

## Electric Drives Experiment 2

### Two-Pole Switch-Mode DC Converter and Experimental Characterization of a DC Motor's Electrical Parameters

#### 2.1 Objective

The objective of this experiment is to introduce students to the two-pole switch-mode DC converter used to generate the armature voltage ( $V_a$ ) for the lab's permanent-magnet DC (PMDC) motor, and to experimentally determine some key electrical characteristics of the PMDC motor (for example,  $k_E$ ,  $R_a$ , and  $L_a$ ). This lab activity was derived from those developed and distributed by the University of Minnesota (UMN).

#### 2.2 MATLAB Simulink Model for $V_a$ , the Armature Voltage

Create a desktop folder named Exp2. Download the "Exp2.mdl" MATLAB Simulink file from the location specified by the TA or instructor. If parentheses were added to the filename during the download process, rename the file back to "Exp2.mdl." Double-click on the "Exp2.mdl" file, which should open the 32-bit version of MATLAB Simulink. The topmost section of the Simulink model should look similar to Figure 2.1. This model of a two-pole switch-mode DC converter will determine the duty ratios for the inverter board's Phase A1 and Phase B1 transistors.

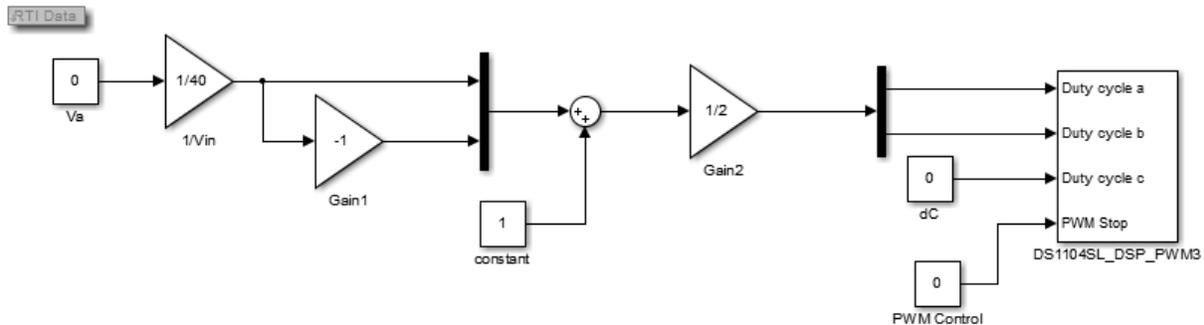


Figure 2.1: MATLAB Simulink model for lab #2

As indicated in the Simulink model, these duty ratio calculations will be used by the DS1104 board to create PWM signals, which will then be sent through the CP1104 board's Slave I/O PWM port to the transistor drivers, located on the inverter board. The equations used to calculate these duty ratios, as modeled in Simulink, follow:

$$d_{A1} = \frac{1}{2} + \frac{1}{2} \frac{V_a}{V_{in}} ; \quad d_{B1} = \frac{1}{2} - \frac{1}{2} \frac{V_a}{V_{in}}$$

where  $V_{in} = 40$  V is the voltage provided by the test bench’s DC power supply, and  $V_a$  is the desired voltage to be applied across the motor’s armature coil (later changed to a non-zero value in ControlDesk). The average voltage output by the Phase A1 transistor is then  $V_{A1} = d_{A1} V_{in}$ . Similarly,  $V_{B1} = d_{B1} V_{in}$ . Since  $V_{A1}$  and  $V_{B1}$  will be fed to opposite ends of the motor’s armature coil, the relative, average voltage across the coil will be  $V_a = V_{A1} - V_{B1}$ .

Using the equations shown above, complete Table 2.1. Include the completed table in your lab report. Theoretically, given the duty ratio equations above and  $V_{in} = 40$  V, what maximum and minimum values of  $V_a$  can be applied to the motor?

**Table 2.1:** Calculated duty ratios and output voltages

$V_{in}$	$V_a$ , Desired	$d_{A1}$	$d_{B1}$	$V_{A1}$	$V_{B1}$	$V_a$ , Output
	0					
	20					
	40					
	-20					
	-40					

In the MATLAB command window, make sure that the current folder is your desktop Exp2 folder. In the MATLAB Simulink window, press Ctrl-B to create and compile the DS1104 executable which will dynamically alter the transistors’ PWM signals to achieve the desired motor armature voltage. Ensure that the entire make process finishes successfully, such that a new executable representing the Experiment #2 MATLAB model is loaded onto the DS1104 board. (Ignore any warnings as long as the executable is uploaded successfully.)

