Electric Motors

Lab #2

Ana Paula Lopez
Diego Munoz
Pierre Henry
Christian Arriaga-Franco

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Abstract

In this lab, a DC electric motor was characterized by measuring the motor's torque, speed, power, and efficiency at different loads and voltages. To do this, an adjustable clutch and precision instruments were used, and measurements were made for 5 V and 12 V inputs for comparing motor performance. The results illustrated the inverse torque–speed relation, nonlinear power–speed relation, and maximum efficiency at medium speeds. Additionally, the lab also demonstrated voltage generation using a brushless DC motor. Overall, these observations demonstrated how electrical energy is converted into mechanical work and indicated how operating conditions affect motor performance.

Objective

The objective of this lab is to familiarize and understand how DC motors operate. This is exclusively regarding the cause and effects of DC motors by changing independent input variables for the motors and recording the corresponding outputs. For DC motors, the only input variable which can be changed is the voltage. However, under this voltage the motor has different outputs meaning that the torque and even power are not constant throughout. In reality, these factors change with RPM or the angular velocity that the shaft rotates at. Regularly, the motor isn't going to be set to certain power or torque values because they depend on something else. If it's turned on, it will just spin at its max speed. This is where the motor is put through certain scenarios that will force it to spin at varying RPMs. In a way, it is necessary to work backwards to understand the behavior of this specific motor. The way these constraints are made is through components such as a load scale, lever arm, and shaft clutch. Changing the stiffness on the clutch essentially produces the values necessary to calculate the power and torque at a specific angular velocity. Continuously repeating this through the range of RPMs the motor can perform at will create a pool of values that are used to make scatterplots such as the output torque, output power, and efficiency - for both 5v and 12v – all with respect to the rpm. These will show the behavior of the DC motor which are essential plots for consumers. One purpose for the motor may be for a fan which will also be covered in this report to understand the engineering behind load curves and why they are important for application. Although not covering AC motors, a small demonstration of three phase generation with brushless DC motors will be performed to see any relations with rotational speed.

Introduction

The best way to understand DC motors and how they react under certain conditions such as the RPM is by putting it through scenarios for which it can give responses to study. The driving component that influences different conditions on this motor is the clutch. The clutch is responsible for pressing two shafts together, hence "clutching" them. The tighter or stiffer the clutch, the more the shafts act as one. If the clutch is all the way open, the shafts are completely split, spinning free from each other. If the clutch is all the way closed, the shafts are tight enough to be thought of as one, spinning together. With the clutch being directly related to how fast the force is spinning about the shaft, it will be used as the guiding component of angular velocity for which we will perform our calculations. This can be used in the calculation for finding the output power, 1a.

$$P_{output} = T * \omega \tag{1a}$$

The angular velocity alone cannot be used to calculate the output power for the motor as shown in equation 1a. Torque is also needed as a multiple to find the output power. In most cases the motor is used to move a load and that force is multiplied by the distance, which is the torque needed.

$$T = Force * Distance \tag{1b}$$

Now that the guiding equations for the torque and power graphs are defined, another important parameter for determining which motor is best in the desired application is efficiency. It could be that one motor produces the desired torque at a lower efficiency than another, therefore wasting more power in the given application. Generally, efficiency is derived from the output over input. Although the formula for power output was defined earlier, the formula for the input of the motor must still be defined and referring back to how the motor is powered, it converts electrical energy into mechanical energy. This means that the power for which we put into the motor depends on the formulation of electrical power which uses the current and voltage induced.

$$Efficiency = \frac{P_{output}}{P_{input}} \tag{1c}$$

$$P_{input} = VI \tag{1d}$$

Quickly looking at the relationship between torque and power vs. the angular velocity, what exactly should the behavior look like. Are they random curves that change with motor and voltage. Truth is that they do change with motor and voltage but the curve that is created does not have a random shape. As a matter of fact, both the torque and power are related as shown in equation 1a but what exactly quantifies torque. The formula for the theoretical values of torque is shown in equation 2a. Keep in mind that the only independent variable in this equation is the angular velocity. All other values are constant.

$$T = \frac{V_S * k * \emptyset}{R_A} - \frac{(k * \emptyset)^2 * \omega}{R_A} \quad (2a)$$

$$P = T * \omega = \frac{V_S * k * \emptyset * \omega}{R_A} - \frac{(k * \emptyset)^2 * \omega^2}{R_A} \quad (2b)$$

Given that all other values beside the angular velocity are constant, it's clear that the torque graph should follow a negative sloped line with a positive y-intercept and the power graph should follow a parabola that intersects the x-axis at both max torque where angular velocity is 0 and no torque where angular velocity is max and should look something like shown in figure 1.

