Lab-5: Synchronous Machine – Car Alternator

Objectives and Overview

The objectives for this sequence of laboratory experiments are:

- Experiment and fully characterize a Car Alternator, which is a small Synchronous Machine, by identifying its equivalent circuit parameters;
- Observe the output voltage regulation by controlling the field current;
- Observe the voltage and current waveforms when the alternator is loaded;
- Improvise a synchronization of two remote AC sources/generators.

By doing a set of measurements, the students will determine parameters of the synchronous machine per-phase equivalent circuit, as shown in Fig. 1.

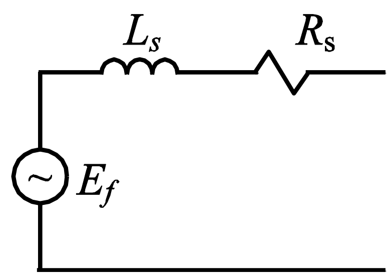


Fig. 1: Synchronous machine per-phase stator equivalent circuit.

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 Synchronous Machine - Car Alternator. The students will also perform a synchronization of the two Synchronous Machines from the nearest benches. Imagine that one generator represents a power system on Vancouver Island (a lab in UVic!) and the other one represents the Mainland electrical grid (our lab at UBC!). Your task will be to establish a synchronized AC link and experiment with exchanging the power flow from one side to the other.

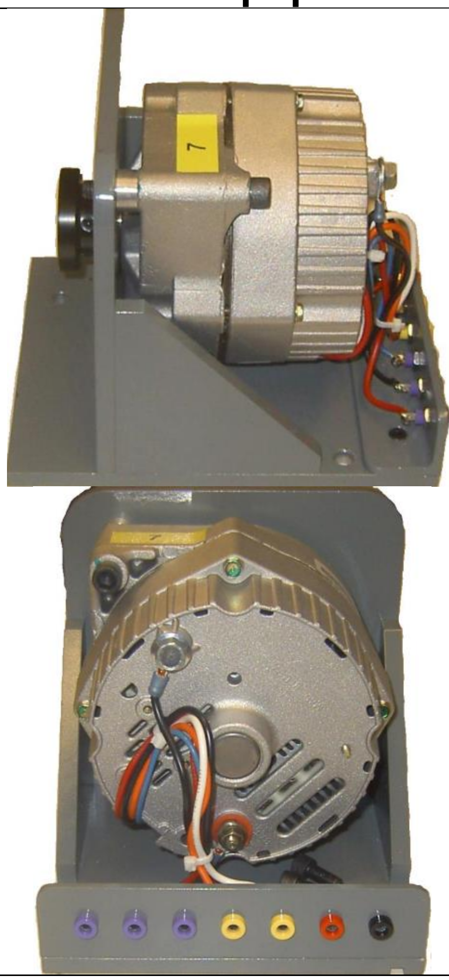
Preparation

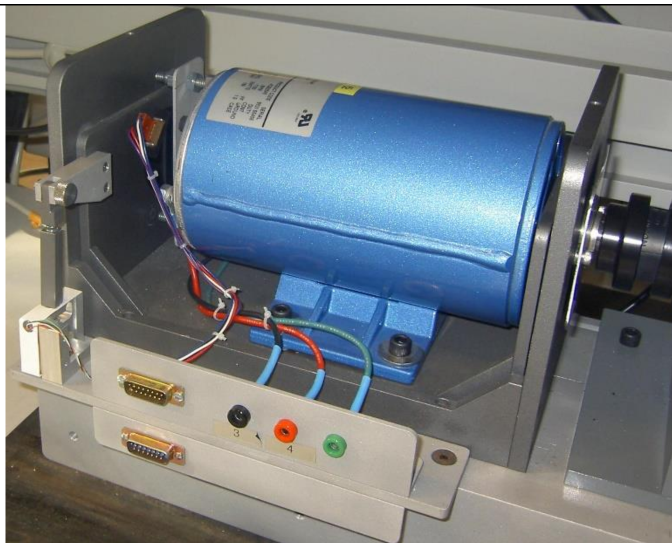
It is expected that the students have read and understood the textbook chapter and reviewed the lecture notes module corresponding to Synchronous Machines. The students should be familiar with the theory and principles of Rotating Magnetic Fields, the principle of operation of Synchronous Machines, procedures for determining equivalent circuit parameters, basic torque-angle characteristics, and the V-characteristic of the unloaded and loaded machine. Since the Automotive Alternator that you will be using is not designed to operate at 60 Hz sinusoidal AC voltages, be prepared to see non-sinusoidal voltages of higher frequencies. The Pre-Lab page should include the following:

