when you start driving.

However, if you look at the motor curve again, you will see that as the CIMs' RPM increases (the drivetrain start moving faster) the current draw decreases. For example, at 25% of the maximum RPM, the CIM's current draw is only 75% of the maximum (that is, 100% minus the 25% RPM), so the maximum currents for the two drivetrains look like this:

4 CIM: 200/(524*0.75) = 51%
6 CIM: 200/(786*0.75) = 34%

Maximum Considerations for a 6 CIM vs. 4 CIM Drivetrain

In addition to bare mechanical power of a 6 CIM vs. a 4 CIM drivetrain, there is also another interesting side effect of the reduced current-per-motor: a 6 CIM drivetrain can achieve maximum power output for longer than a 4 CIM drivetrain.

When running the drivetrain at 200 amps, we calculated these rpms:

4 CIM: 3,264rpm
6 CIM: 3,937rpm

This is the maximum rpm at which the motors can achieve their 200 amp draw with. All the numbers above assume that you are running the motors at 100%; that is, 12v. However, if the motors are run at 6v, the free speed and stall current are both cut in half. When starting the drivetrain from a standstill, it is necessary to reduce the %voltage you are running them at to ensure that they draw less current than the 12v stall (131 amps). You can then ramp them up to 100%.

Eventually, both drivetrains will be drawing 200 amps and running at 3,264 rom (3,264/5330 = 61% of free speed) and 3,937 rpm (74% of free speed). Above those speeds, the current draw, and thus the electrical power and thus the mechanical output power, will decrease. This means that a 4-CIM drivetrain can no longer sustain the maximum acceleration above 61% of the drivetrain's top speed, whereas a 6-CIM drivetrain will be able to hit 74% of the drivetrain's top speed before the acceleration begins to drop off.

For a 15fps free speed drivetrain, this translates to 9.2fps and 11.0fps for 4 CIM and 6 CIM respectively.

I hope these equations can be of some use to you! They're definitely something to consider when designing drivetrain in the future. Good luck, and don't brown out!

Appendix A: Extra Calculations

Here's a few calculations involving the 6 CIM + 2 MiniCIM model (~7.33 CIMs total), 4 CIM + 2 MiniCIM (~5.33 CIMs), 2 CIM + 2 MiniCIM ~3.33 CIM), and 2 CIM model. There are also calculations for 10-775pro and 8-775pro drivetrains.

Keep in mind wire resistance and system resistance will affect your maximum current draw significantly.

Assuming we are drawing 200 amps from the drivetrain, this means that per CIM we are drawing the following currents:

2 CIM: 100 amps/CIM
3.33 CIM: 60 amps/CIM
4 CIM: 50 amps/CIM
5.33 CIM: 38 amps/CIM
6 CIM: 33 amps/CIM
7.33 CIM: 27 amps/CIM
8 775pro: 25 amp/pro
10 775pro: 20 amps/pro

If we follow the dotted blue curve on the graph down to 100/50/33/27 amps, then we get the RPMs of each CIM:

2 CIM: 1,250 rpm
3.33 CIM: 2,931 rpm
4 CIM: 3,264 rpm
5.33 CIM: 3,748 rpm
6 CIM: 3,937 rpm
7.33 CIM: 4,180 rpm
10 775pro: 15,920 rpm
8 775pro: 15,360 rpm
(you can also use the equation (1-i/(stall current-free current))*(free rpm) to do this, where "i" is the motor current)

Follow the rpm up to meet the power curve and you get the following output powers per CIM:

2 CIM: 240 W/CIM
3.33 CIM: 333 W/CIM
4 CIM: 320 W/CIM
5.33 CIM: 280 W/CIM

6 CIM: 260 W/CIM
7.33 CIM: 225 W/CIM
8 775pro: 205 W/pro
10 775pro: 177 W/pro

Multiply by the number of CIMs, and we get the output mechanical power of the drivetrain:

2 CIM: 480w
3.33 CIM: 1,108w
4 CIM: 1,280w
5.33 CIM: 1,490w
6 CIM: 1,540w
7.33 CIM: 1,650w
8 775pro: 1,640w
10 775pro: 1,770w

If we use 4 CIMs as our baseline for "available mechanical power", we get this:

2 CIM: 38%
3.33 CIM: 86%
4 CIM: 100%
5.33 CIM: 117%
6 CIM: 120%
7.33 CIM: 129%
8 775pro: 128%
10 775pro: 138%

MiniCIM and CIM notes:

Note that miniCIMs have slightly different motor curves and have a higher free rpm, so they'll need slightly different gearing to make up for it. Going from 6 CIMs to 6 CIM + 2 MiniCIM is not as dramatic as going from 4 to 6, and the added weight is around 5lbs when you factor in the heavier gearbox. Making a 4-motor gearbox can be difficult, but in the end the combo might give you enough of an advantage to justify it.

Interesting to note is how close the 4 CIM + 2 MiniCIM combo is in terms of power to the 6 CIM. However, because the 6 CIM gearbox only adds a very slight extra amount of weight and space, and makes the gearing a bit easier, it's often easier just to go with 6 CIMs.

775pro notes:

775pro drivetrains beat out CIM and MiniCIM-based drivetrains by a fairly large margin, with a 10-775pro drive dishing out 38% more power than a 4-CIM drivetrain, and 15% more power than a 6-CIM drivetrain. The speed limit before the maximum power output starts dropping off is 15,360/18,730 = 82%, which for a 15fps drivetrain is 12.3fps.

This should also teach you to almost never go with a 2 CIM drive. 115’s 2015 bot was so front-heavy it practically *became* a 2 CIM bot, as it tipped off the back wheels completely. The 62% reduction in power was very noticeable.