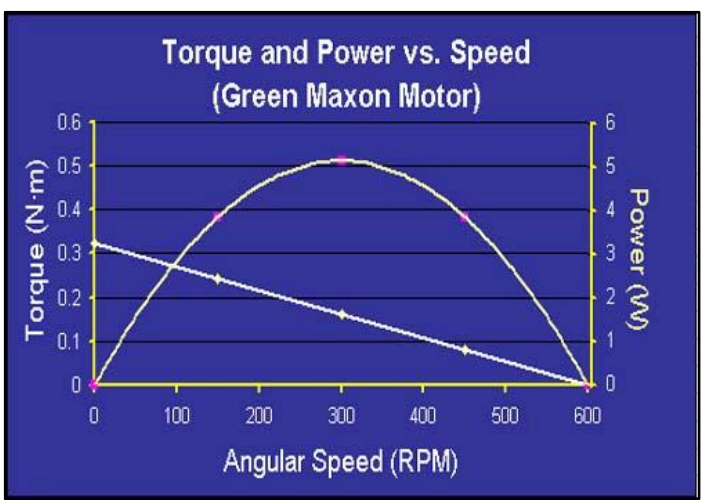

Figure 1:Typical torque and power graph for DC motor.

The equations will be found using the linear regression feature in excel when creating graphs and the relationship between speed and torque/power will be quantified. Not only is this important to check if the behavioral values make sense, the torque and speed relationship can also be used to determine the load curve intersection

Part of this report involves studying a hypothetical fan with a load which will be the fins on the fan. What is used to find the speed at which this fan will rotate is the torque-speed graph and load curve. The load curve is the relationship between torque and acceleration. When a fan first starts, its acceleration is really low but its torque is really high. As it speeds up, the torque decreases which creates a proportional relationship between the acceleration and torque. This relationship can be plotted and the intersection where the torques are the same is the theoretical value for which speed the fan will rotate. The formula for the load curve, considering the units that were measured is shown in equation 2b.

$$\sum T = I\alpha \tag{3a}$$

$$Torque(N-m) = 0.056 * 10^{-6} * \left(AngularVelocity(RPM)\right)^{2} \tag{3b}$$

This covers the behavior and a specific application of basic DC motors but how are brushless DC motors different. Through a procedure during the lab, a demonstration of how a power chart for a brushless DC motor in generation shows how the internal components for DC brushless create an AC-like setting. Brushless DC motors use DC power to create an AC phase inside the motor, instead of a solid stator which has a singular electric field, it has separate electromagnets that are powered using DC. They turn on at the exact times needed for the motor to generate the force vector, with the electric field, and rotate as shown in figure 2. When connecting this motor to another and making the one that’s getting powered, a generator, it will show the power generation as a 3 phase AC. Theoretically, when performing this in the lab, the oscilloscope that the second motor is connected to, should show the sinusoidal waves.

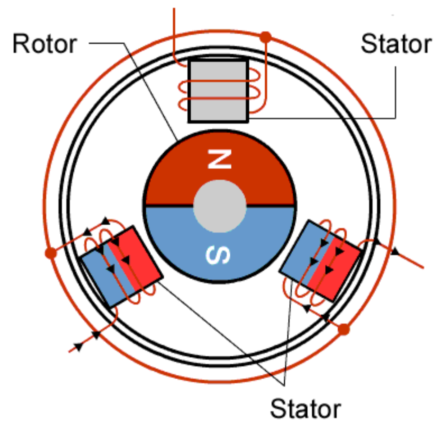

Figure 2: Simple brushless DC motor.

Procedure

Section 1 – DC Electric Motor Characterization

The laboratory equipment used in the DC Electric Motor Characterization are the motor itself, a power supply set to DC voltage, the motor shaft and clutch, the lever arm connected to the motor shaft, a scale, two multimeters, and the platform on which the motor and scale tower were set up.

To begin the experiment, the lever arm length from the center of the shaft to the center of the scale attachment point was recorded. Then load scale was attached to the hook of a support from above, then to the lever arm from below. At this point the lever arm was verified to be approximately perpendicular to the vertical scale, such that a reading from the scale would represent the approximate full reaction force required to resist the torque transferred from the motor to the shaft. The motor was then tested with 5 volts at various clutch thumbwheel settings to verify realistic values were being recorded at the scale.

The first multimeter was then set up for DC voltage, and the second for DC current using the high amperage positive terminal. The first multimeter was placed in parallel with the circuit as depicted in fig.3. The second multimeter was placed in series with the circuit, also depicted in fig.3.

The last stage of the setup was verifying that there was a piece of reflective tape on the motor hub. The tachometer on the infrared function utilized the infrared reflection to track how many revolutions the hub made per minute, and thus the motor angular velocity. After this step, the experiment was ready to be performed.