### 2.3 dSPACE ControlDesk Layout to Change and Monitor $V_a$

Open the ControlDesk software and create a new project and experiment in the same manner as in Experiment 1, this time using the “exp2.sdf” file that you just created in MATLAB as the source for the system’s variable definitions. Once the new project has been created, select the “Instrument Selector” tab, and drag and drop a “Slider” instrument into the layout area. The slider will allow you to change  $V_a$  dynamically. Right-click on the slider and select “Instrument Properties.” On the resulting window, expand the “Range” category to see more options. Unselect the “Use variable range” checkbox, and change the slider’s “Minimum range” to -20 and “Maximum range” to 20. (Although the software algorithm and the lab’s hardware can create a maximum of  $V_a = 40$  V, limiting the value to 20 V will keep you safely inside the lab motor’s speed and current limits for now, avoiding blown fuses.) Select the Enter key so that the change takes effect, and then click in the layout / graphing area to close the properties window.

Expand the model tree in the lower-left corner of the software window until you see the  $V_a$  item. Select  $V_a$ , and then drag and drop its associated “Value” variable (found in the variable list in the lower-central area of the main window) onto the slider instrument.

Drag and drop a “Plotter” instrument onto the layout to display the duty ratios as they are recalculated for each  $V_a$ . Find and select the “Demux2” item in the model tree. Drag and drop the associated “Out1” variable, representing  $d_{AI}$ , onto the plotter’s main graphing area. Drag and drop the “Out2” variable (representing  $d_{BI}$ ) **onto the plotter’s y-axis** so that both variables will have the same y-axis scaling.

Next, drag and drop a “Display” instrument onto the layout. Drag and drop the “Out1” variable representing  $d_{AI}$  onto this new instrument to give you a numeric display of this duty ratio. Change the precision of this display by right-clicking on it and then selecting “Display Values” followed by “Display Formats.” Under the “Converted” category, uncheck “Use variable’s settings.” Check “Use Precision” and then set the precision to “3” for three decimal places.

Right-click on the display instrument you just created, and select “Instrument(s)->Copy.” Then right-click in an open area of the layout and select “Paste Instrument(s) without connections.” Drag and drop the Demux2->Out2 variable onto the new, second display instrument for a numeric measurement of  $d_{BI}$ .

Select the “Measurement Configuration” tab located near the upper-left side of the main ControlDesk software window. Expand the “Duration Triggers” list and then select “Duration Trigger 1.” Use the entry box at the bottom of the Measurement Configuration window to set “Duration Trigger 1” to 10 seconds.

Save your ControlDesk project.

