

Electric Drives Experiment 3

Experimental Characterization of a DC Motor's Mechanical Parameters and its Torque-Speed Behavior

3.1 Objective

The objective of this activity is to experimentally measure some key mechanical parameters and produce two example torque-speed curves for the lab's PMDC motor. This activity was derived from those developed and distributed by the University of Minnesota (UMN).

3.2 Hardware Configuration

The hardware configuration for this lab is the same as it was for labs 1 and 2. As before, obtain the specialized electric drives equipment from the lab cabinet. Remember to use the grounding wrist strap when making connections to the inverter board, to prevent electrostatic discharge from destroying semiconductor components. In addition, while the order of the following setup procedures does not have to be followed exactly, you do need to take care to prevent any power from being supplied to the inverter board (though the 40 V DC power supply, the +/- 12V analog power supply, **or** the 37-pin CP1104 cable) while connecting components together to reduce the possibility of damaging the board with unintended current paths. In addition, keep any items such as cables or papers from draping across the board throughout the lab.

- Set the DC power supply's output to 40 V when no cables are connected to it, and then turn the power supply off.
- Use banana cables to connect the '+' and '-' ports on the DC power supply to the +42V and GND ports on the inverter board, respectively.
- Use banana cables to connect the "Phase A1" port on the inverter board to the **black** connector on the MotorSolver's DC Generator. Similarly, connect "Phase B1" to the DC Generator's **red** connector.
- Use the 8-pin encoder cable to connect the DC Generator's encoder port to the CP1104's "Incl" port.
- Connect the "Curr A1" port on the inverter board with the "ADC-5" port on the CP1104 board.
- Plug in the +/- 12 V power supply, and connect it to the inverter board's "analog power" connection, but leave the associated toggle switch in the off position.
- Connect the 37-pin cable between the inverter board and the CP1104's "Slave I/O PWM" port.
- **As the last step**, connect the CP1104's black cable to the DS1104 board (using the port at the back of the lab computer). Tighten the screws to ensure that the cable is well connected.

3.3 Measurements and Calculations for B and T_f

Open the dSPACE ControlDesk project that you were using at the end of Lab 2. This layout should have a slider for V_a , a plotter and numerical display for I_a , and a numerical display for ω_m . In addition, you should have checkboxes for the Reset and Shutdown variables.

Select the “Start Measuring” icon in ControlDesk, and ensure that the Reset and Shutdown boxes are checked. The armature voltage should be set to zero for now. Turn on the toggle switch for the inverter board’s analog power supply, and turn on the 40 V DC power supply.

Complete Table 3.1, and include it in your lab report. Remember to change V_a slowly using the ControlDesk slider, to prevent current surges from blowing fuses and/or destroying equipment. Note that “ V_a , Actual” will be measured across the motor’s red and black connectors using the test bench DMM, ω_m and I_a will be approximated from the measured values displayed by the ControlDesk instruments (an integer for ω_m and one decimal place precision for I_a), and T_{em} will be calculated as $k_T I_a$. Even though you could use the value of k_E measured in the previous lab as k_T for a permanent magnet DC motor, use the motor’s nameplate value for $k_E = k_T$ in your calculations (converted from V/k-RPM to V-sec/radians), since you might have selected a different MotorSolver kit in this lab. *Record your motor’s nameplate torque constant and your conversion for reference.* Check that your converted value is similar to the value of k_E in V-sec/radians that you calculated in the previous lab.

Table 3.1: Torque-speed data for no-load conditions

V_a , Desired	V_a , Actual	ω_m (rad/sec)	I_a (Amps)	T_{em} , Calculated (N-m)
5				
10				
15				
20				

Press the “Stop Measuring” icon in ControlDesk, and turn off the analog power’s toggle switch as well as the input 40 V DC supply.

Recall the following equation for the drive motor’s electromagnetic torque, T_{em} :

$$T_{em} = k_T I_a = T_L + B\omega_m + T_f + J_{eq} \frac{d\omega_m}{dt}$$

where T_L is the load torque (= 0 in the lab’s present configuration), B is the coefficient of viscous friction (representing frictional components that increase linearly with the motor’s speed), and T_f essentially represents the remaining frictional losses. The last term, $J_{eq} \frac{d\omega_m}{dt}$, is sometimes called the acceleration torque, since it only contributes to the torque when the motor is accelerating or decelerating (i.e., not steady-state). The variable J_{eq} represents the system’s equivalent moment of inertia, which may include more than just the motor’s moment of inertia.