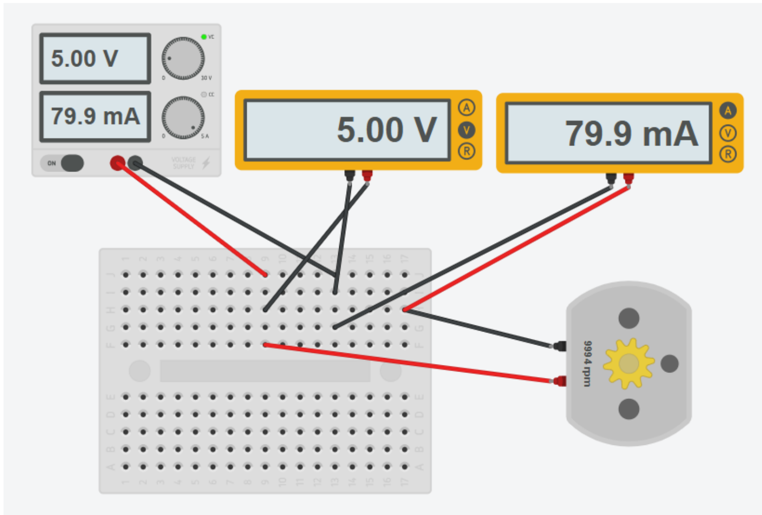

Figure 3: Circuit arrangement with multimeters, created using TinkerCAD

The motor angular velocity, supply voltage, supply current, and the scale load were then collected at as many thumbwheel clutch setting as was reasonably attainable for the 5 VDC setting on the power supply.

The thumbwheel was first tightened all the way to measure the “stall torque”, where the motor is no longer spinning and is completely resisted by the scale attached to the lever arm. After recording the data for the stall torque, the thumbwheel clutch was loosened to the point where the motor hub was rotating as little as possible and the data was recorded. Then, the thumbwheel clutch was loosened incrementally at a very slow rate, while recording data for each setting. Once the thumbwheel clutch was loosened to the point where the motor had very little resistance, it was completely released, and the “no-load speed” or “free spin” data was recorded. The steps from this paragraph were then repeated for the 12 VDC power supply setting.

A second sweep was performed for the 5 VDC supply after utilizing 12 VDC for higher resolution and additional data points.

Section 2 – Brushless DC Motor and 3 Phase Voltage Generation

The equipment used in the brushless motor experiment was the two motors themselves, a DC power supply, a signal generator, an oscilloscope, a speed controller, and tape.

The first motor was connected to the speed controller via the red, black, and yellow leads. Next, collect the speed controller to the power supply with the black lead going into the leftmost port, and the red lead going into the rightmost port. The power supply, oscilloscope, and signal generator were then turned on. The signal generator was set with a pulse width of 1 ms, a period of 60 ms, and an amplitude of 3V high and 0V low. Then, the smaller wires of the motor controller were connected to the yellow port of the signal generator with the hook test leads. The output channel on the signal generator was then turned on. At this point the motor beeped a few times. The pulse width on the signal generator was changed to 1.4 ms to turn on the first motor to verify operation. The pulse with was changed to 1 ms to turn off the motor. The powered motor was then connected to the passive motor with tape. The passive motor was then connected to the oscilloscope with alligator clips to measure the induced voltage from its rotation. As the powered motor speed increased, the change in induced voltage of the passive motor was observed.

Results and Discussion

Section 1 – DC electric Motor Characterization

After putting the motor through the various scenarios with adjusting the clutch, a set of values are created for angular velocity, force, and rpm. These sets of values are then used to perform calculations to create the figures of power, torque, and efficiency shown in the results section. These graphs will be checked to make sure that the torque and power line follow the expected graphs relatively closely.

Before covering the graphs and looking for any possible forms of error, it should be imperative to know that all measurements for the given scenarios were taken once. This creates an assumption that all of the measured values come with no error although some form of error is always present. In this experiment, it’s plausible that the devices to measure voltage current, and rpm, all had some form of error since they would fluctuate and never stayed at an exact value.

