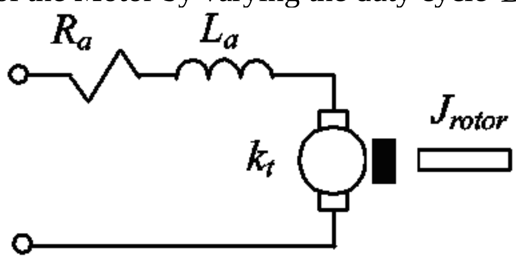
Lab-3: Permanent Magnet Brushed DC Motor

Objectives and Overview

The objectives for this sequence of laboratory experiments are:

- Experiment and fully characterize a small industrial ¼ HP 48V Permanent Magnet DC (PMDC) Motor by identifying its equivalent circuit parameters, friction, and inertia;
- Observe the load characteristics when the Motor is supplied from a variable DC source;
- Observe the load and speed characteristics when the Motor is supplied from a DC-DC converter with variable duty cycle and variable frequency;
- Experiment with the four-quadrant DC-DC converter to operate the Motor in forward and reverse directions.

By performing a set of measurements, students will determine the motor torque and/or voltage constant k_t and/or k_v, the armature winding + brush resistance R_a, armature inductance L_a, combined friction/loss torque as a function of speed $T_{fric}(\omega_r)$, and the moment of inertia J_{rotor}. Based on the determined parameters, the students will develop a steady-state model (equivalent circuit) of the given Motor and then use the model to predict the torque-speed characteristics and compare them with the measured ones. The students will also use a DC-DC converter with PWM to control the Motor by varying the duty cycle D.



Preparation (Pre-Lab)

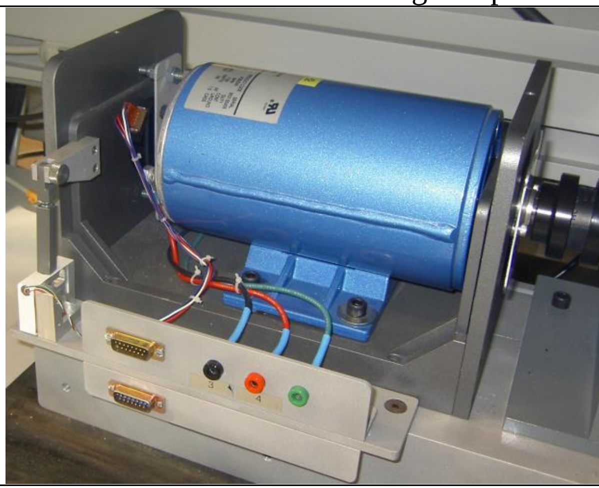
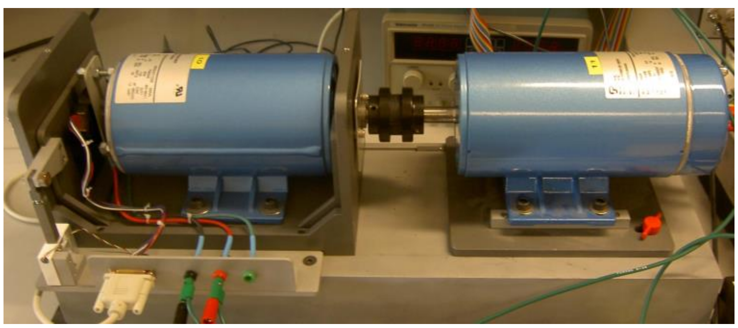
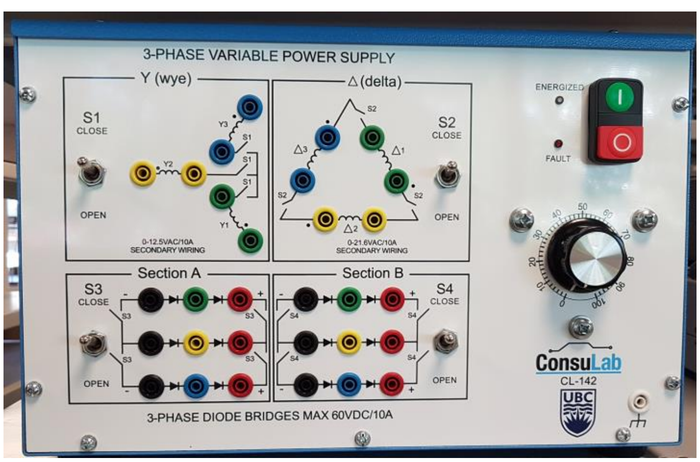
It is expected that the students have read and understood the textbook chapter on DC Motors and reviewed the lecture notes on DC Motors. The students should be familiar with the theory and principles of DC machines' operation and their equivalent circuits. Also, review the DC-DC converter's operation using PWM voltage control and the four quadrants. The Pre-Lab page should include the following:

- Please carefully read this **Lab Manual**. Prepare a list of equations for calculating the equivalent circuit parameters of DC motors using the **Blocked-Rotor** and **No-Load Tests**.
- Assume the Motor is operating in the first quadrant using a DC-DC converter, and at a given speed, $E_a = k_t \omega_r$. Sketch $i_a(t)$ and rewrite the equation $v_a = R_a i_a + L_a \frac{di_a}{dt} + E_a$ to find the expression for the armature inductance L_a when the upper switch of the converter is ON (Hint: replace di_a with ΔI_a and dt with Δt, assuming you have two data points I_1 and I_2). Alternatively, you can also find the armature inductance using the OFF time interval. Also, assume the value of the current ripple is $\Delta I_a = I_2 - I_1$. For simplicity, you may neglect the resistance R_a. Optional: Do not neglect R_a and derive a more accurate equation for L_a.

