Lab-4: Permanent Magnet Synchronous Machine – Brushless DC Motor

1 Objectives and Overview

The goals for this laboratory experiment are:

- To fully characterize a 210W PM Synchronous Machine, which is also a Brushless DC Motor;
- Starting, synchronizing, and operating of Synchronous Motor from a fixed frequency source;
- Operating of PM Synchronous Motor with Hall-sensor-driven Inverter - Brushless DC Motor operation.

By doing a set of initial measurements, the students will determine parameters of the PM synchronous machine per-phase equivalent circuit

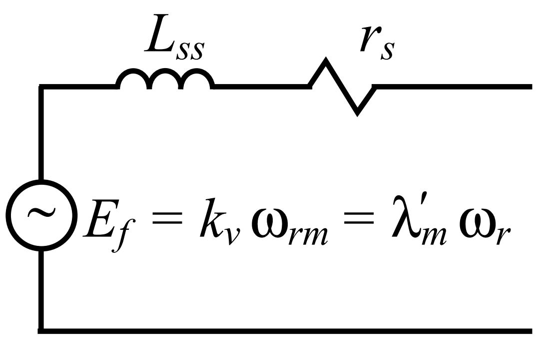


Fig. 1: PM synchronous machine per-phase equivalent circuit.

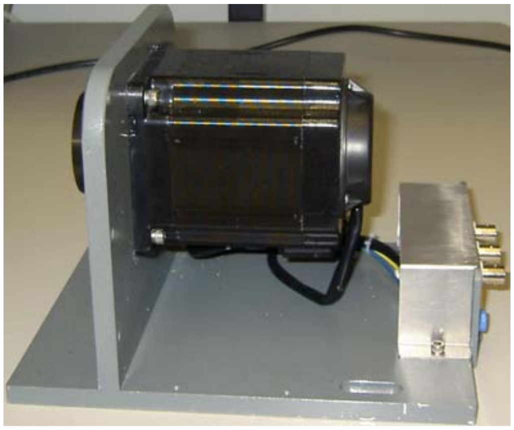
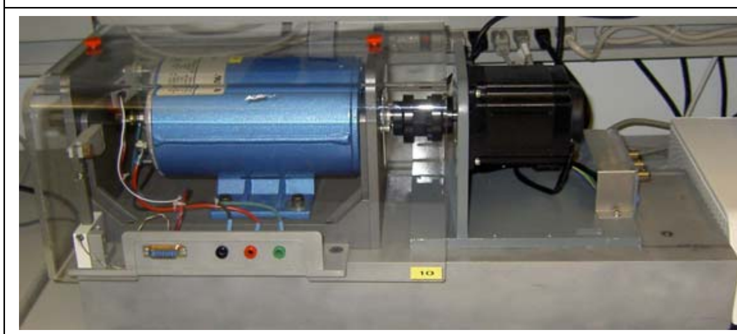
This equivalent circuit and the equations discussed in class assume a symmetric Y-connected winding. Based on the determined parameters, the students will develop a steady-state model (equivalent circuit) of the given PM Synchronous Machine. In the first part of the Lab, the students will perform a synchronization test and motor operation. In the second part, the student will drive the PM Synchronous Machine from an inverter that will be controlled from the Hall-Effect sensors, thus implementing the Brushless DC motor operation.

2 Preparation

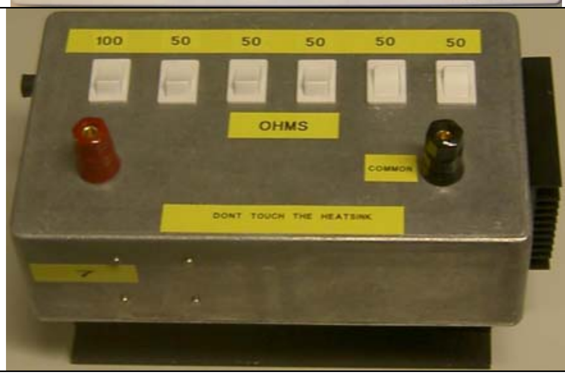
It is expected that the students have read and understood the chapters in the Textbook and reviewed the lecture notes corresponding to both **Synchronous Machines** and **Brushless DC Motors**. The students should be familiar with the theory and principle of Rotating Magnetic Field, Synchronous Machine operation and equivalent circuit. Since the PM Synchronous Machine that you will be using **is not designed** to operate at 60 Hz sinusoidal AC voltages, be prepared to see non-sinusoidal voltages and currents. Also, when operating as a Brushless DC Motor, the frequency may be significantly higher than conventional 60 Hz.

3 Apparatus

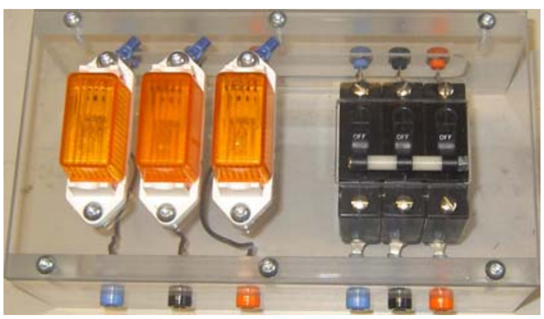
This lab includes the following components:

	**PM Synchronous Machine – Brushless DC Motor:** This is a PM Synchronous Machine that can operate from a fixed frequency source as well as from a variable frequency inverter. The machine is equipped with Hall-Effect sensors, which makes it possible to operate as a Brushless DC Motor. This machine should be mounted on the Motor Bench, wherein the shaft is coupled to the Dynamometer for taking the torque and speed measurements.
	**Prime Mover / Dynamometer Cradle:** A DC machine is mounted in a special cradle to permit measurements of the torque and speed on the shaft. 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. The Dynamometer also has an optical position encoder mounted on the back of its shaft (left side) for measurement of speed.
	**Motor Bench:** The **PM Synchronous Machine** under test should be mounted on the Motor Bench as shown on the left. A DC machine mounted on the Cradle is used as a prime mover as well as mechanical load. The shafts of these two machines should be mechanically coupled.
	**Measurement Box:** This is a multi-functional unit that can measure up to 3 voltages and up to 3 currents simultaneously. 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 voltage and 3 current channels, respectively.

