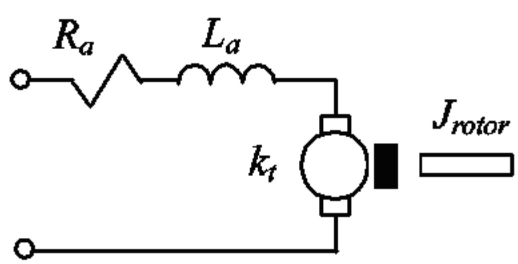
Lab-3: Permanent Magnet Brushed DC Motor

Objectives and Overview

The objectives for this sequence of laboratory experiments are:

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

By doing a set of measurements, the students will determine the motor torque/voltage constant k_t / 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 to the measured ones. The students will also use a DC-DC converter with PWM to control the motor by varying the duty-cycle d.



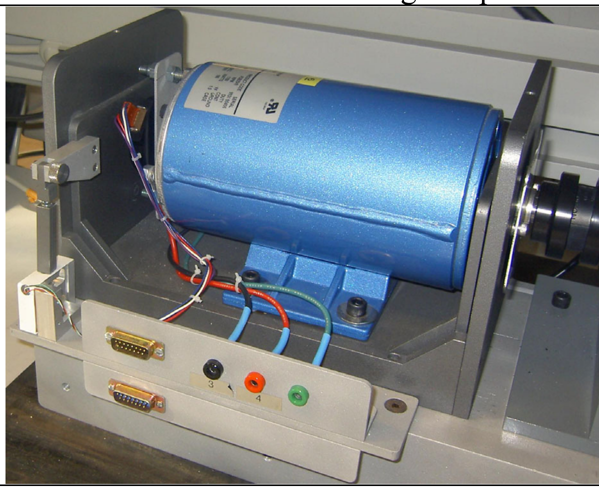
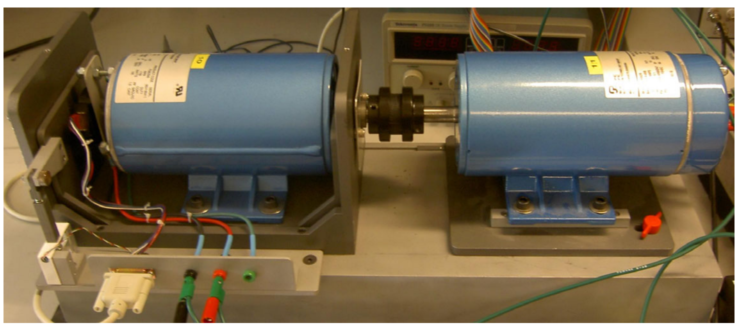
Preparation (Pre-Lab)

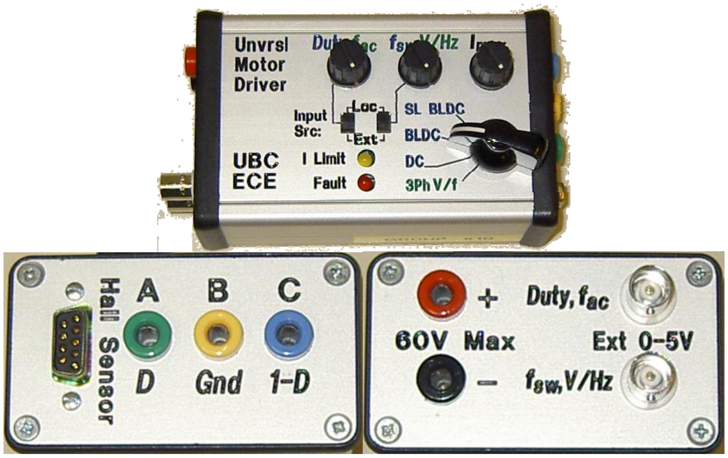
It is expected that the students have read and understood the corresponding chapter in the textbook and reviewed the lecture notes module corresponding to DC Motors. The students should be familiar with the theory and principle of DC machine operation and equivalent circuit. Also, make sure to review the DC-DC converter operation using PWM voltage control and the four quadrants of operation. The Pre-Lab page should include the following:

- Prepare a list of equations for calculating the equivalent circuit parameters using the Blocked-Rotor and No-Load Tests.
- Assume the motor is operating in the first quadrant using DC-DC converter, and at a given speed, $E_a = k_t \omega_r$. Sketch I_a. Rewrite the equation $v_a = R_a i_a + L_a \dfrac{di_a}{dt} + E_a$ to find the expression for the armature inductance 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: Consider resistance R_a.