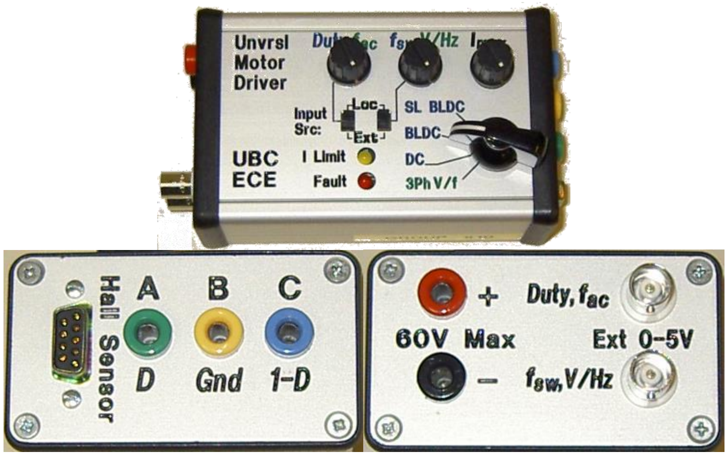
- **<u>Bring your Pre-Lab (either hard or soft copy) to your actual Lab and have TA to check it off. You will not be allowed to conduct any experiment without a reasonable Pre-Lab. Each student needs to complete Pre-Lab, and it cannot be shared between partners.</u>**

Apparatus & Equipment

This Lab includes the following components:

	**Motor Cradle:** The DC motor under investigation is mounted in a special cradle to permit measurements of the output torque. The motor housing is supported along its axis by ball bearings, enabling it to move when the torque is developed on the shaft. The reaction torque is measured from the force acting on a load cell. This allows direct measurement of mechanical torque. Note that the machine's internal friction and loss torque will not be coupled to the torque sensor.
	**Motor Bench:** An additional DC machine, identical to the one mounted on the Cradle, is used to emulate the mechanical load. This machine is mounted on the bench and is coupled through the shaft using a coupling. The torque and speed measurement signals are taken through the black multi-pin cable on the left side of the bench. This cable is then plugged into the back of the Measurement Box.
	**3-Phase AC Power Supply:** This flexible 3-phase AC/DC Power Supply has two 3-phase transformers inside, one that can readily be configured into a 'Y' (wye) and the other that can be configured into "Δ" (Delta) connection, respectively. The front panel shows the transformer wiring and has several switches and connectors for configuring the output. It also has two 3-phase diode bridges for producing the DC output. The Power Supply transformers are fed from an internal 3-phase **Variac** (variable autotransformer) that can be used to adjust the output voltage to the desired level. The Variac knob is located on the right of the front panel. **By varying the Variac knob from 0 to 100%, the**

	output AC voltages may be changed in the range from 0 to about 25 V (rms) per phase.
	**DC Capacitor Box:** The Box contains three electrolytic capacitors that can be switched ON and OFF in parallel. The terminals have polarity, which should not be miswired! If used incorrectly, **electrolytic capacitors can explode!** In this experiment, you may be using a large capacitor (6800µF) to filter the DC voltage at the output of the rectifier.
	**Load Resistor Box:** The Load Box contains several resistors from 100 to 50 Ohms, which can be switched on in parallel to each other. The box is equipped with a cooling fan to help dissipate heat in case a significant amount of power is delivered to the Load. Be careful! This box may get very hot, especially its heat sink, which is located on the bottom. **When the box dissipates more than 50W, turn on the internal fan.**
	**DC Power Supply:** A flexible regulated Xantrex XHR6018 DC Power Supply will be used to supply the DC-DC Converter - Universal Inverter Box in the last task of this laboratory experiment. This power supply has an adjustable output voltage of **0-60V** and a current limit of **0-18A**, which is sufficient for most experiments in this laboratory.



Universal Inverter Box: A multi-purpose inverter was designed to drive various AC and DC motors. In this Lab, you will use this Inverter to operate the DC Motor with Pulse-Width-Modulation (PWM) voltage control. The mode switch should be in **DC** position (blue font) for this mode. The Inverter is also equipped with three knobs to control the duty cycle ***D***, switching frequency $\mathbf{f_{sw}}$, and the current limit $\mathbf{I_{max}}$, respectively. Both **Input Src** control switches should be **turned up for Local control**. This allows the user to operate the Inverter Box using the knobs (instead of external inputs).

Multimeter: Each bench also features an HP 34401A (or equivalent) multimeter, which you will use to measure the DC resistance of transformer windings (with and without the wires). This measurement will be used only to double-check your calculated resistances.

Signal Generator: A digital Function Generator, such as the Rogol DG1022 or equivalent, is located on each bench. You can use this generator to output Sine Waves and other signals of various amplitudes and frequencies, which can be adjusted using the control buttons and knob on the front. In this Lab, you will need to use Ch1 of this generator to produce a variable duty cycle and demonstrate a bidirectional operation of your DC Motor.

Measurement Box:

Each bench is equipped with a multi-functional **Measurement Box** that can measure up to 3 voltages and up to 3 currents simultaneously with the sampling rate of 2.5 MS/sec (2.5MHz). The measured waveforms and their values can be displayed on the PC screen as well as recorded for possible post-processing. Its front panel has 3 current channels (**A1, A2, and A3**) and 3 voltage channels (**V1, V2, and V3**), respectively. The current channels are rated to measure and withstand a continuous current of up to 20 A (peak). The voltage channels are rated to measure and withstand the voltage of up to 50 V (peak). For special measurements only, the voltage measurement in each channel can be rescaled by a factor of 10, thus raising the measurement limit to 500 V (peak). The **Measurement Box** is connected to the Data Acquisition (DAQ) card inside the PC. The **Measurement Box** features a power switch on its back panel, located on the right side. The power switch should be normally turned ON, and the three LEDs on the front panel should also be ON, indicating its normal operation.

The channels are colour-coded. It is strongly recommended that you use appropriate and consistent colour wires for each channel of measurements. This will make it easier for you to wire up your circuits and subsequently check them, finding any mistakes.

Setting Up the DAQ System

Log in to your local PC and locate the LabVIEW **DC Motor Analysis** program. Double-click on the icon and start the program. A window shown in Fig. 1 should appear on your PC screen, indicating that you are ready to take measurements. The **DC Motor Analysis** program interface is set up to display the two voltages (channels **V1** and **V2**) and two currents (channels **A1** and **A2**), **Speed** and **Torque**, as will be needed in this Lab. The measurement window can be triggered using either the voltage or current signal of the first measuring channel (either **V1** or **A1**). The point of triggering also defines the relative angle of the measured signals. The user can select or de-select the measurement of voltages and currents, but the first channel V1 and A1 are always selected. For this Lab, select all two voltages and currents, Speed, and Torque to be measured.