- Prepare a list of equations for calculating the equivalent circuit parameters using the Open-Circuit and Short-Circuit Tests. Write the equation for torque in terms of the parameters and variables of the circuit in Fig. 1.
- Write down the procedure/steps and conditions required for synchronization of a Synchronous Machine with an external fixed-frequency source;

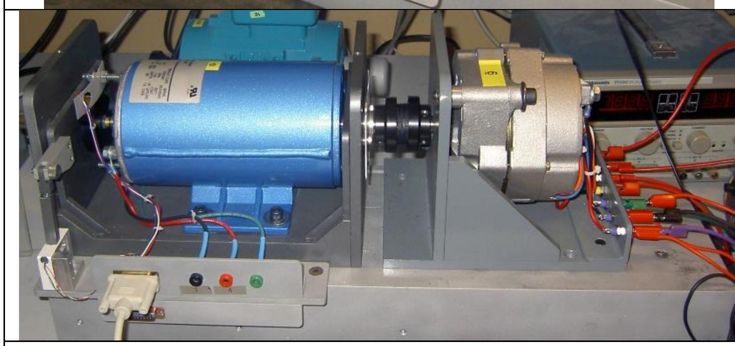
- Sketch the torque-angle characteristic of a Synchronous Machine (with neglected stator resistance) and label the points of max/min torques for motoring and generating;
- Write the equation for torque in terms of parameters and variables of the circuit in Fig. 1;
- **Bring your Pre-Lab (either hard 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.**

Apparatus & Equipment

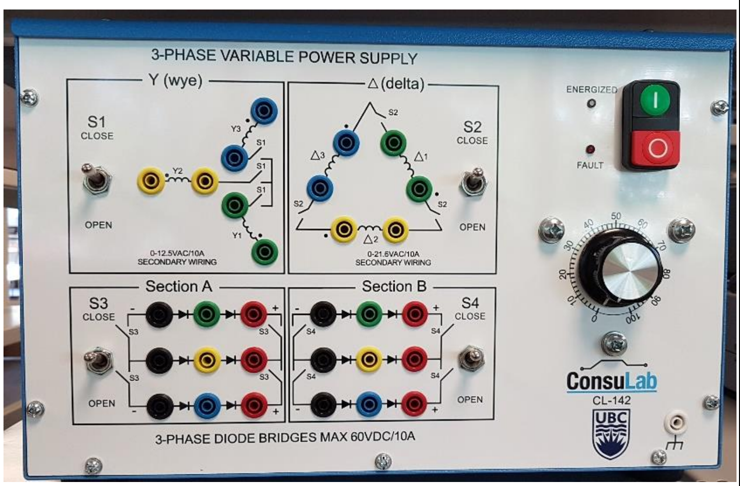
	**Car Alternator:** This is a Synchronous Machine with a wound field winding and a rectifier bridge mounted inside. In a vehicle, this Alternator is coupled to the engine shaft and supplies the internal electrical system with **12-14 V** DC or **24-28 V** DC (depending on the version). The DC is obtained by rectifying the 3-phase AC output voltages. Since engine speed varies widely, the field winding is used to regulate the output voltage by adjusting the field current (flux). This Alternator should be mounted on the Motor Bench, wherein the shaft should be coupled to the Dynamometer for taking measurements.



Dynamometer Cradle: A DC machine is mounted in a special cradle to permit torque and shaft speed measurements. The motor housing is supported along its axis by ball bearings, which allow it to rotate when torque is applied to 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 (on the left) for measuring speed.



Motor Bench: The Car Alternator under test should be mounted on the Motor Bench as shown on the left. A DC machine mounted on the Cradle serves as a prime mover to emulate a mechanical source (e.g., an engine, turbine, etc.). This machine should be coupled to the Alternator through the shaft.



3-Phase AC Power Supply: This flexible 3-phase Power Supply has two 3-phase transformers inside. The secondary windings can readily be configured into 'Y' (wye) and "Δ" (delta) configurations. The front panel shows the transformer wiring and has several switches and connectors for configuring the output. The transformers are fed from an internal 3-phase **Variac** (variable auto-transformer) that can be used to adjust the output voltage. **By varying the Variac knob from 0 to 100%, the output AC voltages may be changed from 0 to about 25 V (rms) per phase.** This power supply will be used to provide the 3-phase variable AC voltages at 60 Hz for the PM Synchronous Machine under test.