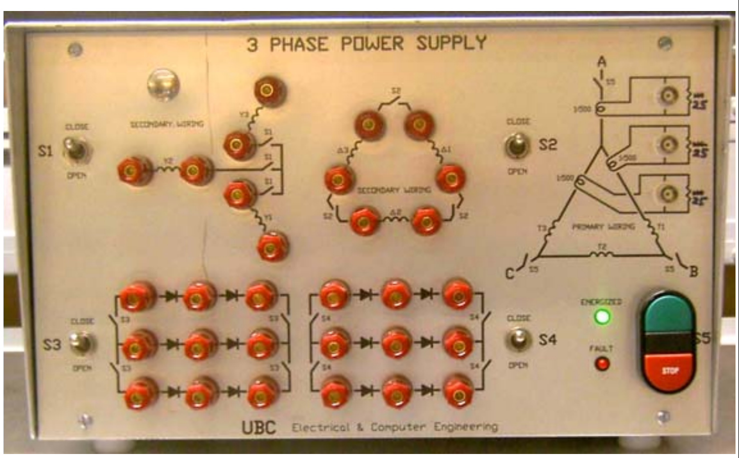
NI ELVIS Box: The Measurement Box must be plugged into the National Instrument unit (NI ELVIS), which in turn connects to the Data Acquisition (DAQ) card inside the PC.



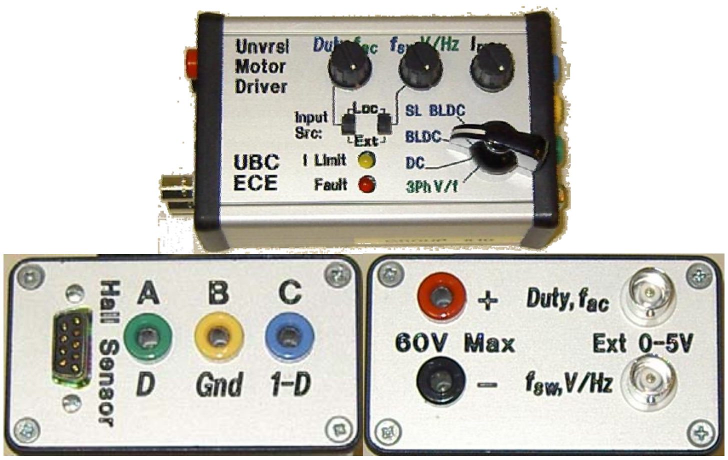
Load Resistor Box: The Load Box contains 50 and 100 Ohm resistors which can be switched on in parallel to each other. The box is equipped with a cooling fan to help dissipate the heat. The fan may be turned on/off by an additional switch in the side. However, the fan will come on automatically if the box is overheated.



3-Phase Breaker & Synchronization Lamps: 3 lamps and a 3-phase switch are mounted together in a box. This box is used fo the Synchronization Test, wherein the students synchronize the operation of PM Synchronous Machine with the source, or the two Synchronous Generators (Alternators).



AC Power Supply: A flexible 3-phase AC/DC Power Supply box was built specifically for the small-motors labs. There are two 3-phase transformers inside, one that can readily be configured into a ‘Y’ (wye) connection and the other that can be configured into “Δ” (delta). Those transformers are fed from an internal 3-phase Variac that can be used to adjust the output voltage to the desired level. It also has two 3-phase diode bridges for producing the DC output. **Right Panel:** The Power Supply transformers are fed from an internal 3-phase Variac that can be used to adjust the output voltage to the desired level.

	**DC Power Supply:** A flexible regulated Xantrex XHR6018 DC Power Supply will be used to supply the DC motors in this Lab 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:** A multi-purpose inverter was designed for driving various AC and DC motors. In this lab, you will use this Inverter to operate the Brushless DC Motor. For this mode, the switch should be in **BLDC** position as shown on the figure. The Inverter is also equipped with two knobs to control the duty cycle and the frequency when implementing the Pulse-Width-Modulation (PWM). The last knob on the right adjusts the current limit.

4 Experimental Part:

Task 1: Setting-Up the Synchronous Motor Experiment

1) Measurement Box and LabView Program:

The **Measurement Box** must be tightly plugged on the top of the National Instrument unit (NI ELVIS). The National Instrument unit (NI ELVIS) has two power switches (one on the front and one on the back – right side) that must be turned on. Login into your local PC and locate the program **3-Phase Motor Analysis**. Double-click on the icon and start the program. The window shown in Fig. 1 should appear on your PC screen indicating that you are ready to start taking measurements. The **3-Phase Motor Analysis** program interface is set up to display the real-time torque, speed, AC voltages, and AC currents in each phase. The program also computes and displays the RMS voltages and currents, the average phase power factor angle, and the total real power. Remember to push buttons **ZERO** before each test to remove any offset when measuring torque and speed. The program can **PAUSE** and **SAVE** the measured data. The program also has digital Filter, which should be turned **OFF**. The button **Subtract Zero Sequence** should be **ON**. The program can display selected variables. In this lab, please remember **to check all the boxes** so as to measure all three phase voltages and currents.

Ask a TA to help you with the program if you have a problem locating and/or running it.