All measured signals (voltages, currents, speed, and torque) are displayed in two ways: On the left side of the panel, all selected variables are displayed as real-time instantaneous waveforms – just like in an oscilloscope. On the right side of the panel, the **AVERAGE** (not the RMS!) values of the voltages (in Volts) and currents (in Amps) are displayed. Both Channels also display the calculated instantaneous real power (Ch1 and Ch2) in Watts. Channel 1 can also display the **PWM frequency** (**Ch1 kHz**) and the **duty cycle** (**Ch1 Duty**) of the switching voltage in channel V1.

The **average real power** in each channel (in Watts) is calculated assuming the instantaneous voltage and current in that channel. The power is calculated by averaging the instantaneous power over the length of the measurement window. For this measurement to be correct, you have to make sure that the voltage and current measurements are from the same Channel (V1 with A1, and V2 with A2), and that the polarities of both voltage and current channels are correctly wired.

Digital Filter: The program can also apply digital filtering to the measured voltages and currents. The user can turn the filter ON and OFF and adjust the cut-off frequency. **For the purpose of this Lab, the filter should be OFF for all measurements.**

Measurement Window: The Measurement Window period (in ms) can be adjusted during measurements to capture the desired waveforms better and to see the details. The program can **PAUSE** and **SAVE** the measured data in a text file for further analysis in programs such as **EXCEL** or **MATLAB**. Once the measurement is **Paused**, the user can also zoom in on any fragment of the recorded window using the **ZOOM** and **POSITION** slide buttons at the bottom of the panel. Pushing the SAVE button brings up the window to save the data file. The user should name and save the file in the appropriate location/folder for future analysis.

Remember to press **Zero A1, Zero A2, Zero Torque, and Zero RPM** before each measurement to zero out any offset that might exist in these measurement channels.

Ask a TA and/or Technician responsible for the Lab if you have any problem locating and/or running this program.

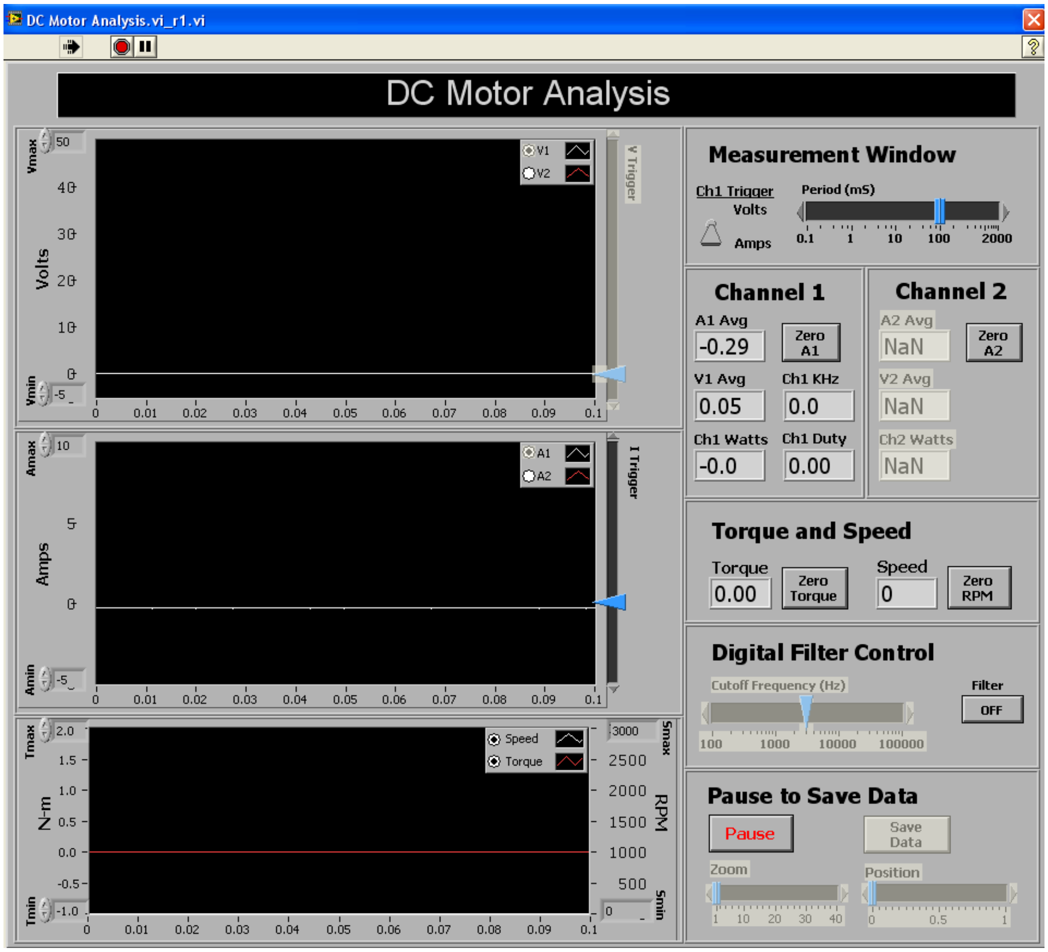


Fig. A: LabVIEW program interface DC Motor Analysis.

Setting Up the Experiment Using a Variable DC Supply

In this section, the students will set up the multi-purpose **AC–DC Power Supply** so that it provides a variable DC voltage to drive the motor under study. The **Power Supply** has two sets of windings, "Y" (wye) and "Δ" (delta), whose output voltage can be readily adjusted by the **Variac Knob** on the front panel. A low-ripple DC supply can be realized by connecting the transformer windings to the rectifiers as shown in Fig. 1 below. **All switches S1 through S4 must be closed.** Each 3-phase diode bridge results in a 6-pulse rectification. However, because the voltages from the "Y" (wye) and "Δ" (delta) windings are shifted by 30 degrees, the 6-pulse ripple produced by each rectifier is also shifted by 30 degrees and is out of phase. By connecting the two rectifiers in series, the overall ripple is reduced and the 12-pulse operation is achieved. You will then use the **Variac Knob** to adjust the voltage magnitude to the desired level. You will use this variable DC Supply to power the motor under study. Please remember that it is a good rule to first connect the current-carrying circuit, and only after that connect the voltmeter channel leads directly to the terminals where you need to measure voltage. In this experiment, you may be using a **large capacitor (6800µF)** to filter the DC voltage at the output of the rectifier.