Synchronization Lamps and Switch: 3 lamps and a 3-phase switch are mounted together in a box. This box is used for the Synchronization Test, wherein the students Synchronize two Generators (Alternators).

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 an adjustable output voltage of **0 - 60V** and a current limit of **0 - 18A**, which is sufficient for most experiments in this laboratory. **For this experiment, limit the current to 3 A!**

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 a sampling rate of 2.5 MS/sec (2.5MHz). The measured waveforms and their values can be displayed on the PC screen and 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 a 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** connects 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 colour-coded. It is strongly recommended that you use appropriate and consistent colour wires for each measurement channel. This will make it easier for you to wire up your circuits, check them, and find any mistakes.

Setting Up the DAQ System

A multi-functional **Measurement Box** is located in the middle of your bench. Log in to your local PC and find the LabVIEW program **3 Phase AC Motor Analysis**. 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 start taking measurements. The **3 Phase AC Motor Analysis** program interface is set up to display the three voltages (channels **V1**, **V2** and **V3**) and three currents (channels **A1**, **A2** and **A3**), **Speed** and **Torque**, as will be needed in this Lab. The measurement window can be triggered by either the voltage or current signal of the first measuring channel (**V1** or **A1**). The triggering point also defines the relative angle between the measured signals. The user can select or un-select the measurement of voltages and currents, but the first channel voltage **V1** and current **A1** are always selected. For this Lab, select all three voltages and currents, as well as **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. The RMS values of the voltages (in Volts) and currents (in Amps) are displayed on the right side of the panel. All three Channels also display the calculated instantaneous real power (Ch1, Ch2 and Ch3) in Watts.

Measuring Real Power: 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**, **V2** with **A2**, and **V3** with **A3**, respectively) 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 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 when taking measurements in the range from 0.1ms to 2s to better capture the desired waveforms and to see the details. The button "**Subtract Zero Sequence**" should be "**ON**." 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.

Saving Recorded Data: The program can **PAUSE** and S**AVE** 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 by using the slide buttons **ZOOM** and **POSITION** on the bottom of the panel. Pushing the **SAVE** button brings the window to save the data file. The user should name and save the file into the appropriate location/folder for future analysis.

Displaying Phasors: The LabVIEW program **3 Phase AC Motor Analysis** includes a Phasor View tab. In each task, you can use the Phasor View to observe the phasor diagram of three-phase voltages and currents. For displaying phasors, the reference is defined by the selected trigger point for either the voltage channel **V1** or the current channel **A1**.

Ask a TA and/or Lab Engineer responsible for the Lab if you have problems locating and/or running this program.