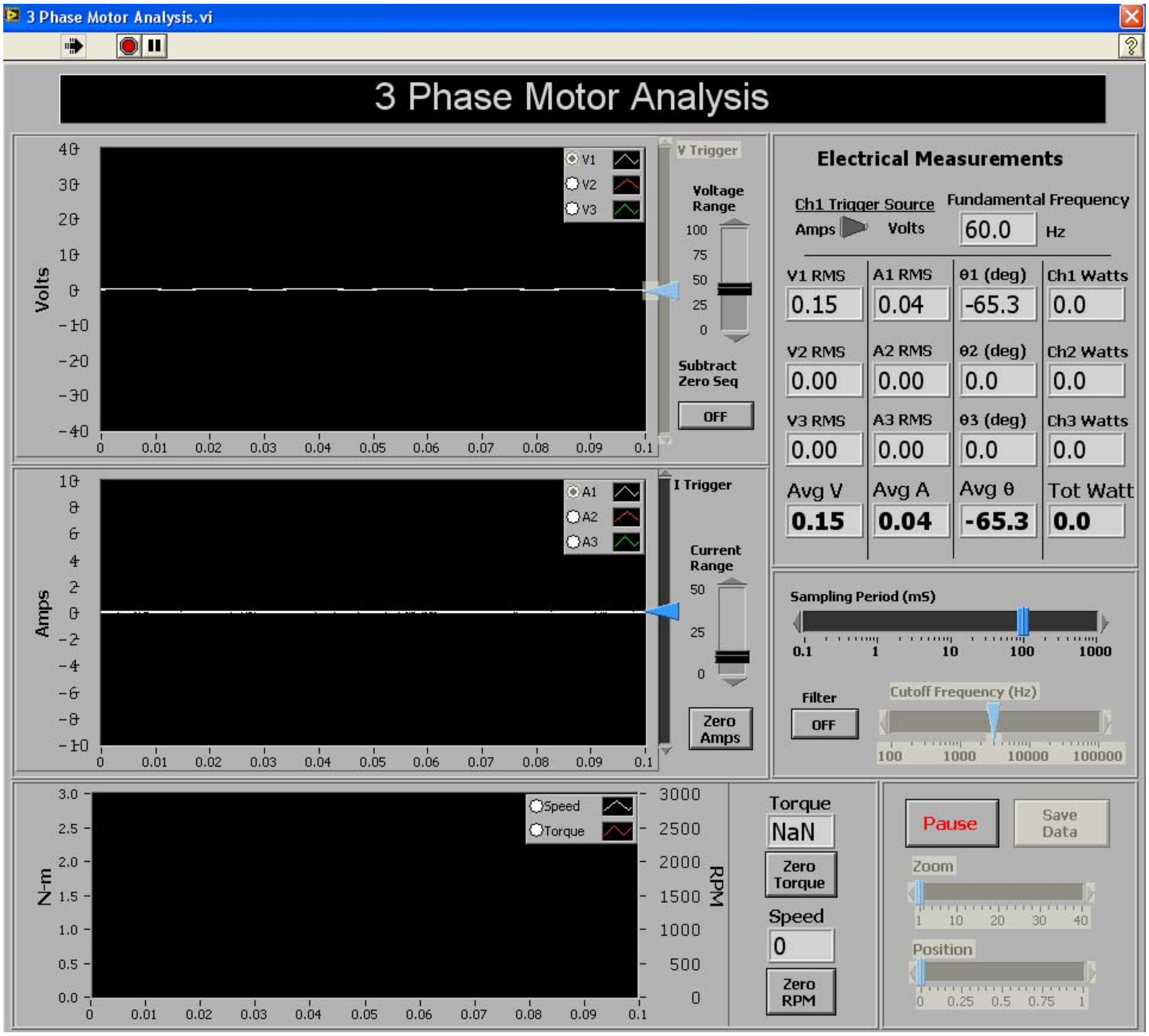


Fig. 1: LabView interface for taking measurements with 3-Phase Motors.

2) AC Power Supply:

The multi-purpose **AC Power Supply** has two sets on windings ‘Y’ (wye) and “Δ” (delta), the output voltage from which can be readily adjusted by the knob on the right side of the box. You can choose either ‘Y’ or “Δ” to provide 3-phase variable AC voltages that you will use to drive the PM Synchronous Motor. Appropriate Switch (**Switch S1 or S2) must be closed.**

3) PM Synchronous Machine:

The **PM Synchronous Machine** must be mounted on the right side of the **Motor Bench** with its shaft tightly coupled to the **DC Machine** in the Cradle. The **PM Synchronous Machine** has several connections on the back side that are shown in detail in Fig. 2. In the first part of the Lab, the three phases A, B, and C are to be connected to the 3-Phase **AC Power Supply** through the **Measurement Box** as shown in Fig. 3 to enable the Synchronous Motor operation. The combined output of Hall Sensors will be used in the second part of the Lab to enable the Brushless DC Motor operation.

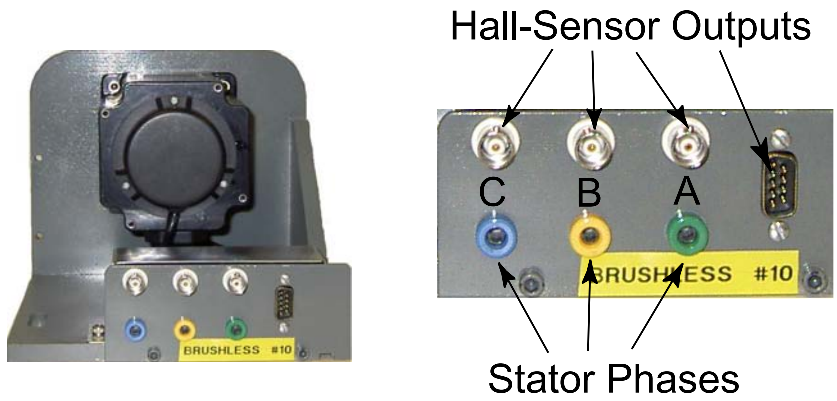


Fig. 2: PM Synchronous Machine terminals.