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 which enable 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 though that internal friction and loss torque of the machine will not be coupled to the torque sensor.
	**Motor Bench:** 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 rubber 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 in to the back of the Measurement Box.
	**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 the heat in case there is a significant power delivered to the load. Be careful! This box may get very hot, especially its heat-sink that is 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 adjustable output voltage 0-60V and current limit 0-18A, which is sufficient for most experiments in this laboratory.



Universal Inverter Box: A multi-purpose inverter was designed for driving 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. For this mode, the mode switch should be in **DC** position (blue font). 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)

Measurement Box:

Each bench is equipped 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 re-scaled 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** has one power switch on its back panel 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 color-coded. It is strongly recommended that you use appropriate and consistent color wires for each channel of measurements. This will make it easier for you to wire-up your circuits and subsequently check it and find any mistakes.

Setting-Up the DAQ System

Login to your local PC and locate the program **DC Motor Analysis**. Double-click on the icon and start the program. A window shown in Fig. A should appear on your PC screen indicating that you are ready to start taking 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 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. The 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 the 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 also has the capability to apply digital filtering to the measured voltages and currents. The user can turn the filter ON and OFF, as well as adjust the cut-off frequency. **For the purpose of this Lab the filter should be OFF in all measurements.**

The Measurement Window period (in ms) can be adjusted during the process of taking measurements in order to better capture the desired waveforms 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 into any fragment of the recorded window by using the slide buttons **ZOOM** and **POSITION** on the bottom of the panel. Pushing the bottom **SAVE** brings the window for saving the data file. The user should name the file and save it into 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.