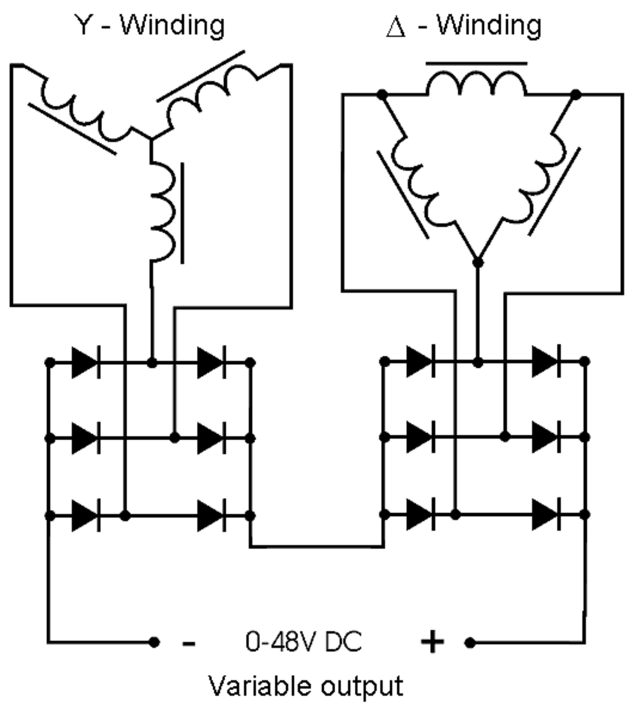


Fig. 1: Variable DC source with 12-pulse rectifier-bridge. An additional capacitor may be used at the output terminals to reduce voltage ripple.

Task 1: Characterization of the Motor under No-Load

Wire up the circuit as shown in Fig. 2 to take the measurements of the **Motor in the Cradle**. Please note that you will need to use a special **red wire with a Switch** to connect the **DC Source** to the current measurement channel. At this point, **do not** mount another DC machine on the bench! Make sure the Motor Cradle under test is not coupled to anything. Use the **Measurement Box** to display and measure the torque, speed, voltage, and current of the Motor under test. Use Channel 1 voltage V1 and Channel 1 current A1 terminals, respectively, as shown in Fig. 2.

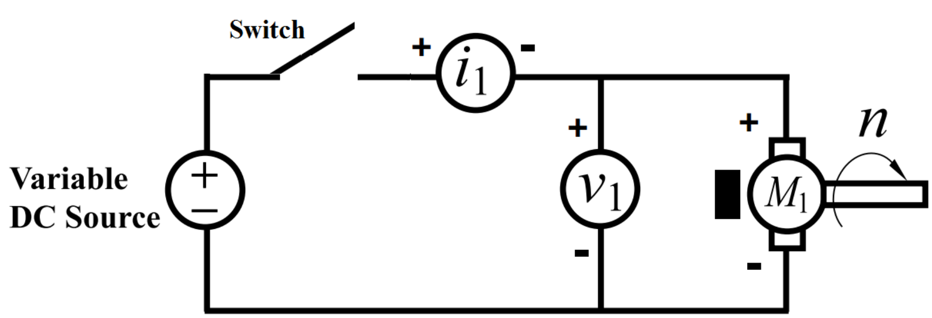


Fig. 2: Wiring diagram for the No-Load Test(s).

Task 1 A: Measuring the DC Resistance: Blocked-Rotor Test

For comparison, use the bench-top **Multimeter** to measure the resistance of the DC Motor at its terminals, and record the result in **Table 1-A** at the appropriate location. A more accurate measurement of the armature DC resistance is obtained by lightly powering the Motor and measuring the voltage and current when the shaft is not spinning – the **Blocked-Rotor Test**. First, the **DC Power Supply** should be OFF, with its knob set to 0 V. The **red wire Switch** should be **ON** to supply the machine.

1) For this measurement only, you **will need to lock the machine shaft**. Ask your TA and/or Lab Technician for a **Metal Lock** to lock the shaft in a special slot on the top of the **Motor Cradle**. Slide the lock plate into place and manually rotate the shaft to ensure the lock clicks in and locks properly.
2) Make sure that the **DC Motor Analysis** program is running on your PC. Press the **Zero** button on the **DC Motor** software interface to remove any possible offset in the current measurements. Turn on the **DC Power Supply** and monitor the voltages and currents on the computer screen. You can adjust the measuring window size to get more stable readings.
3) Slowly increase the voltage V_1 and the **DC Power Supply** current limit until you start noticing that the current is increasing. **Do not exceed the rated (6A) current of the Motor!** Take three measurements at different current levels (from 0.5 to 6A) and record the values in **Table 1-A**. Calculate the resistance R_a for each case as well as their average value. This value of resistance includes the resistance of the winding + the brushes and all wires in your circuit.
4) Turn OFF the **DC Power Supply and remove the shaft lock.** You will **not need** to lock the shaft for other tests. So, you can return the **Metal Lock** to the TA and/or Technician.

Task 1 B: Measuring No-Load Characteristic

1) Make sure the **Motor Cradle** under test is not coupled to anything. So, the Motor will only work against its own friction and all internal rotational losses.
2) Vary the applied voltage V_1 from 5V to about 40V DC and measure the armature current I_1 and speed $n_{no-load}$ in rpm. Take and record about 6 evenly-spaced data measurements. Record the measurements in **Table 1-B**. You will need these measurements to calculate the friction/loss torque as a function of speed $T_{fric}(\omega_r)$.

Task 1 C: Recording the Stopping Transient – Estimating Moment of Inertia

1) Apply 40V DC to the Motor under test (**Motor in Cradle**). Ensure that the **DC Motor** software is set for the longest measurement window (approximately 2000 ms) and that all measurements are stable.
2) Then, with one hand, disconnect the **Power Supply by turning off the switch on the red wire, and** with another hand, quickly push the **PAUSE** button to save the stopping transient. You may need to repeat this test several times until you capture the entire stopping transient well in the measurement window. Once you have captured the transient you want, you can adjust the position and zoom into the recorded interval to better view the transient response. Then press the **SAVE** button to save the captured data to a text file. You will use this data to calculate the moment of inertia for this Motor in Task 5. You may also save a **screenshot** picture of your recorded transient for your record and comparison.