4) Main AC Circuit:

Wire up the circuit as shown in Fig. 3 so that you can simultaneously measure current and voltage in each phase. Make sure that the polarity of each current and voltage channel are connected as shown in Fig. 3 and that the channels are ordered consistently, e.g., Ch.1 current and Ch. 1 voltage are connected to the same phase (same applies to the other channels). All phases must be consistent. **Mismatching the channels will result in incorrect measurements**. Note that Voltmeter Channels form a floating neutral point. This neutral point is used to measure the phase voltages. Although the stator winding is Y-connected, its actual neutral point is not available at the motor terminals. To be able to measure the phase voltages correctly, the button **Subtract Zero Sequence** on the **3-Phase Motor** program interface should be **ON**. Also, **check the boxes to measure all three voltages and currents, as well as torque and speed.**

You will also need the **Synchronization Lamps** and **3-Phase Circuit Breaker,** which are mounted in one box. Use very short wires to connect the Lamps and the Breaker terminals, and use long colour wires elsewhere as appropriate. Make sure that the **3-Phase Circuit Breaker** is initially **OFF**. Please pay a particular attention to the sequence of phases.

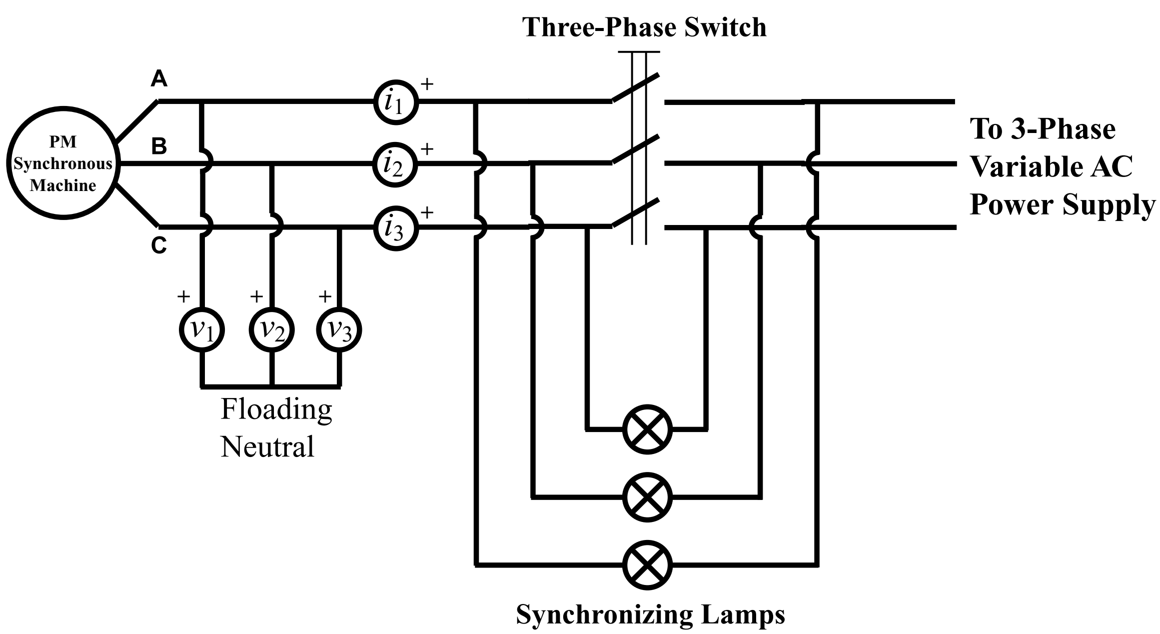


Fig. 3: Wiring circuit for synchronous motor tests and operation.

5) Prime Mover DC Motor – Mechanical Load:

The **DC Machine** in the Cradle is initially used as a prime mover to bring the **PM Synchronous Motor** up to synchronous speed corresponding to the 3-Phase 60 Hz AC Power Supply. For this, the **DC Machine** is supplied from the variable **DC Power Supply** using just two wires as shown in Fig. 4 below. To implement a variable mechanical load on the **PM Synchronous Motor** under test, the two wires are then unplugged from the DC Power Supply and re-connected to the **Load Resistor Box** as shown in Fig. 4.

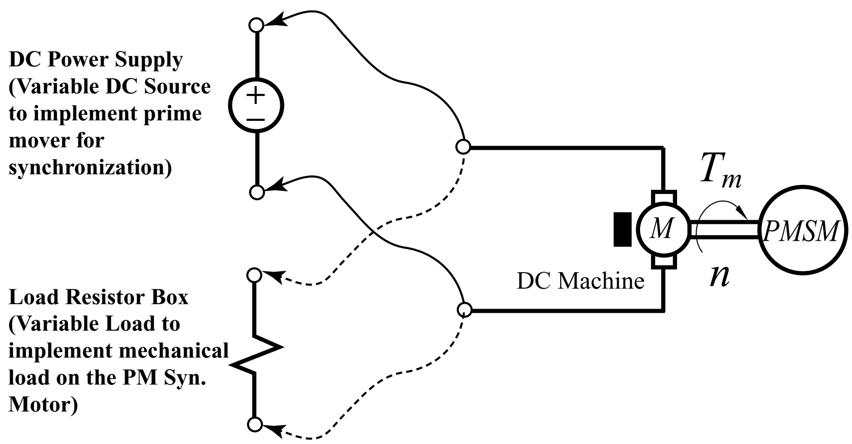


Fig. 4: Wiring of the Prime Mover DC Motor.

Task 2: Measuring Phase Resistance and Inductance

The simplest way to measure the phase winding resistance r_s and total inductance L_{ss} is to connect to **PM Synchronous Motor** to the **3-Phase AC Power Supply** at low voltage and measure the phase voltage and current as well as angle φ between them. Using this information, you should be able to calculate the impedance, resistance, reactance and inductance at 60 Hz, as

$$\frac{V_{ave,rms}}{I_{ave,rms}} = |Z_s|; \quad r_s = |Z_s|\cos(\varphi); \quad x_s = |Z_s|\sin(\varphi); \quad L_{ss} = \frac{x_s}{2\pi 60};$$

Make sure that Main AC Circuit is wired according to Fig. 4 and that the Variac knob of the **AC Power Supply** is set to zero output voltage – turned CCW all the way. Follow the suggested steps:

1) Turn ON the **AC Power Supply** and close the **3-Phase Breaker** to power the **PM Synchronous Motor**. The AC measurements on the **3-Phase Motor** program interface should be almost zero.
2) Very slowly increase the phase voltage by turning the **AC Power Supply** Variac knob CW until the average phase current reaches about 2 to 4 A. The phase voltages and currents should be roughly symmetric and balanced. Record one set of average-per-phase measurements in Table 1 of your report. Later you will perform calculations and complete Table 1.