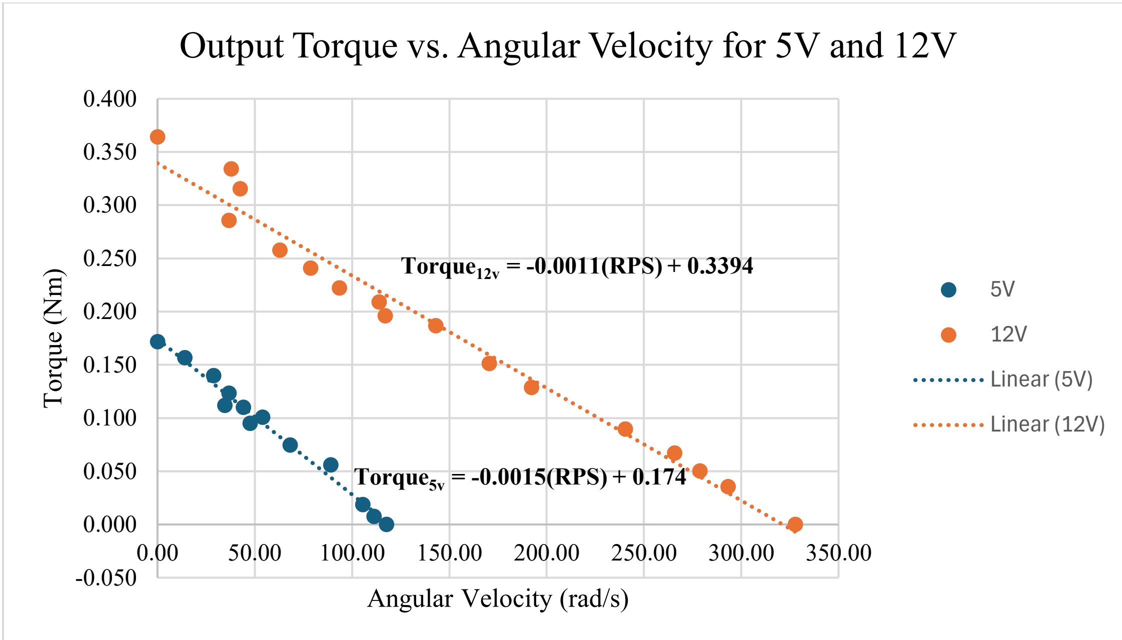

Figure 3: Output Torque vs. Angular velocity for 5V and 12V

Starting with values regarding the torque of the motor, the main features to look for are the line of best fit or the line for linear regression is to see if the values follow the line pretty accurately, are there good x-intercepts, are there good y-intercepts, and do the lines have similar slopes. Just from figure 3, it's clear that the data points which we obtained are not that far off the line of best fit. Although not shown on the graphs, the R-squared values for both of the graphs were well above 95% suggesting that line which is made is an extremely strong fit for the given data points. Next is to check the x and y intercepts. Referring to equation 2a, the graph should have a maximum torque at the point where angular velocity equal to 0, the y-intercept is, and it does. This also means that the torque is greatest when starting the motor, and that also follows the general rules for how a motor operates. Now thinking inversely of when the torque would be the least, following the equation, it should be when the angular velocity is the greatest and figure 3 shows that. Last is the slopes of each line of best fit. Although the lines shown in figure 3 are for different data points, the same motor is getting used for both scenarios. Again, referring back to equation 2a, all other values apart from the angular velocity and voltage are constant, meaning that without changing the properties of the motor, the graph should show that both lines have the same slope with different y-intercepts.

This is where some form of error is present in the fact that there is about a 30% difference in slope values. One possible cause for this could be the fact that the motor was running continuously for about an hour during the process of recording the values at 5 volts so when the voltage was changed to 12 volts and the experiment was done again, the motor may have experienced a change in the constants for slope which is shown in equation 2a. Another byproduct of the motor running for a long time was also the heat. During the procedure, even a set of pliers is provided to turn the thumb clutch because of how hot the motor and shaft get. This is a continuation of what constant may have actually changed to cause a difference in slope because one of them is the electrical resistance. Although we may increase the voltage, if the temperature of the whole system rises, it could cause an increase in electrical resistance through electrons having to move through hyper atoms. With the resistance being in the denominator for the slope, we would essentially be decreasing the overall value with respect to temperature, resulting in a lower slope.