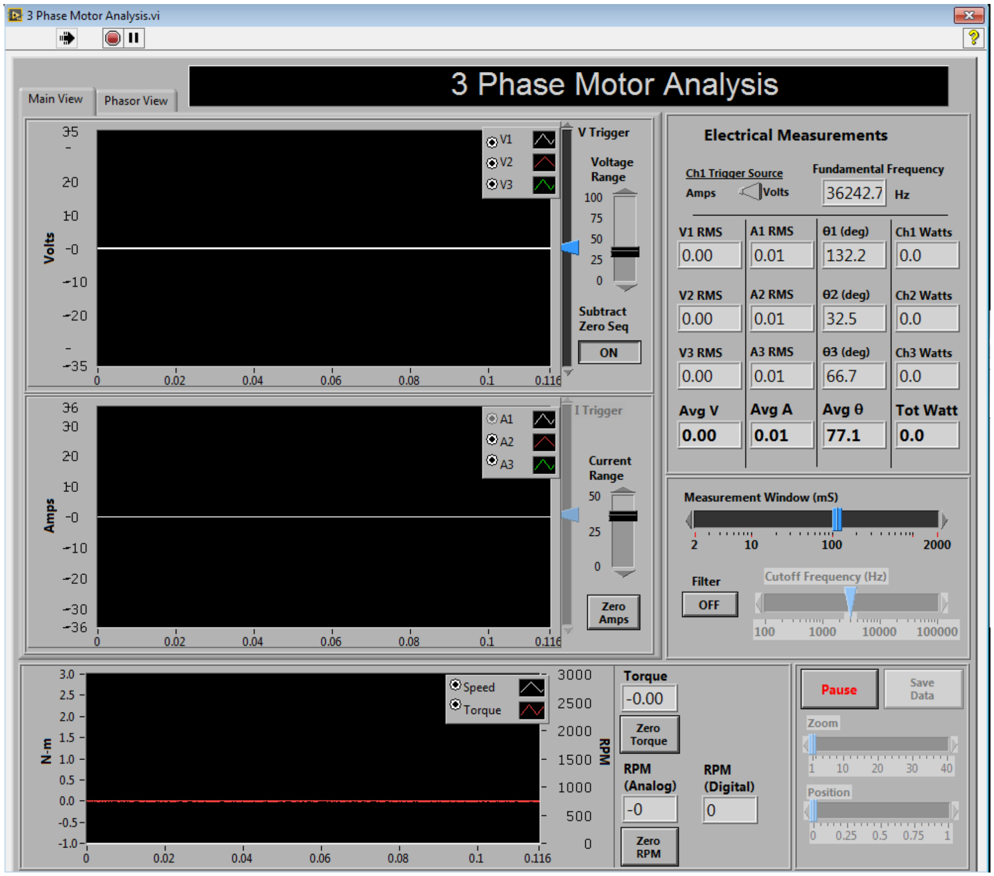


Fig. 2: LabVIEW program interface of 3 Phase Motor Analysis.

Setting Up the Experiment

1) AC Power Supply:

The multi-purpose **AC-DC Power Supply** should be configured to provide a variable DC voltage to drive the DC Motor in the Cradle, which will serve as a Prime Mover to rotate the Alternator. The **Power Supply** has two sets of windings, 'Y' (wye) and "Δ" (delta), whose output voltages can be readily adjusted by the knob on the right side of the box. To get the maximum output voltage, you will need to connect these windings as shown in Fig. 3 (series connection). To reduce ripple on the DC bus, one can also connect a large electrolytic capacitor to the output terminals, though this is optional. This variable DC voltage is used to supply the prime mover DC machine, as shown in Fig. 4.

Please pay particular attention to the windings' polarities, as they are required to properly add the voltages. **Switch S1 must be closed and S2 must be open.** The terminals ABC are then connected to one of the Diode Bridges, which will provide the variable DC voltage output.