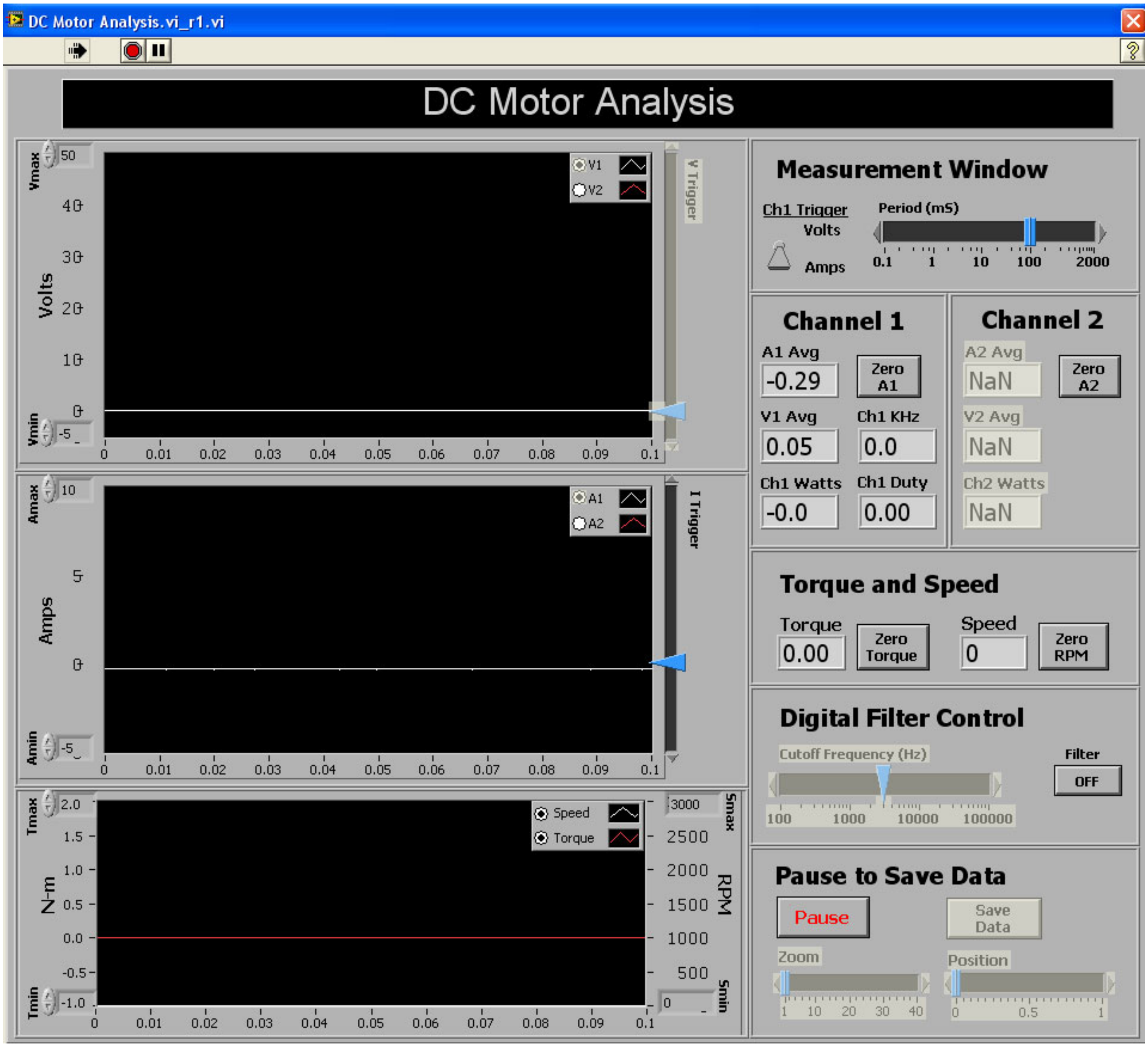


Fig. 1: LabView program interface DC Motor Analysis.

Setting-Up the Experiment

In this part, the students will use the **Xantrex DC Power Supply** as the adjustable dc source. Make sure that initially the voltage and current limit control knobs are turned all the way to zero before turning it ON. You will be using this power supply for the Tasks 1 – 4, circuits on Fig. 2 through Fig. 4. 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.

Task 1: Characterization of the Motor under No-Load

Wire-up the circuit as shown in the Fig. 2 for taking the measurements on the **Motor in 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.

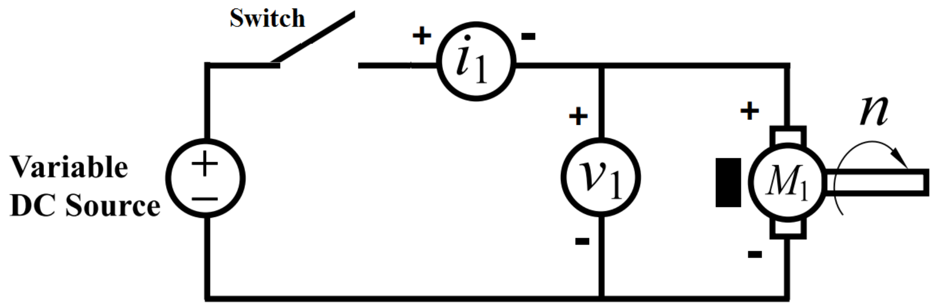


Fig. 2: Wiring diagram for the No-Load Test(s).

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

While it is possible to use the bench top Multimeter for this task, a more accurate result is obtained by lightly powering the motor and measuring the voltage and current when the shaft is **not spinning** – Blocked-Rotor Test. First, the **DC Power Supply** should be OFF and turned to output zero volts. 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 Technician for a **Metal Lock** that can be inserted in a special slot on the top of the **Motor Cradle** to lock the shaft. Slide in the lock plate and manually rotate the shaft to make sure that the lock clicks-in and locks properly.
2) Make sure that the program **DC Motor Analysis** is running on your PC. Press the **Zero** buttons on the **DC Motor** software interface to remove any possible offset in the current measurements. Turn on the **DC Power Supply** and keep monitoring 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 + resistance of 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 be working only 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-space 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**). Make sure that the **DC Motor** software is set for the largest measurement window (approximately 2000ms) and that all measurements are stable.
2) Then, with one hand, disconnect the **Power Supply** by turning OFF the **Switch** in 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. When you have captured the transient that you want, you can also adjust the position and zoom into the recorded interval to better view the transient response. Then, push the **SAVE** button to save the captured data in a text file. You will use this data to calculate the moment of inertia for this motor in Task 5.

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 Cradle** under test using 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 increased the total moment of inertia. Since the machines are very similar, their internal friction may be assumed 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 loud noise, you may need to re-adjust their coupling and mount.
3) Prepare to record another deceleration transient. Then, 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 another hand. You may need to repeat this test several times until you well capture the entire transient and satisfied with the data. You can also adjust the position and zoom into the recorded interval to better view the transient response. Then, push the **SAVE** button to save the data in a text file. You will use this data to calculate the combined moment of inertia for both machines in Task 5.

Task 2: Measuring Load Characteristics

You now should have both machines coupled on the test-bench. Wire-up the circuit as shown in the Fig. 3 for taking 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 of the DC Generator Machine **M2** you will be emulating the mechanical load and changing the mechanical torque applied to the **Motor in 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.