In our case, for example, J_{eq} is the combined inertia of the two motors and the coupler that links them.

Under no-load, steady-state conditions, the torque equation simplifies to:

$$T_{em} = B\omega_m + T_f$$

which is a simple, linear relationship between ω_m and T_{em} . In Table 3.1, you found four (ω_m, T_{em}) points along this line. Follow the steps outlined in lab #2 to have MATLAB estimate a linear fit to your data points. *Save the slope of this linear fit as your estimate for B , and save the y-intercept as your estimate for T_f .* (In your report, paste the output of MATLAB's 'fit' function, and then explicitly state what this indicates about the values of B and T_f .) The variable B should have a magnitude in the 10^{-4} to 10^{-3} range, and T_f should range between 0.05-0.1 N-m, indicating a fairly flat line with the viscous losses having much less effect than the remaining frictional losses at the measured speeds. As you did in lab #2, plot your data points and MATLAB's linear fit to that data, add axis labels and a title to the plot, and *save an image of the plot for your report*. Don't be alarmed if your data points don't seem to fit the line very well – it's a rough approximation.

3.4 Measurements and Calculations for J_{eq}

As shown previously, the full torque equation:

$$T_{em} = k_T I_a = T_L + B\omega_m + T_f + J_{eq} \frac{d\omega_m}{dt}$$

simplifies to the following equation under no-load, steady-state conditions:

$$T_{em} = k_T I_a = B\omega_m + T_f$$

The moment the motor is turned off, however, we will have ($V_a = 0$, $I_a = 0$, $T_{em} = 0$) and the acceleration torque will have to be considered. The torque equation (still with no load torque) then becomes:

$$0 = B\omega_m + T_f + J_{eq} \frac{d\omega_m}{dt}$$

To experimentally determine J_{eq} , you will assume that the components $B\omega_m + T_f$ are the same immediately before and after the motor is turned off. It will be easier and more accurate to use $B\omega_m + T_f = k_T I_a$ immediately before the motor is turned off, so that:

$$J_{eq} \left(\frac{d\omega_m}{dt} \right)_{t=0^+} = - (B\omega_m + T_f)_{t=0^+} = - (B\omega_m + T_f)_{t=0^-} = - (k_T I_a)_{t=0^-}$$

where $t = 0^-$ indicates the moment **before** the motor is turned off and $t = 0^+$ represents the moment right **after** it is turned off. Solving for the moment of inertia provides:

$$J_{eq} = \frac{-(k_T I_a)_{t=0^-}}{\left(\frac{d\omega_m}{dt}\right)_{t=0^+}}$$

To calculate J_{eq} , you will therefore use the $k_E = k_T$ value shown on your motor's nameplate, the measured of I_a before the motor is turned off, and the rotational deceleration immediately after the motor is turned off.

In ControlDesk, create a plotter window and link the motor's speed to it. (Select the item called "speed_rad_sec" in the model tree, and drag its associated "Out1" variable onto the plotter instrument.) Select the "Start Measuring" icon in ControlDesk, and turn on the analog power supply's toggle switch as well as the input 40 V DC power supply. The "Shutdown" box should be checked. Slowly increase the desired armature voltage V_a to 15 V. *Record the armature current (I_a) when the system reaches steady-state.*

Uncheck the "Shutdown" box when you're ready to turn off the motor, and press the "Stop Measuring" icon in ControlDesk when the plotter window shows the transient of ω_m decaying from its steady-state value to near zero. *Save an image of this plotter window.*

In the plotter window, zoom in so that you can see a linear decay in ω_m when the motor was initially turned off, but don't zoom in to the extent that you see the individual data points, as the noise in the encoder data will make it difficult to get a good slope measurement at that level of detail. (If you zoom in too far, type the letter 'u' to undo the zoom steps until you can see the linear slope again.) Right-click on the plot, and select "XY Cursor." Move the resulting cursors to bracket the edges of the linear slope that you want to use in calculating $\frac{d\omega_m}{dt}$ at $t = 0^+$. *Save an image of the plotter window which shows the 'd ω_m ' and 'dt' data (i.e., Y2-Y1 and X2-X1) for your cursor locations, and use that data along with your steady-state I_a measurement to find the motor system's equivalent moment of inertia.* The change in speed, $d\omega_m$, should be negative since the slope of ω_m is negative. The moment of inertia should always be positive, and its magnitude should be in the 10^{-4} to 10^{-3} range for this system.