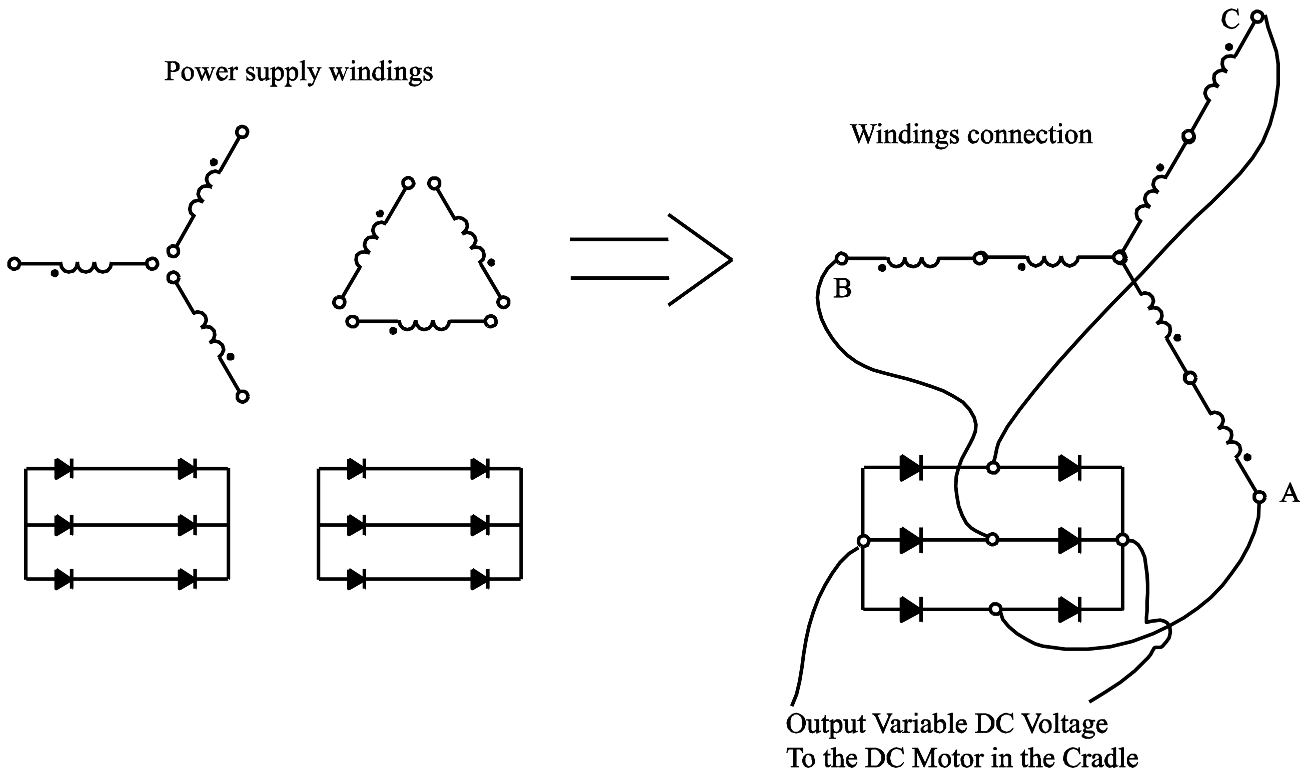


Fig. 3: AC Power Supply wiring to produce the variable DC source.

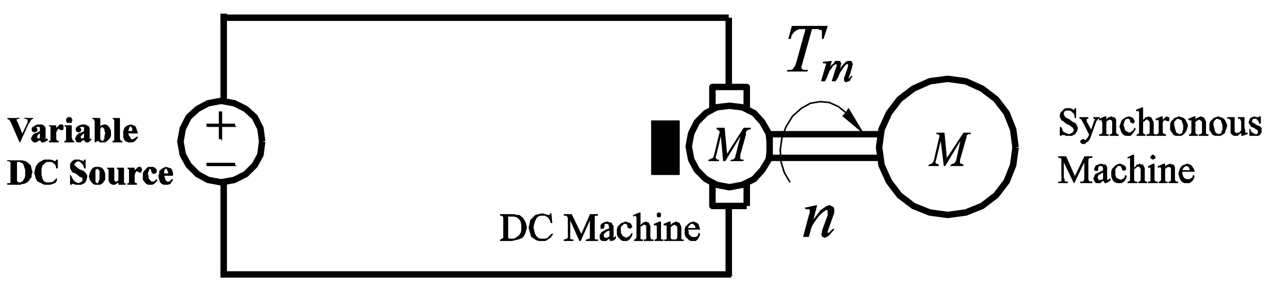


Fig. 4: Wiring of the Prime Mover DC Motor.

2) Prime Mover DC Motor:

The **DC Motor** (Motor in the Cradle) is supplied from the main AC/DC **Power Supply** (configured as shown in Fig. 3) with variable DC voltage, as shown in Fig. 4. The purpose of this Prime Mover is to bring to rotation the Synchronous Machine under study, provide its mechanical input power in case of generating mode, or take the power out (i.e. serve as a load) in case of a motoring mode, respectively.

3) Synchronous Machine - Alternator:

The **Alternator** must be mounted on the right side of the **Motor Bench** with its shaft tightly coupled to the prime mover **DC Motor** (Motor in the Cradle). The **Alternator** has several terminals on the back side that are shown in detail in Fig. 5. The first three terminals (**purple**) correspond to the three phases; the two middle terminals (yellow) are the field winding; and the last two terminals (**red** and **black**) are the rectified DC output. **(Please note that the students will not use the DC output terminals in this Lab!)**