Task 3: Open-Circuit Test

The **Prime Mover DC Motor** should be connected to the **DC Power Supply** as depicted in Fig. 4, top. The **3-Phase Breaker** should be open and the **AC Power Supply** is turned OFF. The terminals of the **PM Synchronous Motor** should be effectively open-circuited. Make sure that the voltage control of the **DC Power Supply** is initially turned down CCW to output zero voltage, and the current limit knob should be turned up CW. Zero-out torque and speed measurements on the **3-Phase Motor Analysis** program interface. On the LabView program **3-Phase Motor Analysis**, the triggering switch should be in the right position to trigger on voltage.

Open-Circuit Voltage vs. Speed Characteristic

1) Turn on the **DC Power Supply** and slightly increase the output voltage to get to motor spinning. Experiment with speed and verify that the **PM Synchronous Motor** output terminal voltage changes in frequency and magnitude.
2) Make several measurements at different speeds from 200 to 2000 rpm and record them in Table 2A. Read the DC voltage measurements directly from the digital display on the **DC Power Supply**.
3) Make a separate measurement that would correspond to the output voltages of the **PM Synchronous Motor** at frequency as close as possible to 60 Hz and record it in Table 2B. This should correspond to DC voltage in the range of 18 to 26 V. Later you will perform calculations and complete Table 2B.
4) Turn OFF the **DC Power Supply** at the point corresponding to the output frequency close 60 Hz.

Task 4: Synchronous Motor Operation

In this Task you will operate the **PM Synchronous Motor** from the fixed frequency 60 Hz **AC Power Supply** and observe its electromechanical characteristics. For that, you will learn how to synchronize and start the operation of **Synchronous Motors** from fixed frequency sources. Both **AC Power Supply** and **DC Power Supply** should be initially turned OFF.

To perform synchronization of a synchronous machine and the source, the following conditions should be satisfied:

1. The voltages of the machine and source must be of the same **sequence**
2. The voltages of the machine and source must be of the same **frequency**
3. The voltages of the machine and source must be of the same **magnitude**
4. The voltages of the machine and source must be of the same **phase**

The corresponding phasors of the synchronous machine back emf voltage and the source voltages are depicted in Fig. 5. Satisfying the four conditions stated above will minimize the difference between the respective voltages shown in Fig. 5 as ΔV. Note that when the **Circuit Breaker** is open, the Synchronization Lamps are connected between the PM Synchronous Motor and the 3-Phase AC Source and will have the voltage difference ΔV applied to them. Therefore, the frequency of this voltage ΔV is equal to the difference between the frequencies of the back emf voltage E and the AC Source voltage V, **assuming they both have the same sequence**.

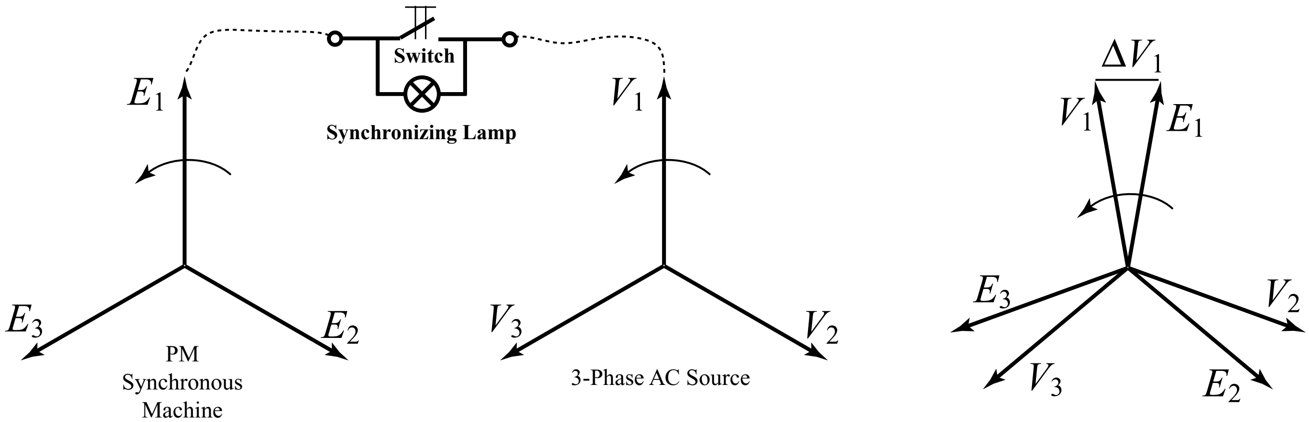


Fig. 5: Phasor diagram depicting the synchronization procedure.

Task 4 A: Synchronization Procedure

1) Make sure the circuit is wired according to Fig. 3. Initially everything should be OFF and the **3-Phase Circuit Breaker** should be **open**. Perform the following steps to synchronize the **PM Synchronous Motor.** On the LabView program **3-Phase Motor Analysis**, the triggering switch should be in the right position to trigger on voltage.
2) Turn ON the **3-AC Power Supply** and adjust the output phase voltage to about **7 V rms** (or the line-to-line voltage to about **12 V rms**). This is done by turning the Variac knob on the right-side panel of the **3-AC Power Supply** about 2/3 in the CW direction. To measure this voltage you can use the **Multi-Meter** available on your bench. In this way you don't need to change the circuit wiring. Ask a TA if you need help in locating and using the **Multi-Meter**.
3) Turn ON the **DC Power Supply**. The **Prime Mover** and **PM Synchronous Motor** should be spinning at speed corresponding to close 60 Hz operation. If needed, adjust the DC voltage to obtain the right speed.
4) The **Synchronization Lamps** should be flashing. If all three lamps are flashing simultaneously, this means that you have the same sequence of phases on the **AC Power Supply** and **PM Synchronous Motor**, and that your connection is correct. If the lamps are flashing sequentially, this means that the phase sequence if different. In this case simply switch any two phases (wires) on the **AC Power Supply**.
5) Very slowly adjust the output of the **DC Power Supply** to get the frequency close to 60 Hz which will make the **Synchronization Lamps** flashing as slow as possible.
6) Wait for the moment when the lamps are going off and quickly close the **3-Phase Circuit Breaker**. This will synchronize the operation. You should observe that the **PM Synchronous Motor** now operates at fixed speed.
7) Try to slowly vary the knob of the **AC Power Supply** and verify that it changes the phase current, but the speed should remain constant! Adjust the AC voltage little bit up/down such that the average phase current is about 6 to 7 A rms.