Turn off the 40 V power supply and the inverter board's analog power supply. Close the ControlDesk and MATLAB windows.

3.5 Measuring the PMDC Motor's Torque-Speed Characteristics

Download the "Exp3.mdl" file from the location specified by your TA or instructor, and save it to a desktop folder called Exp3. Remember to correct the name back to "Exp3.mdl" after downloading the file, if needed. Double-click on the file to open it in 32-bit MATLAB Simulink. The model should look similar to the one shown in Figure 3.1.

Analyze the MATLAB Simulink model. Note that some additional blocks have been included to create the duty ratios and PWM signals for the Phase A2 and Phase B2 transistors, in order to create an armature voltage for the **load** motor. The familiar blocks used to synthesize the **drive**

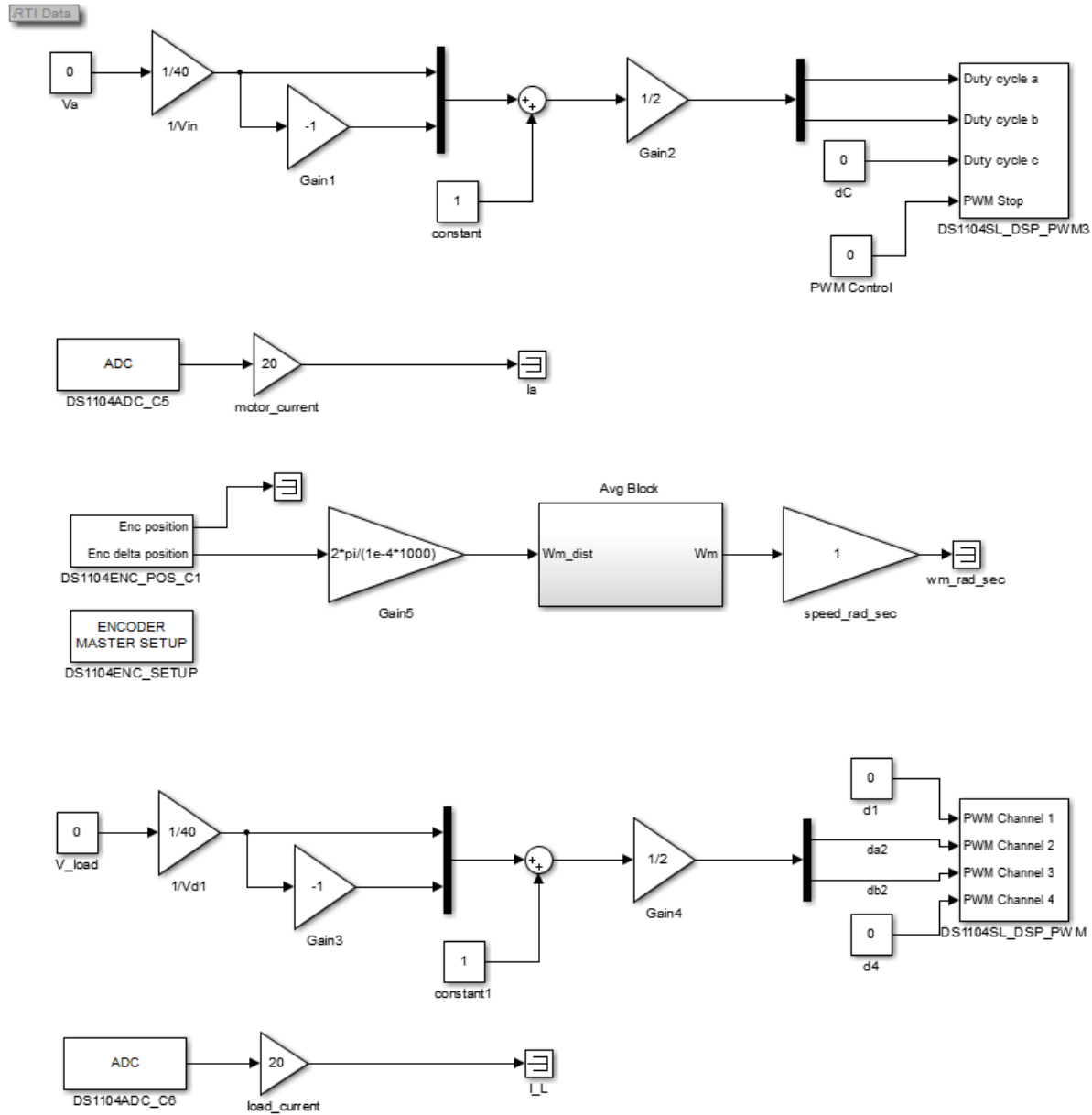


Figure 3.1. MATLAB Simulink model used to create torque-speed curves for the PMDC motor.

motor's armature voltage are located at the top of the Simulink model. Also notice that blocks have been added to access the current sensor data for the **load** motor via the CP1104/DS1104's Analog-to-Digital Converter Channel #6, while the drive motor's current sensor data is still being accessed through the ADC port #5.

To address these additions to the Simulink model, use a BNC-BNC cable to connect the "Curr. A2" port on the right side of the inverter board to the ADC-6 port on the CP1104 board. Also use banana cables to connect the inverter board's "Phase A2" port to the MotorSolver Kit's "DC Motor" (**black** port), and connect "Phase B2" to the DC Motor's **red** port. The "DC Generator" will still serve as the drive motor, powered through the A1 and B1 ports, while the "DC Motor" will serve as an active load driven by the A2 and B2 ports.

Press Ctrl-B in the Simulink window to generate and compile the C-code for Exp3.mdl. Note that if the ControlDesk software is open, MATLAB will not be able to load the new executable onto the DS1104 board, and the “make” process will fail. Do not worry about any other warnings displayed in the MATLAB control window, as long as you see the “MAKE PROCESS SUCCEEDED” message.