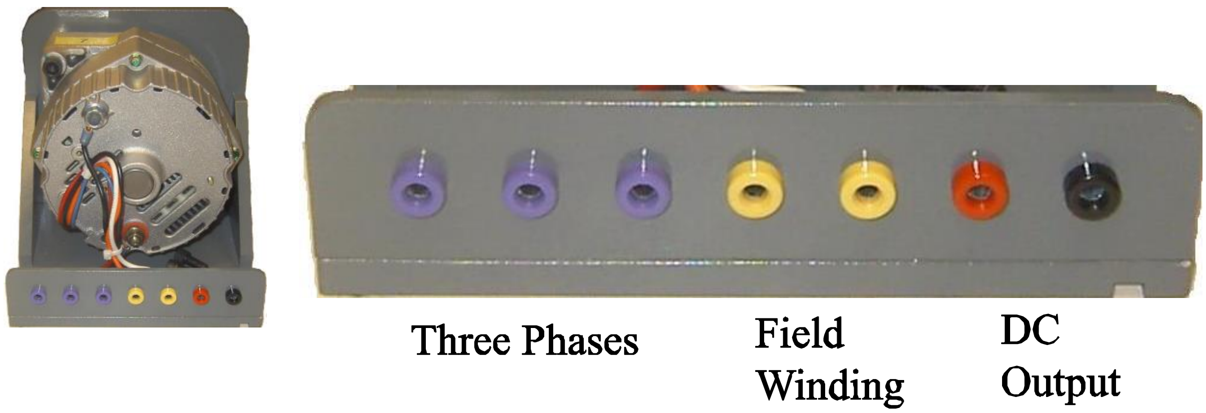


Fig. 5: Alternator terminals.

4) Xantrex DC Power Supply:

This is a regulated power supply capable of delivering high current and voltage (up to 60 V DC and 18 A). The **Power Supply** should be turned OFF initially. To avoid **burning/damaging** the field winding, set the current limit to **3 A**. To do that, please initially turn both voltage and current control knobs all the way to minimum (zero). Then take a long wire and short-circuit the output terminals. Then turn ON the **Power Supply**, and slowly increase the output voltage and current until you see that the power supply is operating in the current-limited mode, supplying the **3 A** short-circuit current at some very low voltage. Then turn OFF the **Power Supply** and **do not change the current limit for the rest of the lab!**

Task 1: Measuring the DC Resistance of Field and Stator Windings

For calculating the parameters of the equivalent circuit, you will also need to measure the Stator Winding resistance R_s and the Field Winding resistance R_f . It is convenient to take this measurement before the machine is connected. The simplest way to measure the winding resistance is to use the Multimeter that is available on your benchtop. This will measure the resistance at low current. To obtain another measurement at high current, you may apply a variable DC source and measure the current and voltage applied to the winding (similarly to the DC Machine Lab). For this measurement, use long wires and the bench **DC Power Supply**. Make sure to apply very low voltage and low current, **2 – 3 A**. **Do not exceed 3 A for the DC measurement!** Write your results in Table 1 of the Lab Report. Remember that when you are measuring the resistance between any two of the 3-phase terminals, you are measuring the resistance of two windings. Therefore, to get the per-phase Stator Winding resistance, divide the result by 2.

Task 2: No Load Measurements

Couple the **Synchronous Machine** (Alternator) to the prime mover **DC Machine** and tighten it with appropriate bolts. Wire up the circuit as shown in Fig. 6 so that you can measure current and voltage in each phase. Always connect the current-carrying circuit first, and only after that can you connect the voltage measurement circuit. Make sure that the polarity of each current and voltage channel is connected as shown in Fig. 6 and that the channels are ordered consistently, e.g., **A1** current and **V1** voltage are connected to the same phase (same applies to the other channels, **A2** with **V2**, and **A3** with **V3**). **Use coloured wires to distinguish among the phases. For example, use Green, Yellow, and Blue, for the three phases, respectively.** Mismatching the channels will result in incorrect measurements. The field winding is supplied from an additional DC **Power Supply** (which should be adjusted to the **current limit of 3 A!)**.