Task 4 B: Synchronous Motor Operation with Sufficient AC Voltage

Prepare the **Load Resistor Box** and make sure that all resistors are initially OFF. Carefully unplug the two wires from the **DC Power Supply** and plug them to the **Load Resistor Box**. You will now start using the **DC machine in the Cradle** to implement the variable mechanical load for the **PM Synchronous Motor**. Note that even when all the resistors are OFF, the **PM Synchronous Motor** is now working against the friction that may be on the order 0.1 to 0.3 Nm.

1) Record the first measurement in Table 3.
2) Then, one-by-one, start switching ON the resistors in the **Load Resistor Box** and record the measurements in Table 3. Your last measurement should be at the maximum mechanical load that is achieved when all the resistors in the **Load Resistor Box** are turned ON.
3) Your motor should not stall even at maximum load. If it still happen, just push the OFF button on the **AC Power Supply** and then open the **3-Phase Circuit Breaker**. You may need to increase the AC voltage just a bit, by 1 V or so. To re-synchronize the **PM Synchronous Motor** just do the following:
    a. Re-connect the **DC machine in the Cradle** back to the **DC Power Supply**, which should still output the same DC voltage roughly corresponding to the speed at 60 Hz.
    b. Watch for the flashing lamps and close the **3-Phase Circuit Breaker** when the lights are going down. Then, carefully unplug the two wires from the **DC Power Supply** and plug them back to the **Load Resistor Box**.

Task 4 C: Synchronous Motor Operation with Possibly Insufficient AC Voltage

Continue from Task 4 B. Turn off one or two resistors in the Load Box to reduce the input electrical power to

You will now start reducing the AC voltage from the **AC Power Supply.** You should observe that the motor speed does not change, but the motor may suddenly stall.

1) Record the first measurement in Table 4.
2) Then, slowly reduce the AC voltage in 0.5 V increments such that the phase current (initially 6-7 A) is reduced by about 1 A increments. Record the measurements in Table 4 up to the point when the motor stalls. Monitor the motor speed, which should remain the same under synchronized operation. As soon as the motor gets out of synchronism, it will start making a loud noise and the speed will drop. When it happens, turn **OFF** the **AC Power Supply**.
3) If you need to re-synchronize the **PM Synchronous Motor** just do the following:
    a. Re-connect the **DC machine in the Cradle** back to the **DC Power Supply**, which should still output the same DC voltage roughly corresponding to the speed at 60 Hz.
    b. Watch for the flashing lamps and close the **3-Phase Circuit Breaker** when the lights are going down. Then, carefully unplug the two wires from the **DC Power Supply** and plug them back to the **Load Resistor Box**.

Task 5: Brushless DC (BLDC) Motor Operation (Servo Motor)

In this Task, you will use the 3-Phase **Universal Inverter** to drive the **PM Synchronous Machine** using the Hall Sensor signals. Please make sure that the settings on the inverter box correspond to BLDC mode with local (manual) control. The **Universal Inverter Box** is also equipped with control circuitry that can implement PWM of the output voltages. The duty cycle control knob is shown in Fig. 6. Initially, set the PWM duty cycle to **minimum** and the switching frequency to **about half** of the dial. Check that your initial settings are as shown in Fig. 6 below. The **DC Machine in the Cradle** should be connected to the **Load Resistor Box**, as before according to Fig. 4. Iinitially all resistors in the **Load Resistor Box** should be OFF. Keep most of the wiring of the **PM Synchronous Machine** and the **Measurement Box**. The remaining part of the circuit should be connected using the **Universal Inverter** according to Fig. 7. **Make sure to correctly match the phases on the PM Synchronous Machine and Universal Inverter according their respective color-coding (Green, Yellow, and Blue)**. Use color wires! Note that you will need an additional **9-Pin Cable** to connect the Hall-Sensors to the inverter controls.