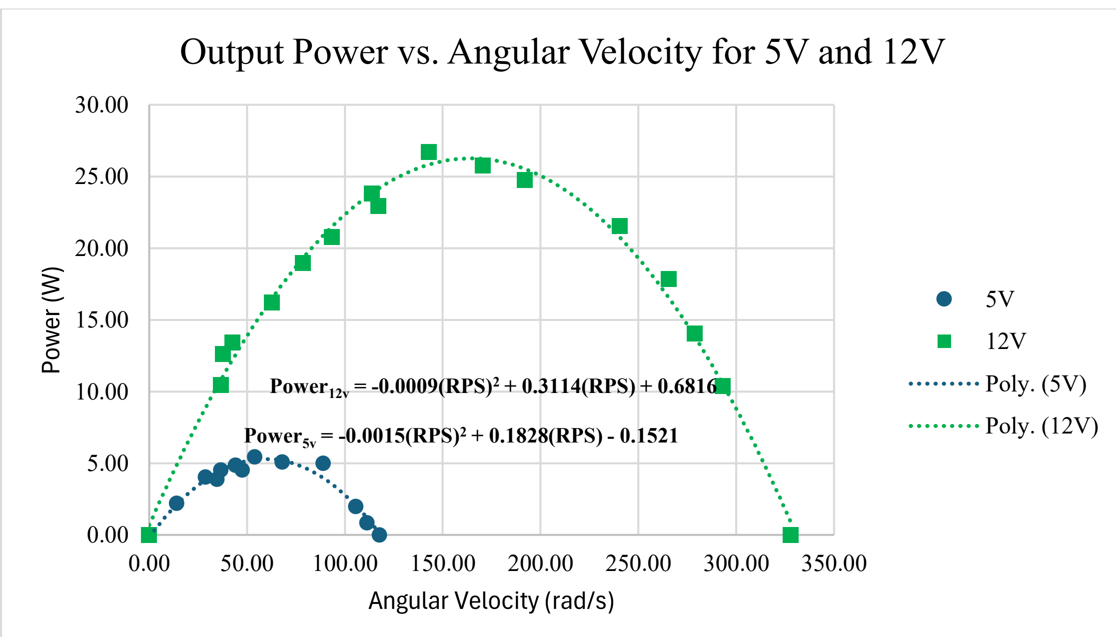

Figure 4: Output Power vs. Angular Velocity for 5V and 12V

The important values for the power chart are considering shapes and key points which include intercepts. For the most part the graphs followed polynomial shapes of the second degree which is what they are supposed to look like according to equation 2b. The difference between the previous set is that the graphs relative to each other are not comparable. Unlike the slope which should be similar, the constants for this graph will be different, especially since voltage now plays a role into constants which are multiplied by the independent variable, RDS. Another comment is that ideally the line of best fits should not have any constant at the end of each equation. Having this is a sign of error and considering that there may have already been some previous error with the torque, it's inevitable that there is some with this graph too.

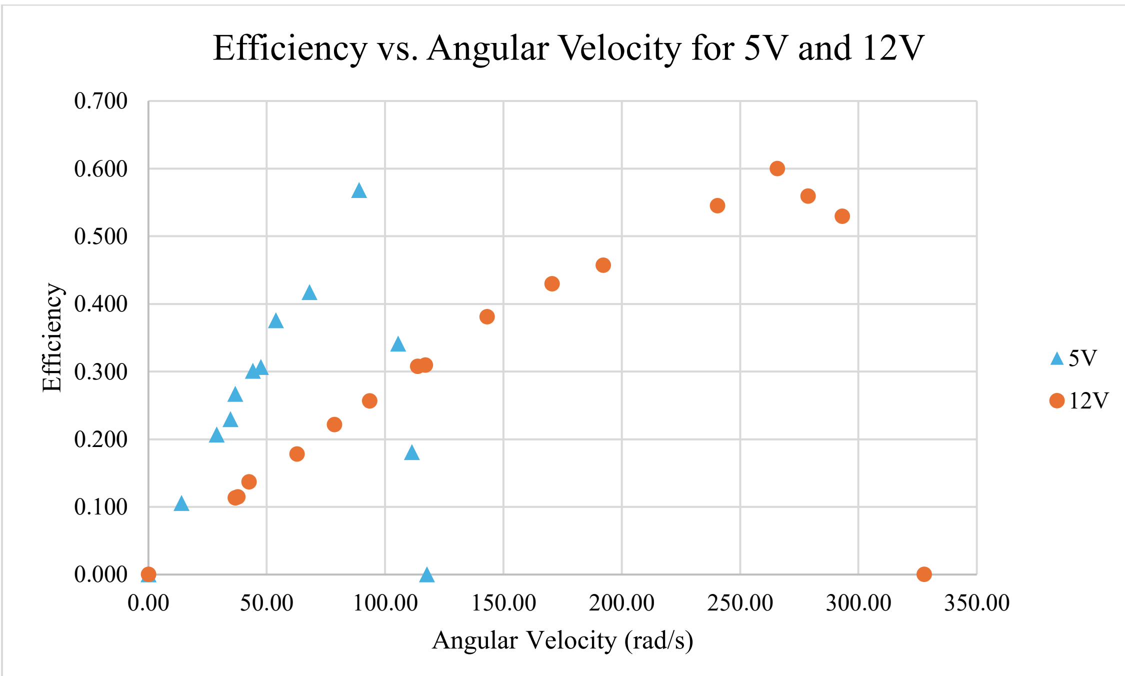

Figure 5: Efficiency vs. Angular Velocity for 5V and 12V

The efficiency graph is necessarily following any relative shapes, but it does have a common feature among them. This is the fact that the maximum efficiency is bright before the maximum angular velocity for the given application. In both cases the maximum speed does seem to follow that trend where its maximum is right before the end where it drops off drastically. This graph is most important to compare with after finding out which scenario you may have your motor in. Take a scenario where the motor is being ran at around 80 rad/s with 12 volts. Although power and torque are both greater than running the motor at

5 volts, there is a big difference in how efficient the motor is. With 12 volts, it may be running around 25% efficient while if you were to change it to 5 volts, the efficiency would jump up to above 50%.