Task 1 D: Recording the Stopping Transient of two Machines – Estimating the Combined Moment of Inertia

1) Very carefully slide the Load-Motor (another identical PMDC Motor) into position and couple it to the **Motor in the Cradle** under test using a metal coupling. Secure the Motor using the specially provided screws with **red** heads-handles. Now, you have two machines coupled on the test bench, which increases the total moment of inertia. Since the machines are very similar, their internal friction may be assumed to be the same.
2) Again, apply 40V DC to the Motor under test (**Motor in Cradle**). Make sure that both machines are spinning without significant noise (vibrations) and that all measurements are stable. If your machines are making a loud noise, you may need to re-adjust their coupling and mount.
3) Prepare to record another deceleration transient. Disconnect the **Power Supply** by turning OFF the **red wire Switch** with one hand and quickly push the **PAUSE** button to save the stopping transient with the other hand. You may need to repeat this test several times until you capture the entire transient well and are satisfied with the data. You can also adjust the position and zoom into the recorded interval to better view the transient response. Then press the **SAVE** button to save the data to a text file. You will use this data to calculate the combined moment of inertia for both machines in Task 5. You may also save a **screenshot** picture of your recorded transient for your record and comparison.

Task 2: Measuring Load Characteristics

You should now have both machines coupled on the test bench. Wire up the circuit as shown in Fig. 3 to take the measurements on both DC machines. Connect the voltmeter **V1** across the DC Machine **M1** terminals directly (not to the DC power supply!). Use the **Measurement Box** to display and measure the torque, speed, voltages, and currents on both machines, as depicted in Fig. 3. The second DC Machine **M2** will be used as a Generator loaded by the variable resistor via the **Load Resistor Box.** During this test, the **Load Resistor Box** may get very **hot!** By adjusting the load on the DC Generator Machine M2, you will emulate the mechanical load and change the mechanical torque applied to the **Motor in the Cradle** under test (DC Machine **M1**). You may need to increase the current limit of the **DC Power Supply** in order to keep the specified voltage for the subsequent tests.

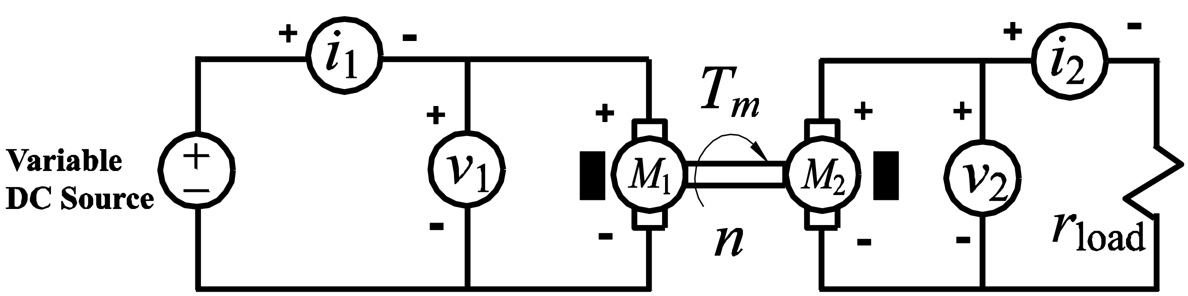


Fig. 3: Wiring diagram for the Load Characteristic(s).

Task 2 A: Load Characteristic – Speed Regulation

1) Switch OFF all load resistors in the **Load Resistor Box** and adjust the **Power Supply** to output about 40 - 45V. Record this set of measurements in the first column of **Table 2-A**. Use the first measurement under no load (no-load open-circuit voltage and speed) to calculate the voltage constant k_v and record it in **Table 2-A**. Remember that as you increase the load, it may be necessary to adjust the supply voltage V1 to the same value when the voltage drops under load!
2) Then, switch on the resistors in the **Load Resistor Box** one at a time, thus increasing the load torque. Take about 6 measurements and record the values in **Table 2-A**. Ensure the last measurement (last column of **Table 2-A**) corresponds to the case when **all** resistors are **ON**. This will be the maximum load. During this test, the **Load Resistor Box** may get very **hot**. This box has an internal cooling fan that has to be turned ON to reduce its temperature.

Task 2 B: Speed Control by Adjusting Voltage

1) Switch ON **all** load resistors in the **Load Resistor Box**. This will correspond to a mechanical load with maximum torque.
2) Vary the **DC Power Supply** to output 5 - 45V and record about 6 evenly-spaced measurements from almost zero speed (slightly spinning) to the maximum speed at maximum voltage. Write the measurements in **Table 2-B**.

Task 3: Speed Control Using DC-DC Converter (Inverter Box)

Keep the configuration of Task 2 (Fig. 3) with the **Measurement Box**, except now your Variable DC Source will be provided through the **Universal Inverter Box (DC-DC Converter)**. The **Inverter Box** takes the input DC voltage from the **DC Power Supply** (**red** for **positive**, and **black** for **negative** terminals, respectively), and outputs the Pulse-Width Modulated (PWM) voltage (chopped voltage) with variable frequency and duty cycle.

Connect the **Inverter Box** to the **Xantrex DC Power Supply** as depicted in Fig. 4. Pay attention to the polarity of the wires. Then, connect the motor circuit (circuit of Fig. 3) to the **Inverter Box** output terminals as shown in Fig. 4. Use the middle **B** terminal (yellow, **Gnd**) for the negative (ground), and use the left A terminal (**green**, **D**) for the positive output modulated with duty cycle D. You will be using only one "leg" of the Inverter to control the DC Motor. So, you can control the motor speed in one direction only (Quadrants I and II).

***Configuring the Universal Inverter Box*:**

The **mode** switch on the **Universal Inverter Box** should be in "**DC**" position, indicating that you will be operating it in DC-DC converter mode while driving your DC Motor. The **Input Src** control switches should be **turned up for Local control** using the knobs. Initially, set the switching frequency to a minimum, around 2.4 kHz, and turn the duty cycle to a minimum. The third knob controlling the current limit should be approximately turned to a middle position. Ask a TA to help you configure the circuit and the **Universal Inverter Box** if needed.