Once you’ve created the new executable associated with your new control system, open ControlDesk. Open the project / layout that you were using earlier in this lab. Select the “Project” tab on the left edge of the ControlDesk window, and right-click on the “exp2.sdf” filename. Select the “Replace Variable Description...” option, and load the “exp3.sdf” variable description that you just created in MATLAB. Since the variable names that you’ve been plotting are the same as the variable names in the “exp3.sdf” file, most of your instruments should still have valid variables associated with them, but check for and replace any variable links that may have been invalidated.

Copy the slider used for V_a (right-click on the slider, select “Instrument(s)->Copy”, and then right-click in the layout area and select “Paste Instrument(s) without connections”). Drag the “V_load->Value” variable onto the new slider. Alter the slider limits so that V_a runs from 0 to 20 V and V_{load} ranges from -20 to zero volts (right click on the slider, select “Instrument Properties”, expand the “Range” section, and update the appropriate value).

Delete the plotter used to display ω_m , and create a new plotter window for the load current. Drag the “load_current->Out1” variable onto the plotter. Also create a numeric display for the load current, similar to what you already have for the drive motor’s current. Your layout should now have a slider for both V_a and V_{load} , a plotter and numeric display for both I_a (“motor_current”) and I_{load} (“load_current”), and a numeric display for ω_m (“speed_rad_sec”). The SD and Reset checkboxes may be deleted.

Select the “Start Measuring” icon in ControlDesk. **Set the V_a and V_{load} sliders to zero.** Turn on the inverter board’s analog power supply, and then turn on the 40 V input DC power supply. Ensure that the DC power supply’s current limit is at its highest value by rotating the Current->Course and Fine knobs clockwise as far as possible. Select the “Reset” button on the inverter board to clear any lingering effects of the Shutdown option used in the previous section.