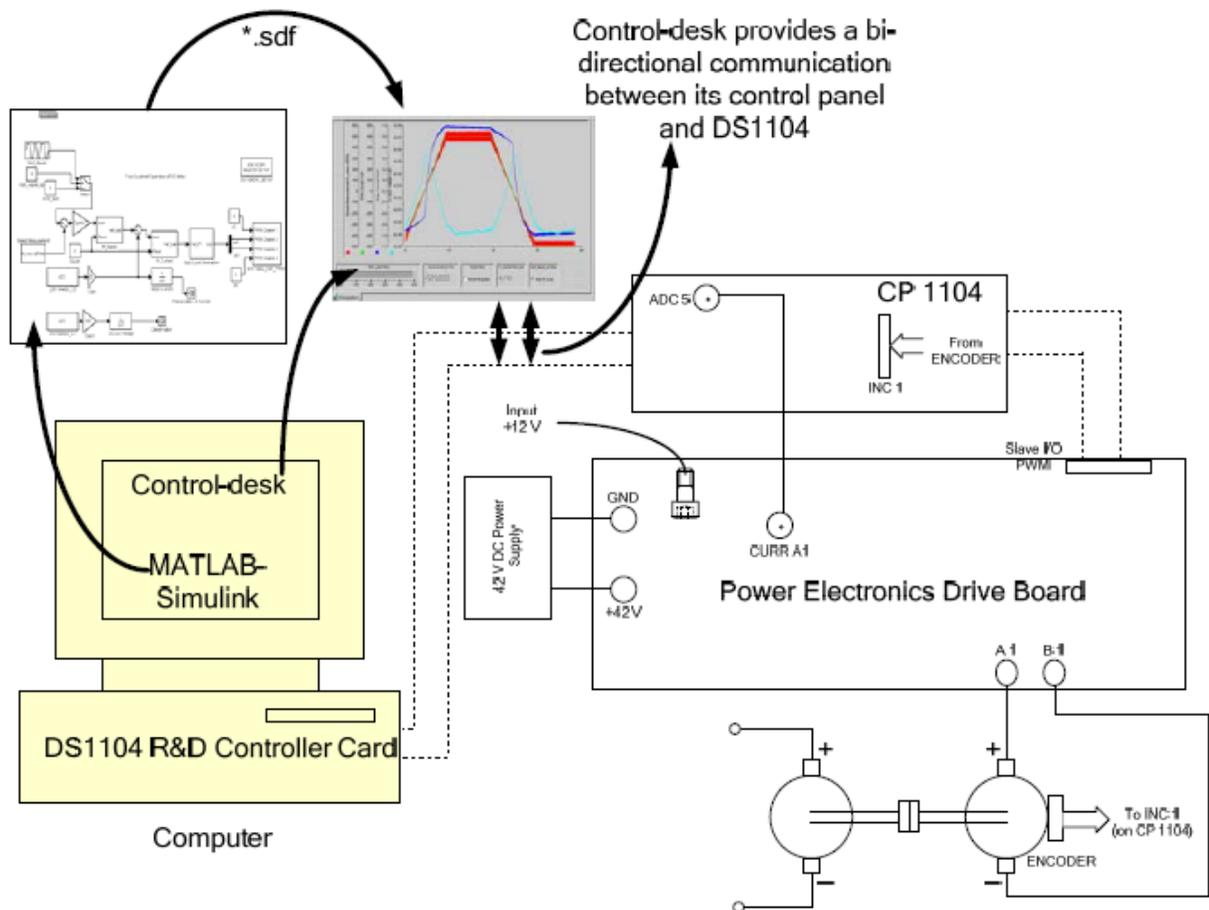
## 2.4 Hardware Configuration

Obtain the specialized electric drives equipment from the lab cabinet. The team member who is grounded via the wrist strap should set up the equipment as outlined below. Recall that the rationale behind using the wrist strap is to prevent electrostatic discharge from destroying semiconductor components on the inverter board, which has indeed happened in this lab. In addition, the rationale behind the ordering of the steps below is to prevent 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 which provides digital power) while you’re making connections, as you could easily create alternate current paths by draping a cable or brushing a hand against two different voltages. This has been another cause of damaged boards in this 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. Ensure that the ‘-’ and GND ports on the DC power supply are **not** hard-wired together.
- 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 “Inc1” 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 for now.
- Connect the 37-pin cable between the inverter board and the CP1104’s “Slave I/O PWM” port.
- Ensure that no cables, papers, or anything else is draping across the inverter board.
- **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.

A diagram of the hardware connections is shown in Figure 2.2.



**Figure 2.2:** Diagram showing hardware connections for lab #2 (UMN).

## 2.5 Data Collection for Duty Ratios and $V_a$

Select the “Start Measuring” icon in the ControlDesk toolbar, and then turn on the inverter board’s analog power supply (i.e., set the analog power toggle switch to the “ON” position). Finally, turn on the 40V DC power supply. Using either the slider or the numeric input in ControlDesk, **slowly** change the desired value of  $V_a$  and observe the motor’s response. If you accidentally input a large step change in  $V_a$  - for example by moving the slider too quickly - the motor will draw an excessive current and the motor fault protections will be triggered. To start over, you will need to change  $V_a$  to a small value in ControlDesk, then press the “Reset” button located in the upper-right corner of the inverter board.