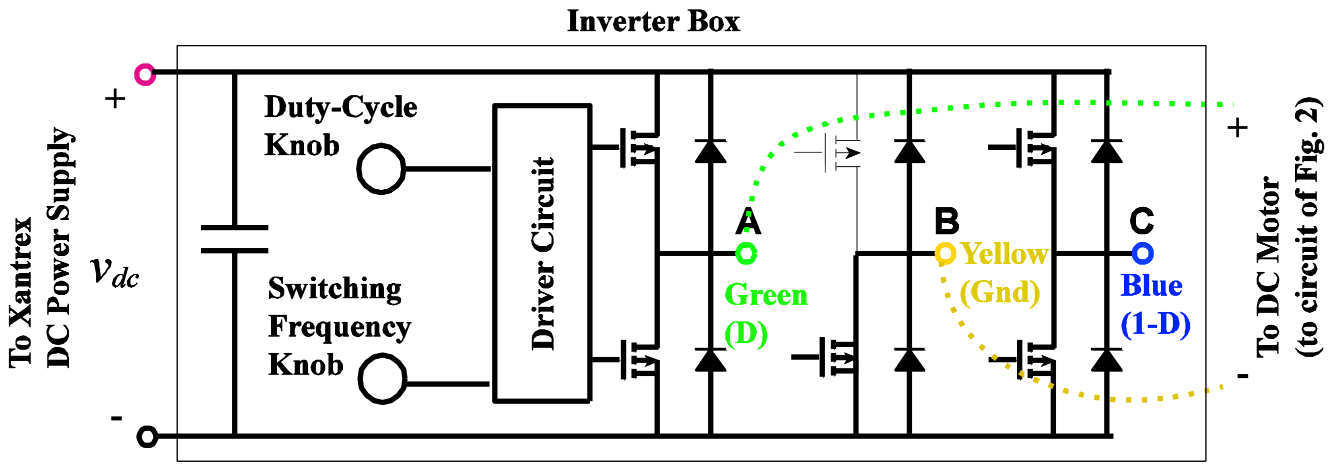


Fig. 4: Wiring diagram for the Variable DC Supply using the Universal Inverter Box.

Task 3 A: Speed Control by Adjusting the Duty Cycle (at 2.4 kHz PWM)

1) Switch **ON** all load resistors in the **Load Resistor Box**. This corresponds to a mechanical load at maximum torque. Turn on the **DC Power Supply** and slowly increase the output voltage from 0 to about 50 V DC. Set the initial switching frequency low to approximately 2.4 kHz.
2) Vary the **PWM Voltage Controller** duty-cycle ***D*** output in the range 0.1 – 0.9 and record about 5 evenly-spaced measurements from low speed to maximum speed. Write the measurements in **Table 3-A**.
3) Set the duty-cycle ***D*** to 0.5. Observe and **PAUSE / SAVE** the waveforms. You will use this data to determine the current ripple and estimate the inductance. For your records, you can also use the **Print Screen** key or save screenshots for later comparison.

Task 3 B: Speed Control by Adjusting the Duty Cycle (at 10 kHz PWM)

1) Continue from the configuration of Task 3 A, step 3 with the duty-cycle ***D*** set to 0.5. Increase the switching frequency to 10 kHz. You should notice that the current ripple is much smaller than it was at a switching frequency of 2.4 kHz. Observe and **SAVE** the waveforms. You will use this data to determine the current ripple. For your records, you can also use the **Print Screen** key to save these images for later comparison.
2) Vary the **PWM Voltage Controller** duty-cycle ***D*** output in the range 0.1 – 0.9 and make sure they are similar to the values you used in Task 3 A. Write the measurements in **Table 3-B**. Comment on some possible differences between this and the previous case. You should notice the difference in the current ripple ΔI_1 and even the acoustic noise during these two tests.

Task 4: Efficiency of Converter and Bi-directional Operation

Keep the configuration as in Task 3 (Fig. 3 and Fig. 4) with the **Universal Inverter Box**. Set the switching frequency to 5 kHz, and turn the duty cycle to a minimum as well. The knob controlling the current limit should be turned to approximately the middle & max position. If needed, ask a TA for help to configure your circuit and the **Universal Inverter Box**.

Task 4 A: Efficiency under load at 5 kHz PWM

1) Switch **ON all load resistors** in the **Load Resistor Box** and switch ON its internal fan for cooling. This corresponds to a mechanical load at maximum torque. Turn on the **DC Power Supply** and slowly increase the output to 50 V DC.
2) Vary the duty-cycle ***D*** in the range 0.1 – 0.9 and observe the changes in speed and torque, similar to Task 3 A.
3) Choose any duty-cycle ***D*** between 0.3 and 0.7 you like, and record only one set of measurements in **Table 4**. You will need this measurement to calculate the energy conversion efficiency of the system at all stages and put the results in **Table 4**. You also need to record the DC supply **current**!
4) After that, you can turn **OFF** the **DC Power Supply,** leaving the voltage knob at the same level.

Task 4 B: Bi-Directional Speed Control by Adjusting the Duty-Cycle

1) The same **Inverter Box** can also be used to operate the **DC Motor** in all four quadrants by using two of its "Legs." So, instead of using A (**green, D**) and B (yellow, **Gnd**) inverter terminals, now supply the Motor from A (**green, D**) and C (**blue, 1-D**) terminals, respectively. **Put the duty cycle knob in its middle position** and turn ON the **DC Power Supply**. Observe that the Motor may start to spin slowly in one direction or the other, depending on the effective duty cycle for this differential connection.
2) Observe the waveforms of voltages and currents of the **Motor** under test, and **slowly** change the duty cycle ***D*** in the range of 0.1 – 0.9. You should observe that the Motor can be made to spin in forward and reverse directions. Note that changing the duty cycle rapidly may cause the Motor to operate in regenerative braking mode, reversing the energy flow from the spinning (decelerating) motor back to the DC Power Supply. Please avoid this mode and change the speed and direction **slowly**! Since the given **DC Power Supply cannot** absorb the regenerated energy, it may shut itself OFF automatically to protect against overvoltage. If this happens, you will need to **restart the DC Power Supply**. Observe and **SAVE** the waveforms and/or **screenshots** for forward operation and reverse operation for future analysis and discussions in your report.
3) Turn **OFF** the DC Power Supply.