When looking at the graph, it's noted that the efficiency never reaches 100 percent and that will most likely never happen. Referring to equation 1c and how we calculate the efficiency, the power output will never reach the same power input we have for various reasons. The motor we are using is a simple DC motor with brushes and a permanent magnet that will create a force while interacting with the magnetic field that is created by the wounding of wire in the rotor. Apart from the induction of current through the wounding of wire, the rest of the motor is mechanical meaning that a lot of parts come into contact with each other. This may include bearings, brushes, and solid parts like the shaft and rotor itself. Through these points of contact and even some loss in current through small resistivity of wires, the torque that is created will not reach high enough value at the right RPM to make the overall power value go up. After the majority of the torque is applied and the shaft is rotating, it will be easier for the shaft to rotate, requiring less force or torque. Think about the brushes that induce electricity into the wires. There may be a loss of energy from heat of the thermal conduction that's happening during contact. This and the small resistivity of going through the wire like stated before could be where the electrical energy gets transferred into another kind of energy. This would explain why the voltage that we read from one lead of the motor to another never reaches 5. Although we set the power supplies to the respective voltages, there is resistance inside the motor from drawing power, and losses in current with the given the surroundings like temperature, which will obviously decrease the change in voltage. This direct correlation goes back to efficiency and how the voltage from the input can show signs of loss so it's most likely that some are seen for the power output.

Section #2 – Brushless DC Motor and 3 Phase Voltage Generation

When the powered motor was turned on, the induced voltage of the passive motor was observed on the oscilloscope. As the speed of the powered motor increased, the induced voltage increased. Observations were limited by how quickly the tape came off the motors.

<u>Section 3 - Hypothetical Load of a Fan (NOT DONE IN LAB)</u>

When considering the operation of a fan's rotation on a motor, the fan acts as a load on the motor as it is usually attached separately. There are two main factors when determining if the fan can spin: the motor's performance torque and the fan's load torque. Calculating both against pre-recorded angular velocities assists in determining the speed the motor must operate at to be able to rotate the fan effectively.

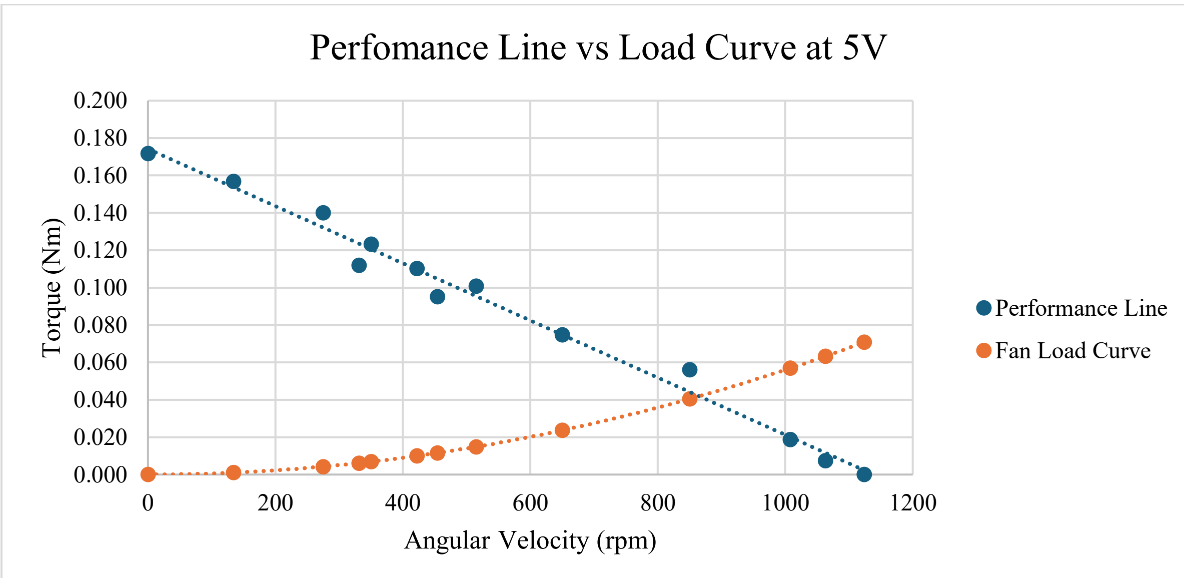

Figure 6: Plot of calculated performance line vs fan load at 5V created in Microsoft Excel