*Complete Table 2.2 with measured values and include it in your report. You will set  $V_a$  using the slider in ControlDesk, read the duty ratios from the ControlDesk’s “Display” instruments, and then measure the average values of  $V_{A1}$  and  $V_{B1}$  using the test bench’s digital multimeter (DMM). To measure  $V_{A1}$ , put the positive DMM probe into the “Phase A1” connection on the inverter board, and put the negative DMM probe into the “Phase C1” connection (which was assigned a duty ratio of zero and is therefore at ground potential right now). Be very careful that the probes’ cables do not drape across the inverter board, and take care that you don’t accidentally short adjacent components on the board with the probe tips. Similarly, measure  $V_{B1}$  by connecting the DMM probes between the inverter board’s “Phase B1” and “Phase C1” ports. Compare the -20, 0, and 20 V duty ratios that you calculated for Table 2.1 with these measured duty ratios. Also, how well did the measured armature voltage match the desired value, and what might be the cause any differences? Take a screen capture of the entire ControlDesk window during one of your data acquisitions, and include it in your report.*

**Table 2.2:** Measured duty ratios and output voltages

$V_a$ , Desired	$d_{A1}$	$d_{B1}$	$V_{A1}$	$V_{B1}$	$V_{A1}-V_{B1}$
0					
10					
20					
-10					
-20					

**Turn off the DC power supply**, and turn off the analog power’s toggle switch. Press the “Stop Measuring” button in ControlDesk.

## 2.6 Experimental Characterization of $k_E$

In ControlDesk, delete one of the numerical displays associated with the duty ratios. In the model tree, find and select the “speed\_rad\_sec” item. Then drag and drop its associated “Out1” variable onto the remaining numerical display, to show you the motor’s precise rotational speed ( $\omega_m$ ).

Recall that a permanent magnet DC (PMDC) motor’s voltage constant,  $k_E$ , linearly relates the motor’s rotational speed ( $\omega_m$ ) to the EMF induced across its armature coil ( $e_a$ ):

$$e_a = k_E \omega_m$$

To experimentally determine  $k_E$ , you will measure the EMF induced across a PMDC motor at several rotational speeds and then calculate the slope that best represents your ( $e_a$ ,  $\omega_m$ ) data points. Note that you will need to measure the EMF induced across a PMDC motor as it is passively rotated by a second, drive motor. In this case, you will supply the armature voltage ( $V_a$ ) to MotorSolver’s “DC Generator” as usual, and you will use the test bench’s DMM to measure the EMF induced across the identical but passive “DC Motor.” The polarity of the induced EMF does not matter – just measure its average magnitude, the absolute value of the DC voltage displayed on the DMM.

In preparation for taking data, first select the “Start Measuring” icon in ControlDesk so that PWM signals are being sent to the inverter board. Then turn on the +/- 12V analog power supply, and lastly turn on the 40 V DC power supply. *Complete Table 2.3*, where you set  $V_a$  using the Control Desk slider, record an approximate value of the measured  $\omega_m$  values displayed in ControlDesk (pick an approximate integer value), you calculate the RPM values from the  $\omega_m$  data, and you record the average  $e_a$  values measured by the DMM across the motor labeled “DC motor” (NOT the motor powered by the inverter board). *Take one screenshot of the ControlDesk window showing the graphical displays during an example data acquisition.* When you have completed the table, **turn off the 40 V DC power supply** and the +/- 12V analog power supply, and press the “Stop Measuring” icon in ControlDesk.

**Table 2.3:** Induced EMF ( $e_a$ ) at different rotational speeds

$V_a$ , Desired	$\omega_m$	RPM	$e_a$
5			
10			
15			
20			

Back in the MATLAB command window, enter your  $\omega_m$  values as a vector, e.g., “w = [1 3 4 6]” (without the quotes when you type it in). Enter your EMF values as another vector. Use MATLAB’s ‘fit’ function to fit your ( $\omega_m$   $e_a$ ) points to a line as follows, taking care to leave out the semicolon at the end of this command:

$$f = \text{fit}(w', \text{EMF}', \text{'poly1'})$$

The primes after the ‘w’ and ‘EMF’ vectors are needed to convert them into the column format expected by the ‘fit’ function. The ‘poly1’ entry specifies that you would like to fit your data to a polynomial of order 1, that is, a line. The ‘fit’ function should output an estimate for the slope (p1) and y-intercept (p2) of a line that best fits your data. The y-intercept should be close to zero. *Explain why, in your report.* The slope of the line is an estimate for the motor’s voltage constant,  $k_E$ . *Save this estimate for  $k_E$  in V-s/radian, and comment on how the number of measured data*

*points affects the accuracy of this estimate.* For example, would the estimate be better or worse if two rather than eight data points were collected?