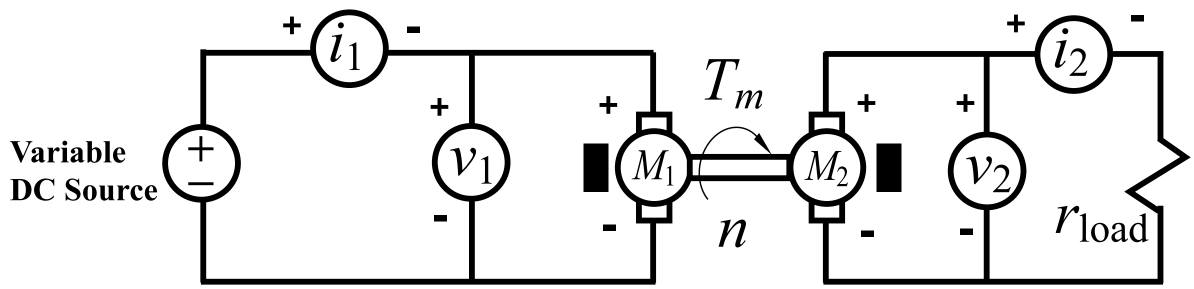


Fig. 3: Wiring diagram for the Load Characteristic(s).

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. Make sure 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

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 **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 the 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 will be able to control the motor speed in one direction only (Quadrant 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 for 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 which is around 2.4 kHz, and turn the duty cycle to minimum as well. The third knob controlling the current limit should be approximately turned to a middle position. If needed, ask a TA for help you configure the circuit and the **Universal Inverter Box**.

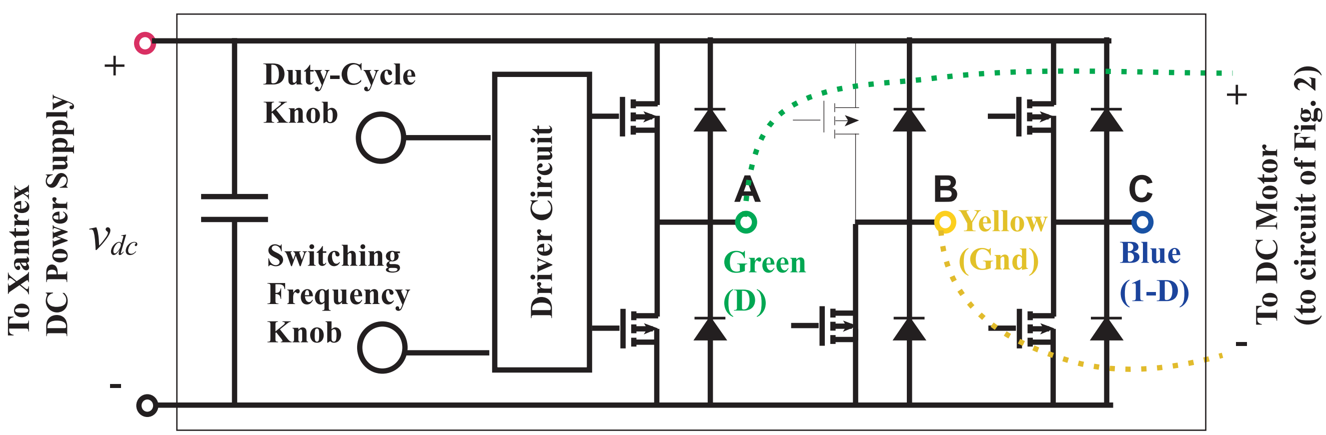


Fig. 4: Wiring diagram for the Variable DC Supply using the Universal Inverter Box.

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 will correspond to a mechanical load with 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 the 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 for determining the current ripple and estimating the inductance. For your record, you can also do the **Print Screen** or save the screenshots and save these images for later comparison.

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

1) Continue from 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 switching frequency of 2.4 kHz. Observe and **SAVE** the waveforms. You will use this data for determining the current ripple. For your record, you can also do the **Print Screen** and save these bitmap 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 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 minimum as well. The knob controlling the current limit should be approximately turned to a middle to 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 will correspond to a mechanical load with 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, record only one set of measurement in Table 4. You will need this measurement to calculate the energy conversion efficiency at all stages and put the results in Table 4.
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 terminal A (**green, D**) and terminal B (**yellow, Gnd**) inverter terminals, now supply the motor from terminal A (**green, D**) and terminal C (**blue, 1-D**), respectively. **<u>Put the duty cycle knob in its middle position</u>** 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 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 very fast may cause the motor to operate in a regenerative breaking mode, which will reverse the energy flow

from the spinning (decelerating) motor back to the DC Power Supply. Please avoid this regeneration mode and change the speed and direction **slowly**! Since the given **DC Power Supply cannot** absorb the regenerated energy back, it may shut off itself automatically for protection against over-voltage. If this happens, you will need to **re-start the DC Power Supply**. Observe and **SAVE** the waveforms and/or **screenshots** for forward operation and then for reverse operation, for your 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