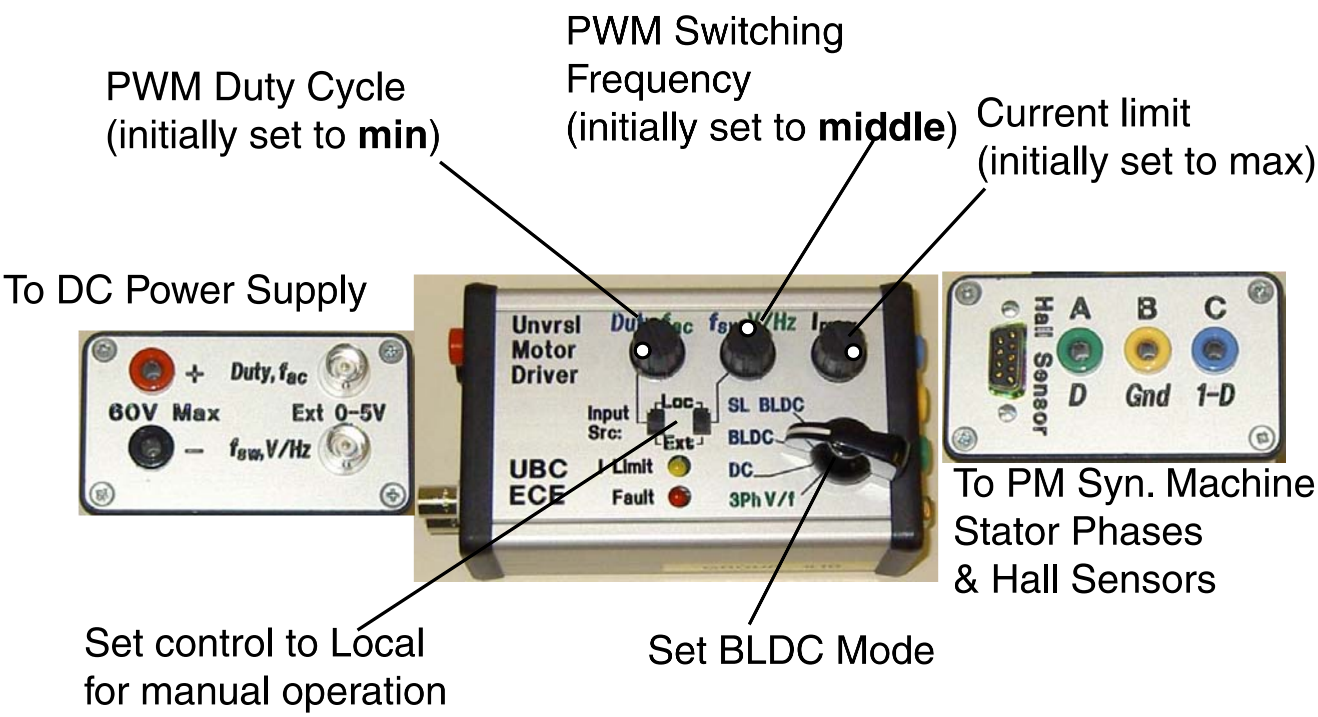


Fig. 6: Universal Inverter Box and its settings for the Blushless DC Motor operation.

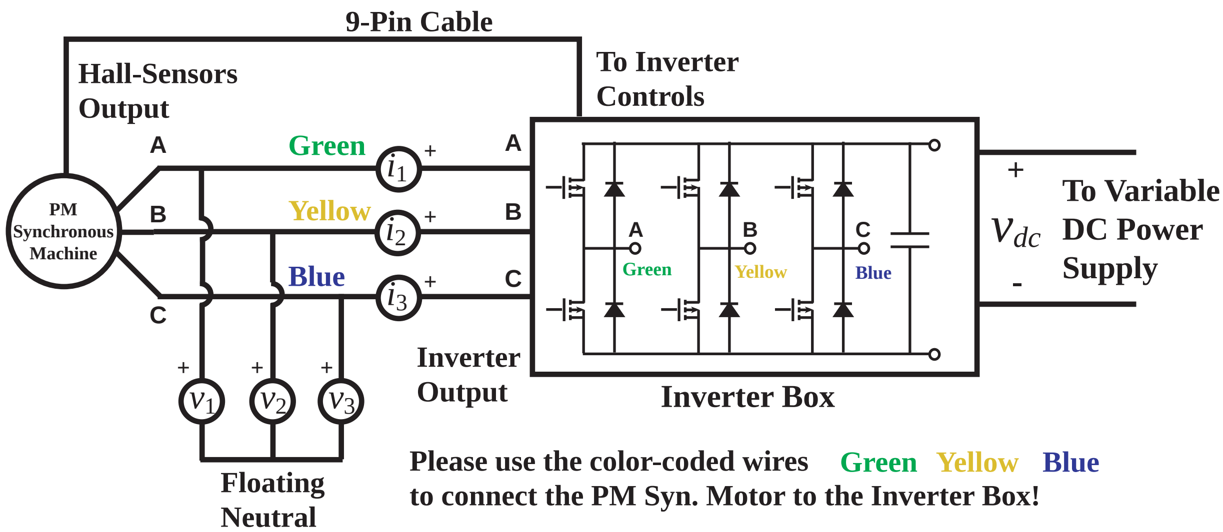


Fig. 7: Wiring diagram for Blushless DC Motor operation with Universal Inverter.

Task 5 A: Load Characteristic at Fixed DC Voltage

1) Zero out torque and speed measurements on your LabView program. Turn ON the **DC Power Supply** and slowly increase the output voltage to 36 V. Then, slowly increase the duty cycle toward the maximum value. Your motor should start spinning, and the speed should be quite fast when you turn the duty cycle all the way to its maximum value.
   Note: If the motor is **making an unusual loud noise and vibrates**, it can be because you have incorrectly wired the motor phases to the Inverter Box. If this is the case, turn **OFF** the **DC Power Supply** and check your connection circuit. It is best if you use the color wires (**Green, Yellow,** and **Blue**) to match the motor and inverter phases.
2) Assuming your circuit is correct, set the duty cycle know to maximum. The motor should be spinning quite fast. At this point, the **BLDC Motor** is working only against the friction due to both machines. Record the first measurement in Table 5. You will read the DC current measurement right from the digital display on the **DC Power Supply** front panel.
3) Start switching ON resistors on the Load Resistor Box. This will increase mechanical load applied to the **BLDC Motor**. Record several measurements in Table 5, with the last measurement corresponding to about 230 to 270 W of electrical power coming out of the inverter ($P_e(total)$)into the **PM Synchronous Machine**).
4) Later you will perform calculations and complete Table 5.

Task 5 B: Controlling the BLDC Motor

1) Continue from the maximum load measurement of Task 5A part 2 (230 to 270 W). Now you can verify that this type of motor can be controlled by adjusting the DC voltage, just like you could do with a conventional DC motor. Vary the output of the **DC Power Supply** in the range from 15 to 45 V and observe that doing so also changes the speed very effectively.
2) Set the DC voltage at 45 V dc. Now, slowly vary the duty cycle from min to max (and vise versa) and observe the behavior of the motor. Note the difference of the voltage waveforms due to PWM action.

Task 6: Calculations and Analysis

Task 6 A: Complete calculations in each of the Tables and fill-in Fig. A in your report.