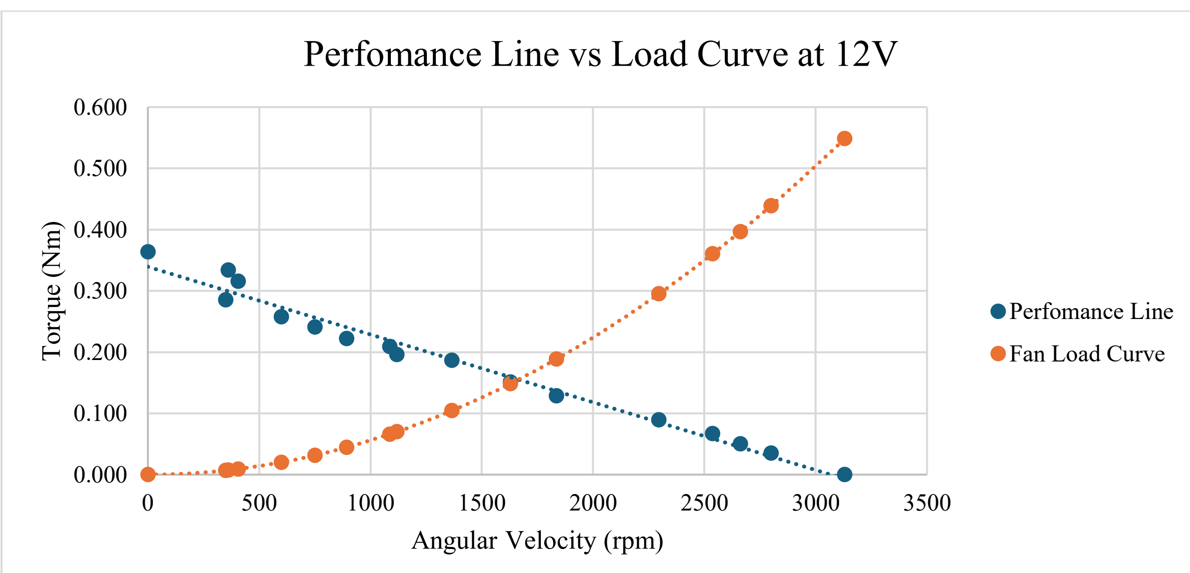

Figure 7: Plot of calculated performance line vs fan load at 12V created in Microsoft Excel

As seen in Figure 6 and Figure 7, as the torque decreases in the motor, the fan's load torque increases. This is an important trend because where these lines intersect is the speed at which the fan starts to rotate. Trend lines were utilized to simplify the observations made in the graphs. The performance trend line is linear while the fan load is on a curve partially resembling a parabola to best represent the plots. The performance trend serves as the capability of the motor in this case its torque capability as the angular velocity increases. The fan's load curve can be portrayed as the speed that is demanded from the motor to operate. At 5V the fan begins to work or reaches its equilibrium point at 850 rpm as seen in Figure 5 at any point before that the motor stalls. Comparing this to Figure 6, the fan operates around 1628 rpm when being supplied 12V.

The similar shapes of the graphs in Figure 6 and Figure 7 support the assumption that increasing or decreasing the voltage will result in the same similarities in the shapes. The area to the right of the equilibrium points and under the performance line represents where the fan can operate but sacrifices optimization. Relatively, the difference between the rpm to get from 0 to the equilibrium point is larger for the 5V graph than the 12V. Figure 5 gives more insight into how operating a motor at 12V is generally more efficient than its 5V counterpart.

Conclusion/References

A DC motor's torque, power, and efficiency were tested to show their behavior under different voltages and angular velocities. The testing also revealed potential sources of error in the measurement process. The torque vs. angular velocity results showed that both the 5V and 12V data sets followed the motor's expected linear trend. This was reflected in strong R-squared values above 95%. For power vs. angular velocity, the theoretical predictions were confirmed, as the data matched the expected second-degree polynomial curve. The nonzero constant in the line of best fit suggests systematic measurement errors. These might stem from voltage fluctuations, current inaccuracies, or environmental factors. The efficiency vs. angular velocity results supported theoretical expectations. Maximum efficiency occurred just before maximum angular velocity. The data confirmed that DC motors rarely approach 100% efficiency due to mechanical and electrical losses, which reduce effective output power compared to input power. Although the 12V setup produced higher torque and power, it operated at much lower efficiency. This demonstrates that higher performance does not always mean higher efficiency.

The performance of and the torque load generated by what directly connects to a motor should be taken into consideration when deciding the speed at which to run the motor without risk of stalling. The torque load constrains a motor's capabilities with larger voltages allowing those constraints to be met at relatively lower speeds. Viewing where the lines of a motors performance and torque load intersect represents the lowest speed the motor can operate at without stalling. When considering the application of a motor it is important to be aware of how the motors performance and load interact with each other.

Appendix/Questions

Section 1 – Raw data and sample calculations

Table 1: Complete motor data table for 5V

5 VDC Power Source								
Point	**Angular Velocity (rad/s)**	**Scale Load (kg)**	**Motor Load (Nm)**	**Voltage (V)**	**Current (A)**	**Output Power (W)**	**Input Power (W)**	**Motor Efficiency**
Stall	0.00	0.46	0.172	4.433	5.7	0.00	25.27	0.000
1	14.03	0.42	0.157	4.56	4.56	2.20	20.79	0.106
2	28.80	0.375	0.140	4.591	4.24	4.03	19.47	0.207
3	36.65	0.33	0.123	4.65	3.64	4.52	16.93	0.267
4	34.66	0.3	0.112	4.63	3.65	3.88	16.90	0.230
5	44.19	0.295	0.110	4.67	3.46	4.87	16.16	0.301
6	53.93	0.27	0.101	4.7	3.08	5.44	14.48	0.376
7	47.54	0.255	0.095	4.67	3.16	4.53	14.76	0.307
8	68.07	0.2	0.075	4.74	2.57	5.08	12.18	0.417
9	89.01	0.15	0.056	4.832	1.815	4.99	8.77	0.568
10	105.56	0.05	0.019	4.894	1.18	1.97	5.77	0.341
11	111.32	0.02	0.007	4.917	0.934	0.83	4.59	0.181
Free Spin	117.70	0	0.000	4.93	0.72	0.00	3.55	0.000