Slowly increase V_a to a 3.0 Volts, and notice the direction of rotation for the coupler that joins the two motors. **Return V_a to zero Volts**, and then slowly change V_{load} to -3.0 Volts. Does a negative V_{load} cause the motors to spin in the same direction as a positive V_a ? If not, return V_{load} to 0.0 Volts, turn off the 40 V input DC power supply, and switch the red and black banana cable connections on the DC Motor. Turn on the 40 V input DC power supply, and again test the rotation caused by a positive V_a and a negative V_{load} . Do not proceed until $V_a = +3$ V and $V_{load} = -3$ V produce the same direction of shaft rotation.

Starting with both V_a and V_{load} at 0 V, increase V_a to +3 V and V_{load} to -3 V. Then increase the values to $V_a = +6$ V and $V_{load} = -6$ V. Increase again for $V_a = +9$ V and $V_{load} = -9$ V, again for +/- 12 Volts, and again for +/- 15 V. If you accidentally apply a large voltage on one motor compared to the other and get overcurrent faults, you will need to set both voltages back to zero

in the ControlDesk window, press the “Reset” button on the inverter board, and try slowly increasing the magnitudes of both voltages in step with each other.

You should now have a desired voltage of $V_a = +15$ V and $V_{load} = -15$ V. Measure the actual voltages across each motor (across the motor’s black and red ports) using the test bench multimeter, and enter the measured values into Table 3.2. Use ControlDesk’s numerical displays for I_a , I_{load} , and ω_m to estimate those values to one decimal place of precision for Table 3.2. The **drive** motor’s current, I_a , should be approximately equal to the no-load current listed on the motor’s nameplate in this configuration. *Include that DC Generator nameplate value in your report, and compare it your measured value.*

Next, decrease the **magnitude** of V_{load} (e.g., from -15 V to -14 V) until you read a **drive** (motor) current value close to $I_a = 2.0$ Amps. Enter the values associated with this situation into the second row of the table. Repeat the process for drive currents near 3.0 and 4.0 Amps.

Table 3.2: Torque-speed data for the PMDC motor

V_a	V_a , Actual	V_{Load}	V_{Load} , Actual	I_a Desired (Amps)	I_a (Amps)	I_{Load} (Amps)	ω_m (rad/sec)
15		-15		No-Load			
15				2			
15				3			
15				4			
10		-10		No-Load			
10				2			
10				3			
10				4			

Reduce the **drive** motor’s voltage, V_a , to 10 V, and change the **load** motor’s voltage to -10 V. *Complete the remaining sections of Table 3.2*, following the same process used in collecting the $V_a = 15$ V data. Once you have completed Table 3.2, slowly reduce the drive motor’s voltage by a few Volts, and then reduce the magnitude of the load motor’s voltage by a few Volts. Repeat the process of reducing the voltage to one motor and then the other motor in small steps until both voltages are zero. The main concern here is keeping the motor currents below 5 Amps, the limit of the test bench power supply, as well as below the motors’ 6 Amp current limit. When both motor voltages are zero, press the “Stop Measuring” icon in ControlDesk, **turn off the 40 V DC power supply**, and then turn off the inverter board’s analog power.

Complete Table 3.3 through calculations - using the value of $k_E = k_T$ shown on the drive motor’s nameplate (converted from V/kRPM to V-sec/radians), the measured (rather than desired) values from Table 3.2, and the following equations: $T_{em} = k_T I_a$, $P_{in} = V_a I_a$, $P_{out} \sim T_{em} \omega_m$ (this assumes no mechanical losses), and percent efficiency $\eta = \frac{P_{out}}{P_{in}} \times 100$.

Table 3.3: Power and efficiency data for the PMDC motor

V_a	T_{em} (N-m)	P_{in} (Watts)	P_{out} (Watts)	<i>Efficiency</i> (%)
15				
15				
15				
15				
10				
10				
10				
10				

Plot the torque-speed curves for $V_a = 15$ and 10 V in MATLAB, with T_{em} plotted on the x-axis and ω_m on the y-axis. Plot the $V_a = 15$ and $V_a = 10$ V data as different lines on the same graph (for example, plot(T1,w1,'r-',T2,w2,'b--')). As a check of your data entries, note that the plots should show that the motor's speed decreases as its torque increases. The speed should also decrease as the applied armature voltage decreases. As with your previous plots, provide appropriate labels (including units) for the x- and y-axes, and create a title for the plot. Also provide a legend to indicate which line represents which voltage (for example, legend('Va = 15V','Va = 10V')). Note that you can also alter many of the plot's parameters via the graphing window ("Edit->Axes Properties"), if you prefer that method to the command line.