4) **Optional Demonstration by the TA:** Keep the configuration from Task 4 B, but now switch the duty cycle control to External control by moving the switch to down position. Configure the Signal Generator to produce the sinusoidal or triangular output with the 2.5 V offset and 0 to +5V peak-to-peak value, with the very low frequency of 0.05 to 0.1 Hz. Use additional BNC to BNC cable and check with the Measurement Box or the Oscilloscope that your generator signal corresponds to the above specifications. Then set the output signal amplitude to a minimum value.
5) Turn ON the **DC Power Supply**. You should observe that machines are slowly spinning and may be changing their directions. Experiment with increasing the signal amplitude and frequency and observer how your motors can follow. The frequency should be very low since your DC Motors have large inertia and will not be able to follow fast changes in speed. You can now imagine that one can design an external controller that may be programmed to control the subject DC Motors in a pre-defined pattern to follow some 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 $k_t = \dfrac{V_a - I_a R_a}{\omega_r}$ 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 connected 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 now can estimate with reasonable accuracy the system moment of inertia based on the rate of deceleration 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, and 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. A together with all other parameters.
7) Complete Fig. A 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 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. It is 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 on the same plot the measured and the predicted characteristics. 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 date 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) What can you say about the accuracy of equivalent circuit compared to your measurements?
2) Which method of the speed control (Task 2 or Task 3/4) in your opinion is more practical for large motors and/or automotive/robotics applications? Briefly explain.
3) Plot on different plots the armature current and voltage (3 to 6 cycles) for the Task 3 A step 3) and Task 3 B step 1). What can you say about the effect of switching frequency on the operation of your DC motor?
4) In the energy conversion chain presented in Table 4, which element appears to be the least efficient and why?
5) Compare and discuss the captured waveforms of voltages and currents for the bi-directional operation in Task 4 B, with what you discussed in your lecture notes?

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 14 – 18).
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 have used for this lab.

Note: The lab reports must be typed. No exception!

ELEC 344

Lab Experiment: ___

Section: ___

Bench #: ___

Partners	Student ID #:	% participation	Signatures

Date Performed:

Date Submitted:

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

V_1, V			I_1, A			**Calculate** R_a, Ω		
						Average		

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

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

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

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						
$SR = \left(n_1 - n_{6,load}\right)/ n_{6,load}$						
DC Machine (Generator) Voltage Constant $k_v = V_{2,oc} / \omega_r$						

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, ***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					

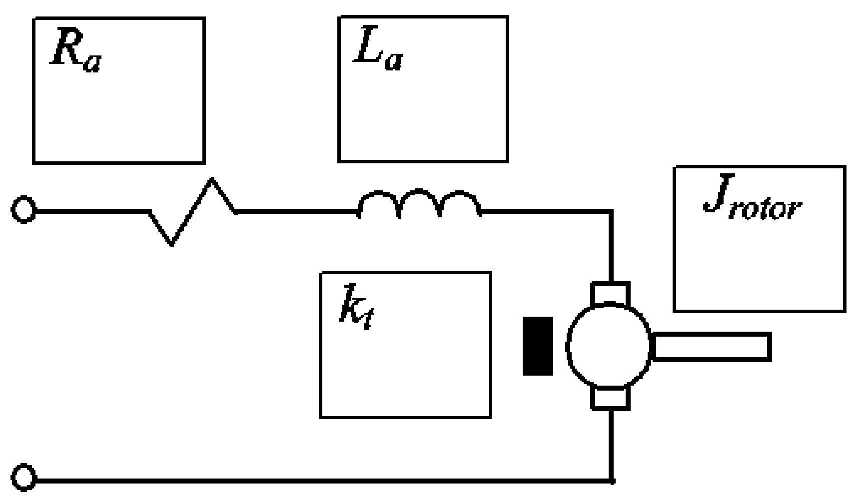


Fig. A. DC Machine Equivalent Circuit. Fill-in the corresponding boxes with machine parameters that you have identified. Make sure to include the units.

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

Measurement #	1
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 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 the 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 to deliver the energy to the final resistor load.