Table 2: Complete motor data table for 12V

12 VDC Power Source								
Point	**Angular Velocity (rad/s)**	**Scale Load (kg)**	**Motor Load (Nm)**	**Voltage (V)**	**Current (A)**	**Output Power (W)**	**Input Power (W)**	**Motor Efficiency**
Stall	0.00	0.975	0.364	10.94	10.7	0.00	117.06	0.000
1	37.80	0.895	0.334	11.02	10.0	12.63	110.20	0.115
2	42.52	0.845	0.315	11.13	8.8	13.41	97.94	0.137
3	36.65	0.765	0.286	11.12	8.31	10.47	92.41	0.113
4	62.83	0.69	0.258	11.17	8.14	16.19	90.92	0.178

5	78.64	0.645	0.241	11.22	7.62	18.94	85.50	0.222
6	93.51	0.595	0.222	11.25	7.2	20.77	81.00	0.256
7	113.83	0.56	0.209	11.29	6.85	23.80	77.34	0.308
8	117.08	0.525	0.196	11.34	6.54	22.95	74.16	0.309
9	143.05	0.5	0.187	11.38	6.16	26.70	70.10	0.381
10	170.48	0.405	0.151	11.47	5.23	25.78	59.99	0.430
11	192.16	0.345	0.129	11.55	4.69	24.75	54.17	0.457
12	240.44	0.24	0.090	11.66	3.39	21.55	39.53	0.545
13	265.67	0.18	0.067	11.76	2.53	17.85	29.75	0.600
14	278.76	0.135	0.050	11.79	2.13	14.05	25.11	0.560
15	293.22	0.095	0.035	11.83	1.66	10.40	19.64	0.530
Free Spin	327.77	0	0.000	11.93	0.7	0.00	8.35	0.000

<u>Sample calculation – Torque – 5V – Point 1</u>

$$Torque\ (T) = Force\ (F) * Distance\ (D)$$

$$Torque\ (T) = \left(9.81\frac{m}{s^2} * 0.42kg\right) * (0.03806m) = 0.157Nm$$

*Distance is of lever arm

<u>Sample calculation – Output Power – 5V – Point 1</u>

$$Power_{out}(W) = Torque\ (T) * Angular\ velocity(\omega - rad/s)$$

$$Power_{out}(W) = (0.157Nm) * \left(134\frac{rotations}{min}\right)\left(\frac{2\pi\ rad}{1\ rotation}\right)\left(\frac{1\ min}{60\ sec}\right) = 2.20\ W$$

*Angular velocity was measured in RPM and converted to rad/s in formula

<u>Sample calculation – Input Power – 5V – Point 1</u>

$$Power_{in}(W) = Voltage\ (V) * Current\ (I)$$

$$Power_{in}(W) = 4.56\ v * 4.56\ A = 20.79\ W$$

<u>Sample calculation – Efficiency – 5V – Point 1</u>

$$Efficiency = \frac{Power_{out}(W)}{Power_{in}(W)}$$

$$Efficiency_{5v,P1} = \frac{2.20\ W}{20.79\ W} = 0.106$$

<u>Section 3 – Raw data and sample calculations</u>

Table 3: Calculated motor torque and fan load torque for given angular velocity at 5V

Angular Velocity (rpm)	Motor Performance Torque (Nm)	Fan Load Torque (Nm)
0	0.172	0
134	0.157	0.001005536
275	0.140	0.004235
350	0.123	0.00686
331	0.112	0.006135416
422	0.110	0.009972704
515	0.101	0.0148526
454	0.095	0.011542496
650	0.075	0.02366
850	0.056	0.04046
1008	0.019	0.056899584
1063	0.007	0.063278264
1124	0.000	0.070749056

Table 4: Calculated motor torque and fan load torque for given angular velocity at 12V

Angular Velocity (rpm)	Motor Performance Torque (Nm)	Fan Load Torque (Nm)
0	0.364	0
361	0.334	0.007297976
406	0.315	0.009230816
350	0.286	0.00686
600	0.258	0.02016
751	0.241	0.031584056
893	0.222	0.044657144
1087	0.209	0.066167864
1118	0.196	0.069995744
1366	0.187	0.104493536

1628	0.151	0.148421504
1835	0.129	0.1885646
2296	0.090	0.295210496
2537	0.067	0.360436664
2662	0.050	0.396829664
2800	0.035	0.43904
3130	0.000	0.5486264

<u>Sample calculation – Fan Load Torque</u>

$$Torque(Nm) = 0.056 * 10^{-6} * (Angular\ Velocity\ (rpm))^2$$

$$Torque(Nm)_{@134\ rpm} = 0.056 * 10^{-6} * (361\ rpm)^2 = 0.0001005536\ Nm$$