Task 4 C: Bi-Directional operation using Signal Generator to externally control Duty Cycle

1) Keep the configuration from Task 4 B, but now switch the duty cycle control to External control by moving the switch to a down position. Configure the **Signal Generator** (**Channel**

1) to produce the sinusoidal or triangular output with a 2.5 V offset and 0 to +5V peak-to-peak value, with a very low frequency of 0.05 to 0.1 Hz. (**Note:** Only Channel 1 is capable of specifying the needed 2.5 V offset). Use an additional BNC to BNC cable and check with the **Measurement Box** or the **Oscilloscope** to ensure that your generator signal corresponds to the above specifications. Then, the output signal amplitude is set to a minimum value.

2) Turn ON the **DC Power Supply**. You should observe that the machines are slowly spinning and may be changing direction. Experiment with increasing the signal amplitude and frequency, and observe how your motors can follow. The frequency should be very low, since your DC Motors have high inertia and cannot follow rapid speed changes. You can now imagine designing an external controller that can be programmed to control the subject DC Motors in a predefined pattern to achieve specific objectives.

Task 5: Calculations and Analysis

This part must be included with your Lab Report:

Task 5 A: Determining Motor Parameters

1) Calculate the armature resistance R_a and record the value in Table 1-A.
2) Calculate the motor constant from the no-load data obtained in Table 1-B, Task 1. This is readily done by generating the value of $k_t = \frac{V_a - I_a R_a}{\omega_r}$ for each measured point and averaging the result. Also, calculate the voltage constant k_v for the second DC Machine that was used as a generator and record this number in Table 2-A. You have to use the open-circuit voltage (before you connect the load resistor). What can you say about these two constants and their values? Are they similar or different, and why?
3) Calculate the friction torque T_{fric} in Table 1-B, which represents your combined rotational loss. Plot $T_{fric}(n)$ as a function of rotor speed n. This will require using the recently found torque constant k_t. What can you say about the curve? Is the loss predominantly from sliding friction, viscous damping, or windage (turbulent airflow)?
4) Given that you now know the friction torque at all speeds, you can estimate the system moment of inertia with reasonable accuracy based on the deceleration rate inferred from your $\frac{dE_a}{dt}$ measurement and recorded in Task 1 C. Calculate the moment of inertia J_{rotor} using your best estimate of the friction torque at the speed where $\frac{dE_a}{dt}$ was measured. In particular, you will have to use $J_{rotor} \frac{d\omega_r}{dt} = \frac{J_{rotor}}{k_t} \frac{dE_a}{dt} = T_{fric}(\omega_r)$.
5) Based on the recorded stopping transient in Task 1 D, calculate the combined moment of inertia of both machines $J_{combined}$ (when they are coupled), and compare the result with J_{rotor} obtained in Step 4 above.

6) Based on the recorded data from Task 3, estimate the armature inductance L_a. You will need to use the current ripple and voltage information from Task 3 A or B, as well as the equations from your Pre-Lab. First, for a less accurate estimate, you can neglect the resistance R_a and use the equation: $v_a = L_a \frac{\Delta i_a}{\Delta t} + E_a$. Optional: You may use more accurate equations that you have derived in your Pre-Lab, assuming that you know the value of R_a. Compare these two results in terms of accuracy. Write the value of inductance in Fig. B together with all other parameters.
7) Complete Fig. B by filling in all remaining machine parameters.
8) Based on your measurements in Task 2B, Table 2-B, establish the equivalent mechanical load torque vs. speed characteristic of the DC machine acting as a generator and loaded with Resistor Box (with all resistors connected), $T_{m-load}(n)$, and plot it. Generally, load torque should increase with the speed. Comment on or explain the shape of this characteristic. Is it linear or not, and why? You will also need this for other calculations using your model or equivalent circuit.

Task 5 B: Equivalent Circuit vs. Measured Comparison

1) Use the equivalent circuit of the DC machine that you have used as the Motor, and calculate and plot the speed-torque characteristic $n(T_m)$ corresponding to the input voltage in your Task 2A, Table 2-A. Do not forget to include the effects of friction in your predicted curve (T_e vs. T_m)! Superimpose the measured and predicted characteristics on the same plot. Comment on the results and the expected vs. measured speed-voltage regulation.
2) Use the equivalent circuit of the DC machine and calculate the speed-voltage characteristic $n(V_1)$ of the loaded machine (use $T_{m-load}(n)$ that you have established before). Do not forget to include the effects of friction in your predicted curve. Superimpose on the same plot the characteristic measured in Task 2 B, Table 2-B, and the predicted characteristic. Comment on the results.
3) Calculate and plot the motor efficiency vs. current $\eta(I_1)$ characteristic based on machine equivalent circuit (plus the measured friction). On the same plot, also show the efficiency of the single machine established from the measured data in Task 2 A, Table 2-A. Compare the results. Calculate/note at what current the Motor has maximum efficiency.

Task 5 C: General Questions

1) Were there any differences in your measurement of the armature resistance? If so, how can you explain them?
2) What can you say about the accuracy of the equivalent circuit compared to your measurements?
3) Which method of speed control (Task 2 or Task 3/4), in your opinion, is more practical for large motors and/or automotive/robotics applications? Briefly explain.
4) Also, plot on different plots the armature current and voltage (3 to 6 cycles) for Task 3-A-3 and Task 3-B-1. What can you say about the effect of switching frequency?

5) In the energy conversion chain presented in Table 7, which element appears to be the least efficient, and why?
6) Compare and discuss the captured waveforms of voltages and currents for the bi-directional operation in Task 4 B, with what we discussed in the lecture notes. Did you use the complementary or differential PWM in this task?

Reporting

Prepare the Lab Report that includes:

1) Title Page (all filled-in, with electronic signatures).
2) Pre-Lab (scanned or pictures of pages)
3) Pages with the measured data and your comments (pages 16 – 19).
4) Additional pages with **Calculations and Analysis**, discussions, and/or answers to questions, plots and/or screenshots with comments, as required in Task 5.
5) Brief **Conclusion/Summary** stating what you and your lab partner have learned in this Lab.
6) **Appendix:** Please include any additional MATLAB code or Windows of Simulink models that you may have used for this Lab.

Note: All reports must be typed. No exception.

Submit your report in electronic form <u>as a single PDF file</u> to the Canvas system for this course before the stated deadline.