A2 with **V2**, and **A3** with **V3**

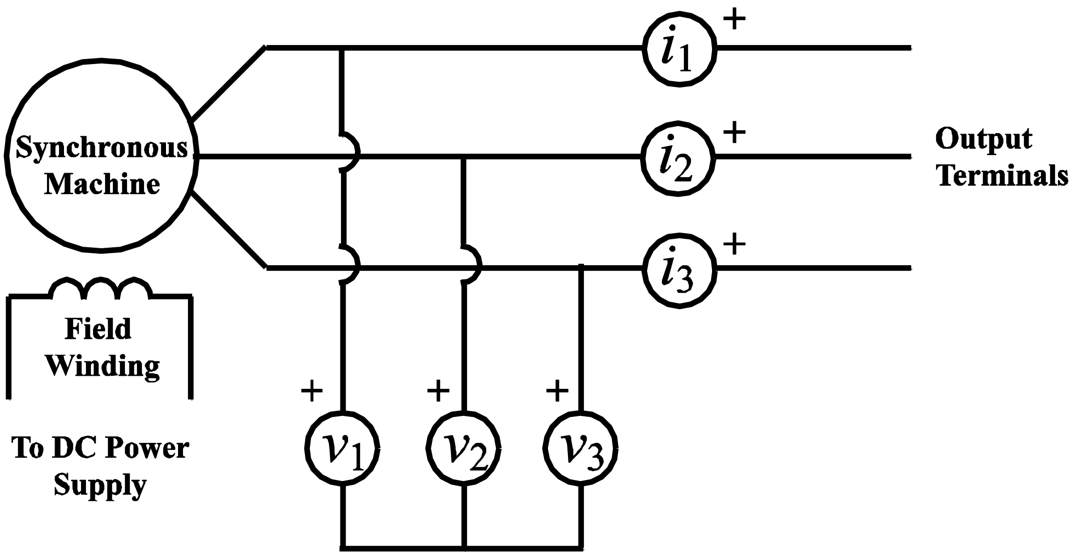


Fig. 6: Wiring diagram for taking the phase voltage and current measurements.

Note that Voltmeter Channels form a floating neutral point. This neutral point is used to measure the phase voltages. Although the machine winding is Y-connected, its actual neutral point is not available at the motor terminals. Remember to press the **ZERO** button before each test to remove any offset when measuring currents, torque, and speed. Verify your circuit according to Fig. 3, 4 and 6. Also, make sure the option **Subtract Zero Seq** is set to **ON**. The Alternator output terminals should be open-circuited as shown in Fig. 6. Verify that the software program is working and **ZERO** any possible offset in torque and speed.

Task 2 A: Output Voltage vs. Speed Characteristic

1) Turn on the **Xantrex DC Power Supply** and increase the field current **to about 2 A**. Keep this value constant for the duration of this sub-task (Task 2 A).
2) Turn on the main **AC/DC Power Supply** and slowly increase the applied voltage from 0V to its maximum. You should observe the Motor-Alternator spinning at a speed above 2000 rpm, and the software program displays the voltage measurements for each phase individually, as well as the average value among the three phases. **Set the program to trigger on voltage V1, and adjust the trigger point so that the voltage in this channel has an angle close to 0.**
3) Reduce the DC machine voltage back to zero. Now, slowly increase the voltage and the motor speed. Use Table 2 and record several measurements from very low speed to the maximum speed. Include one measurement at 2000 rpm in the second last column. Record the average rms phase voltage, torque, and speed for each measurement. Note the frequencies of the output voltages. How do they compare to 60 Hz?
4) Leave the system running for the next measurement (Task 2 B).

Task 2 B: Open-Circuit Characteristic (OCC)

1) Reduce the field current to zero. In this sub-task, you will need to adjust the DC Motor speed to keep it constant at about **2000** rpm.
2) Use Table 3 and record the first measurement corresponding to the zero field current. Then, slowly increase the field current and record the rest of the measurements up to the 3 A maximum field current that you can get from the **Xantrex DC Power Supply**.
3) **PAUSE** and **SAVE** several cycles of the voltage waveforms at about **2000** rpm and field current 2 A.
4) Reduce the field winding voltage (and current) back to zero and turn OFF the **Power Supply**.

Task 3: Short-Circuit Characteristic

Keep the overall circuit the same, except now the **Alternator** output terminals (see Fig. 6) should be short-circuited through the **Measurement Box** current measurement channels. Verify that the software program is working and ZERO any possible offset in torque and speed. Try to perform this test quickly, as the Alternator will get warm and may get hot if you run it for a long time under high current.

1) Make sure that the field current is zero and turn ON the main **AC/DC Power Supply**. In this sub-task, you will need to adjust the DC Motor speed to about **2000** rpm and keep it constant. Record the first measurement in Table 4.
2) Then, slowly increase the field current using the **Xantrex DC Power Supply** and take several measurements. For this task only, **do not increase the field current to higher than 1 A**. Remember to maintain the speed constant. Include one measurement at a field current equal to 1 A in the last column.
3) **PAUSE** and **SAVE** several cycles of the current waveforms at about **2000** rpm and field current 1 A.
4) Reduce the field current back to zero and turn OFF the main **AC/DC Power Supply**.