Task 6 B: Questions

1) Based on your observations in Task 4 B and C, what determines the maximum torque that you can get out a PM Synchronous Motor? Can you provide an equation to support your answer?
2) How does the efficiency of this BLDC motor compares to that of the Brushed DC Motor in your previous lab? Can you roughly assign the percent of losses to the Inverter, PM Syn. Machine, etc.
3) Which method in Task 5 B is more practical for controlling the motor speed and why?

Task 7: Reporting

Prepare the Lab Report that includes:

1) Title Page (all filled-in, with signatures)
2) Pages with the measured and calculated data (pages 14 – 17),
3) Additional page with answers to questions in Task 6, and brief Conclusion/Summary stating what you and your lab partner have learned in this Lab.

EECE _____

Lab Experiment:

Section:

Bench #:

Partners	Student ID #:	% participation	Signatures

Date Performed:

Date Submitted:

Table 1: Impedance Measurement

Measured Values (average-per-phase)			Calculated Parameters (average-per-phase)			
Phase Voltage $V_{s,ph}(rms), V$	Phase Current $I_{s,ph}(rms), A$	Phase Angle φ_{ph}, deg	Impedance $\lvert Z_s \rvert, \Omega$	Resistance r_s, Ω	Reactance x_s, Ω	Inductance L_{ss}, mH

Table 2A: Open-Circuit Characteristic

Measurement #	1	2	3	4	5	6
DC Voltage V_{dc}, V						
Speed n, rpm						
Average phase voltage $V_{s,ph}(ave, rms), V$						
Frequency of phase voltage f_e, Hz						

Table 2B: Open-Circuit Measurement at 60 Hz

Measured Values				Calculated Parameters		
Speed n, rpm	Average phase voltage $V_{s,ph}(ave, rms), V$	Frequency of phase voltage f_e, Hz	DC Voltage V_{dc}, V	Voltage Constant $K_v, \frac{V(peak)}{\text{rpm}}$	Strength of PM $\lambda'_m, \frac{V \cdot \sec}{rad}$	Number of magnetic poles P

Table 3: Load Characteristic with Sufficient AC Voltage

Measurement #	1 Init. meas. All resistors OFF	2	3	4	5	6
Average phase current $I_{s,ph}(ave, rms), A$						
Average phase voltage $V_{s,ph}(ave, rms), V$						
Input electrical power $P_{e,}(total), W$						
Torque T_m, Nm						
Speed n, rpm						

Calculated values using the maximum load	Input electrical power $P_{e,}(total), W$	Output mechanical power $P_{m,}(total), W$	Efficiency $\eta, \%$

Table 4: Load Characteristic with Small/Insufficient AC Voltage

Measurement #	1 Init. meas. All resistors ON	2	3	4	5	6
Average phase current $I_{s,ph}(ave, rms), A$						
Average phase voltage $V_{s,ph}(ave, rms), V$						
Input electrical power $P_{e,}(total), W$						
Torque T_m, Nm						
Speed n, rpm						

Table 5: Load Characteristic with Fixed DC Voltage, Vdc = 36V.

Measurement #	1 Init. meas. All resistors OFF	2	3	4	5	6
Input inverter DC current $I_{inv,dc}, A$						
Inverter output power $P_{e,}(total), W$						
Torque T_m, Nm						
Speed n, rpm						

Calculated values using the maximum load	Torque Constant $K_t = \frac{\Delta T}{\Delta I_{inv}} \approx \frac{T_{m,6} - T_{m,2}}{I_{inv,6} - I_{inv,2}}$	Efficiency of the PM Syn. Machine $\eta, \%$ $\eta = \frac{P_{mech}}{P_{e,total}} = \frac{T_m \cdot n}{P_{e,total}} \cdot \frac{\pi}{30}$	Efficiency of the Inverter $\eta, \%$ $\eta = \frac{P_{e,total}}{P_{inv,dc}} = \frac{P_{e,total}}{I_{inv,dc} \cdot V_{dc}}$	Total efficiency of the BLDC Motor $\eta, \%$

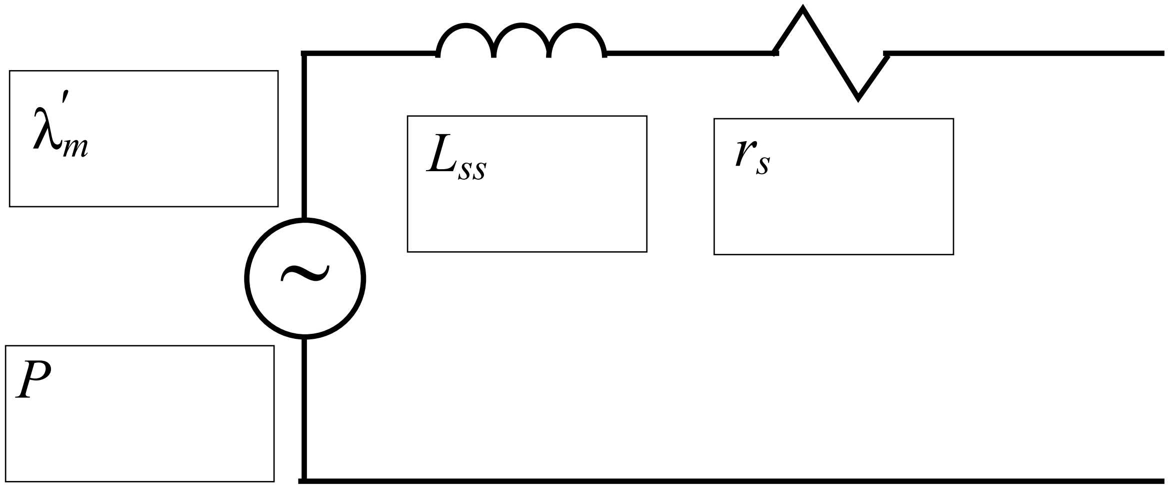


Fig. A. PMSM Equivalent Circuit. Fill-in the corresponding boxes with machine parameters. Make sure to include the units.