Plot your data and the linear fit on the same graph as follows:

```
plot(f, w, EMF)
```

Add label names and a title to your plot, similar to the following:

```
xlabel('w (radians/sec)')
ylabel('EMF (Volts)')
title('EMF Induced Across the PMDC Motor, Used to Determine k_E')
```

In the MATLAB figure, select the pulldown option for **Edit->Copy Figure** and then *paste a copy of your plot into MS Word, for use in your lab report.*

In the MATLAB command window, enter your RPM values from Table 2.3 as a vector, and then fit the (RPM, EMF) data to a line as before:

```
f = fit(RPM', EMF', 'poly1')
```

The slope of this line is again  $k_E$ , but this time in units of Volts/RPM. *Record this value, and discuss how it compares to the value listed on your motor* (the Motorsolver kit's "DC Motor").

## 2.7 Experimental Characterization of $R_a$ and $L_a$

The blocked rotor test will be used to experimentally characterize the resistance and inductance of the PMDC's armature coil. Recall that the electrical circuit model for the PMDC motor results in the following relation:

$$v_a = e_a + R_a I_a + L_a \frac{di_a}{dt}$$

When the rotor is blocked so that it cannot spin,  $\omega_m = 0$  and therefore  $e_a = 0$ . Under steady-state conditions,  $\frac{di_a}{dt} = 0$  as well. Therefore, when the rotor is blocked and the system has reached steady-state conditions,  $V_a = R_a I_a$  across the armature coil. You will set  $V_a$  in ControlDesk and measure  $I_a$  in steady-state conditions, and then  $R_a$  can be easily calculated.

In ControlDesk, copy and paste the Numeric Display to create a new one. In the model tree, select the "motor\_current" item, and then drag and drop the "Out1" variable onto the new Numeric Display.

Delete the existing Plotter. Create a new Plotter and drag the motor current variable onto it. You should now have a slider for  $V_a$ , a numeric display for  $\omega_m$ , and a numeric display and plot for  $I_a$ .

Select the "Start Measuring" icon in ControlDesk, and set  $V_a$  to 2.0 V. (Note that the voltage must be low so that the rotor can be easily stopped manually, and so the resulting short-circuit

current will not exceed the motor's limit.) Turn on the inverter board's analog power, and then turn on the 40 V DC power supply. Ensure that the power supply's current limit is at its highest possible value by rotating the Current->Course and Fine knobs clockwise as far as possible. Use the test bench's DMM to measure the actual voltage being applied to the PMDC motor (across the motor's red and black connectors), and *record this value as the actual  $V_a$  to be used in subsequent calculations.*

On the MotorSolver kit, grasp the coupler that joins the two motors, to block the rotor from spinning. *Record  $I_a$  once the system appears to be in steady-state (a few seconds).* If the current is oscillating, approximate an average value for  $I_a$ . *Also save a screenshot of the ControlDesk window. How does this "short-circuit" current compare to the motor's maximum rating of 6.0 Amps? What would happen if you increased  $V_a$  when conducting this experiment?*

*Use  $V_a$  and  $I_a$  to estimate  $R_a$ .* For the motors in our lab, your value should be in the range of 0.3-0.7 Ohms. When this measurement is complete, press the "Stop Measuring" icon in ControlDesk.

The inductance of the PMDC motor's armature coil will also be measured under blocked-rotor conditions, as close as possible to the moment that the voltage is applied to the coil. Under these conditions, the induced EMF is zero (no rotation) and the current is close to zero (just applied the voltage, and inductance is limiting the change in current), so the circuit equation listed previously simplifies to:

$$v_a = L_a \frac{di_a}{dt}$$

To aid in measuring the change in current when the voltage is applied, add two check button instruments to the ControlDesk layout. Drag and drop the Reset->Value ("Reset") variable into one checkbox, and put the SD->Value ("Shutdown") variable into the second checkbox.