Your plots should indicate that the torque would continue to increase until $\omega_m = 0$, when the motor wouldn't be able to spin anymore. *Why didn't we continue testing until we reached this point?* Recall that the motor's maximum current is rated at 6.0 Amps, and the test bench's power supply can provide 5.0 Amps.

Create a plot showing P_{out} vs. speed (with speed on the x-axis) for the two armature voltages (for example, "plot(w1,P1,w2,P2)"), and a third plot showing efficiency vs. speed for the two armature voltages. Analyze the trends shown in the plots; for example, discuss how the output power (or load torque) affects the motor's speed, and how the armature voltage affects the motor's speed at a given load torque.

Close the ControlDesk and MATLAB software programs.

3.6 Shutdown Procedures

Remember to turn off and remove the three power sources first to reduce the probability of damaging the board while you remove the other cables.

- Turn off the high-power DC power supply first, without reducing its output voltage.
- Turn off the toggle switch associated with +/- 12V power supply, and unplug this power supply.

- Remove the ribbon cable from the inverter board and the CP1104 board.
- Remove the black cable from the DS1104 PC board (at the back of the lab computer).
- Remove the two BNC-BNC cables and the encoder cable.
- Remove all banana cables and store them at the lab benches as usual.
- Replace the inverter board inside the protective electrostatic cover.
- Carefully return all of the specialized electric drives components to a table near the lab's cabinet. The TA or the instructor will place the equipment back into the cabinet.
- Check that all of the test bench equipment is turned off, and leave the test bench area clean and organized. Your lab grade will be lowered if you are not careful with the lab equipment and/or if you leave trash in the test bench area.

3.7 Lab Report

The group of students at each lab station should submit a lab report. The report should focus on presenting and analyzing the data collected in this lab, although your instructor or TA may provide additional questions or requirements for your report. The requested data were often emphasized in the procedures with italicized text. The report should have section headings to help organize your information. Each figure should have a label and a brief description placed below the image, as demonstrated in these procedures, and each figure should be referenced in the text. Your analysis should be written in prose (i.e., complete sentences); the report should not just contain a collection of images and numbers. Think about writing the report such that you can use it later in the semester as a study guide. Show the equations or processes used to calculate values that were not directly measured. Your instructor or TA will announce the due date and method for submitting your report.

Checklist of items requested in these lab procedures:

- ☐ Complete Table 3.1: Torque-speed data for no-load conditions.
- ☐ Record your motor's nameplate torque constant and its conversion to V-sec/radians for reference.
- ☐ Save the slope of the linear fit to your (ω_m , T_{em}) data as your estimate for B , and save the y-intercept as your estimate for T_f .
- ☐ Save an image of the MATLAB plot showing your (ω_m , T_{em}) data and the linear fit to those data.
- ☐ Record the armature current (I_a) when the PMDC motor reaches steady-state conditions (after 15 V was applied to its armature coil).
- ☐ Save an image of the plotter window showing the transient of ω_m decaying from its steady-state value to near zero.

- ☐ Save an image of the plotter window which shows the ' $d\omega_m$ ' and ' dt ' data immediately after the motor was turned off.
- ☐ Show your calculation for the drive system's equivalent moment of inertia.
- ☐ Record the no-load current value listed on the DC Generator's nameplate, and compare it your measured no-load armature current (first row of Table 3.2).
- ☐ Complete Tables 3.2 and 3.3.
- ☐ Plot the PMDC motor's torque-speed curves in MATLAB, with T_{em} on the x-axis and ω_m on the y-axis. Plot the $V_a = 15$ and $V_a = 10$ V data as different lines on the same graph.
- ☐ Why didn't we continue collecting torque-speed data until we reached the point $\omega_m = 0$?
- ☐ Create a plot showing P_{out} vs. speed curves for the two armature voltages.
- ☐ Create a plot showing efficiency vs. speed curves for the two armature voltages.
- ☐ Analyze the trends seen in the last three plots; for example, discuss how the output power (load torque) affects the motor's speed, and how the armature voltage affects the motor's speed at a given output power.