Name your file as YourName_yourID_LabX_report.pdf

ELEC 342

Lab Experiment #3

Section: ___

Bench #: ___

Partners	Student ID #:	% participation	Signatures

Date Performed:

Date Submitted:

Task 1A, Table 1A: Armature + Brush + Wires Resistance Measurement

<table>
<tr><td colspan="3">V_1, V</td><td colspan="3">I_1, A (Do not exceed 6 A)</td><td colspan="3">**Calculate** R_a, Ω</td></tr>
<tr><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td></td><td></td><td></td></tr>
<tr><td colspan="3">Average</td></tr>
<tr><td colspan="6">Multimeter measurement (for comparison)</td><td colspan="3"></td></tr>
</table>

Task 1B, Table 1B: No-Load Measurement

<table>
<tr><td>**Measurement**</td><td>**1**</td><td>**2**</td><td>**3**</td><td>**4**</td><td>**5**</td><td>**6**</td></tr>
<tr><td>$V_1(ave), V$</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$I_1(ave), A$</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$n_1(ave), rpm$</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>**Calculation**</td><td colspan="6"></td></tr>
<tr><td>k_t, $[V \cdot \sec/rad]$</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Average k_t</td><td colspan="6"></td></tr>
<tr><td>T_{fric}, Nm</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Task 2A, Table 2A: Load Test Measurement (up to 6 measurement points)

<table>
<tr><td>Measurement #</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td></tr>
<tr><td colspan="7"></td></tr>
<tr><td>$V_1(ave), V$</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$I_1(ave), A$</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$P_1(ave), W$</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="7"></td></tr>
<tr><td>$V_2(ave), V$</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$I_2(ave), A$</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>$P_2(ave), W$</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="7"></td></tr>
<tr><td>n, rpm</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>T_m, Nm</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>P_2 / P_1</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="3">$SR = (n_1 - n_{6,load}) / n_{6,load}$</td><td colspan="4"></td></tr>
<tr><td colspan="3">DC Machine (Generator) Voltage Constant
$k_v = V_{2,oc} / \omega_r$</td><td colspan="4"></td></tr>
</table>

Task 2B, Table 2B: Motor Speed Control by Adjusting Voltage

Measurement #	1	2	3	4	5	6
$V_1(ave), V$						
$I_1(ave), A$						
$P_1(ave), W$						
$V_2(ave), V$						
$I_2(ave), A$						
$P_2(ave), W$						
n, rpm						
T_m, Nm						
P_2 / P_1						

Task 3A, Table 3A: Motor Speed Control by Duty-Cycle (2.4 kHz): Vdc =

Measurement #	1	2	3	4	5
Duty-Cycle, $\boldsymbol{D}$					
$V_1(ave), V$					
$I_1(ave), A$					
Current Ripple $\Delta I_1, A$					
$P_1(ave), W$					
$V_2(ave), V$					
$I_2(ave), A$					
$P_2(ave), W$					
n, rpm					
T_m, Nm					
P_2 / P_1					

Task 3B, Table 3B: Motor Speed Control by Duty-Cycle (10 kHz): Vdc =

Measurement #	1	2	3	4	5
Duty-Cycle, $\boldsymbol{D}$					
$V_1(ave), V$					
$I_1(ave), A$					
Current Ripple $\Delta I_1, A$					
$P_1(ave), W$					
$V_2(ave), V$					
$I_2(ave), A$					
$P_2(ave), W$					
n, rpm					
T_m, Nm					
P_2 / P_1					

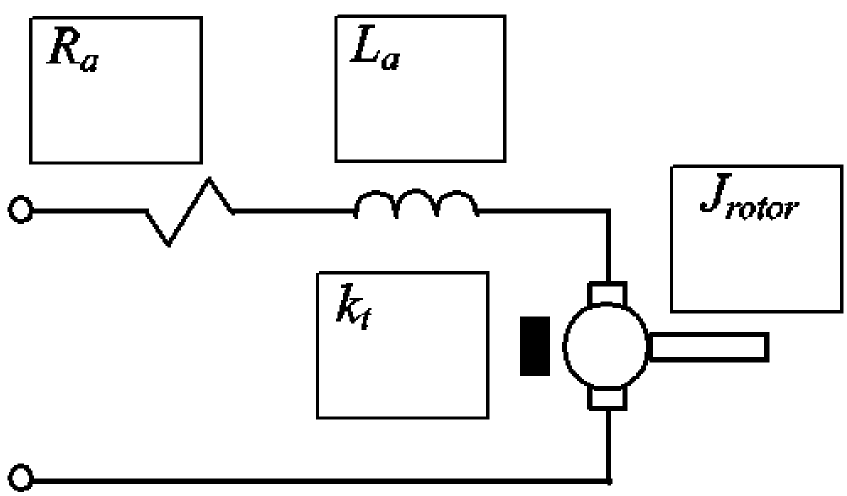


Fig. B. DC Machine Equivalent Circuit. Fill in the corresponding boxes with machine parameters that you have identified. Make sure to include the units.

Task 4, Table 4: Motor Speed Control using Universal Inverter Box (at 5 kHz)

Duty-Cycle, $\boldsymbol{D}$	
$V_1(ave), V$	
$I_1(ave), A$	
$P_1(ave), W$	
$V_2(ave), V$	
$I_2(ave), A$	
$P_2(ave), W$	
n, rpm	
T_m, Nm	

<table>
<tr><td colspan="7">Use the set of measurements and complete the following section of the Table.</td></tr>
<tr><td colspan="2">Input to Inverter Box</td><td rowspan="4">Input power at the DC Motor terminals P_{dc-mot}, W</td><td rowspan="4">Output mechanical power P_m, W</td><td rowspan="4">Efficiency of the Inverter, % P_{dc-mot}/P_{inv}</td><td rowspan="4">Efficiency of the Motor, % P_m/P_{dc-mot}</td><td rowspan="4">Efficiency of Inverter-Motor combined, % P_m/P_{invt}</td></tr>
<tr><td>Voltage, Vdc</td><td>Current, A</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Total input power to the Inverter Box P_{inv}, W</td></tr>
<tr><td colspan="2"></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Consider the chain of components that you had in this Lab, including the following:

DC Source, **DC-DC Converter**, **DC Machine 1**, **DC Machine 2**, and **Load Resistors Box**.

Using the data you recorded in Table 4, calculate and fill in the energy conversion efficiency at each energy conversion stage in the above chain. Comment on the efficiency of these stages in delivering the energy to the final resistor load.