Press the "Start Measuring" icon in ControlDesk. Ensure that the "Reset" button is checked. Uncheck the SD/Shutdown box, which will turn off the inverter board's transistors and therefore the motor. **The red LEDs indicating motor faults will turn on when the Shutdown box is unchecked, but it's not a problem in this case** – the LEDs will turn off again when the box is checked again. Have one team member hold the coupler between the two motors. A second team member should then check the Shutdown box and uncheck the Reset box, which will cause the armature voltage to be reapplied. You should have a plot which shows the current rising from zero Amps to its steady-state value. You may want to press either "Stop Measuring" or the "Stop" button in the Measurement Configuration window to freeze your data displays. If you miss the relevant data, uncheck and recheck the Shutdown checkbox again.

*Save a screen capture showing your transient current waveform rising from zero Amps to its steady-state value.* Then zoom in to the region when the current first starts to rise from zero, by dragging a bounding box around that area of the Plotter window. Zoom in repeatedly until you see the individual data points as dots being connected by line segments. The time spacing in the plotter window will be near 0.001 seconds at the final zoom level. Right-click on the plotter window, and select "XY Cursor." Move the resulting cursors to bracket the two data points that

you want to use in calculating  $\frac{di_a}{dt}$ . These points should be very close to the instant that the current began to increase from zero, so the assumption that  $i_a = 0$  and therefore  $i_a R_a = 0$  still holds. Note that  $dt$  is listed as X2-X1 at the top of the plotter window, and  $di_a$  is shown as Y2-Y1 in the table below the graph (you may need to expand the plotter window horizontally to see these values).

*Save an image of the plotter window (right-click, Print, Copy to Clipboard) which includes the  $di_a$  and  $dt$  information, and use that data and your applied armature voltage to calculate  $L_a$ . Your value should be in the range of 0.5-1.5 mH. **Save your work, and close the ControlDesk and MATLAB windows.***

## 2.8 Shutdown Procedures

Take care that you do not accidentally drape any cables or other items across the inverter board while power is being applied to the board. The board has three power sources: the 40 V DC power supply, the +/- 12V analog power supply, and the digital power supplied through the 37-pin CP1104 cable. Turn off and remove these power sources first to reduce the probability of damaging the board.

- **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 BNC-BNC and encoder cables.
- 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 the lab's 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.

## 2.9 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 2.1: Calculated duty ratios and output voltages.
- Theoretically, given the two-pole switch-mode converter's duty ratio equations and  $V_{in} = 40$  V, what maximum and minimum values of  $V_a$  can be applied to the motor?
- Complete Table 2.2: Measured duty ratios and output voltages.
- Compare the -20, 0, and 20 V duty ratios that you calculated for Table 2.1 with the measured duty ratios in Table 2.2. Also, how well did the measured armature voltage match the desired value, and what might be the cause of any differences?
- Save a screen capture of the ControlDesk window showing an example set of duty ratios and the associated (desired) armature voltage.
- Complete Table 2.3: Induced EMF ( $e_a$ ) at different rotational speeds.
- Take one screenshot of the ControlDesk window showing the graphical displays during an example data acquisition for Table 2.3.
- Explain why the y-intercept of your ( $e_a$  vs.  $\omega_m$ ) line should be zero.
- Save the estimate for  $k_E$ , the slope of your ( $e_a$  vs.  $\omega_m$ ) data, and comment on how the number of measured data points affects the accuracy of this estimate.
- Save the plot of ( $e_a$  vs.  $\omega_m$ ) which shows your data points as well as the linear approximation of your data.
- Save the estimate for  $k_E$  as the slope of your ( $e_a$  vs.  $RPM$ ) data, and comment on how this estimate compares to the value listed on the kit's "DC Motor".
- Record the measured value of  $V_a$  to be used in calculating  $R_a$  and  $L_a$ .
- Record the steady-state value of  $I_a$  used to calculate  $R_a$ . How does this "short-circuit current" compare to the motor's maximum allowable current of 6.0 Amps? What would happen if you increased  $V_a$  when conducting this experiment?
- Save a screenshot of the ControlDesk plot  $I_a$  of in steady-state conditions.
- Use  $V_a$  and  $I_a$  to estimate  $R_a$ .
- Save two screen captures of the transient portion of the  $I_a$  waveform: one which shows the current starting from zero and reaching steady-state, and which is zoomed to show the individual data points when the current is initially turned on.
- Calculate  $L_a$ . Show the values used in this calculation.