Task 4: Synchronization of Two Generators

In this Task, the students will perform the synchronized operation of two Synchronous Machines (Alternators). To do that, two groups of students and two Motor Benches are required. If needed, the participating motor benches should be pulled closer together to allow wiring the circuit shown in Fig. 7. You will need to use the box with **Synchronization Lamps** and **3-Phase Switch**. Also, use the long wires and make sure all phases are connected correctly in the same sequence. Make sure that the **3-Phase Switch** is initially **OFF**. Remember that in order to minimize the transients and, in particular, high currents, it is necessary to ensure the following conditions have been met before closing the 3-Phase Switch:

1. The voltages on both sides are of the same **sequence**
2. The voltages on both sides are of the same **frequency**
3. The voltages on both sides are of the same **magnitude**
4. The voltages on both sides are of the same **phase**

This will minimize the difference between the respective voltages, shown as ΔV in Fig. 8.

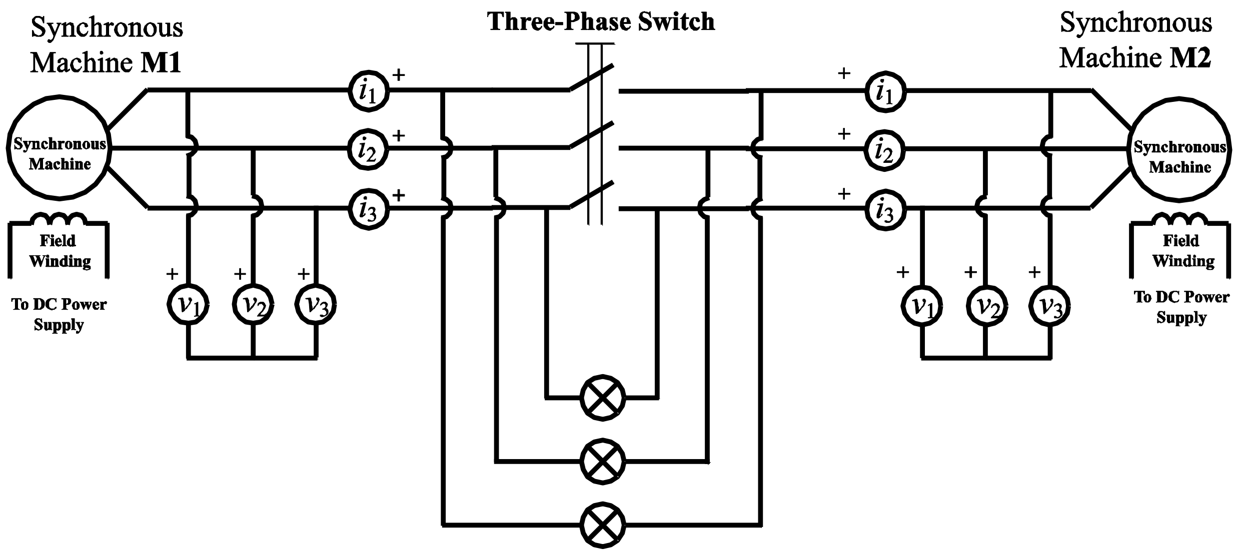


Fig. 7: Circuit for synchronized operation of two synchronous machines.

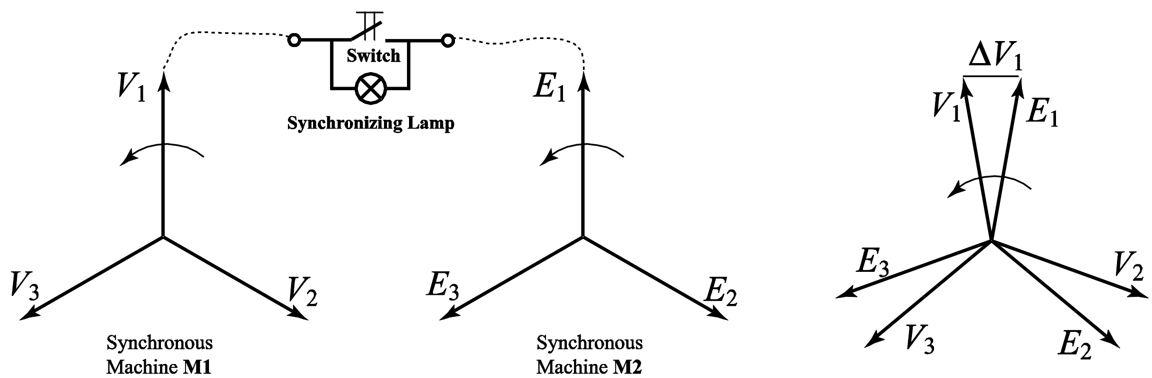


Fig. 8: 3-phase phasors of the two machines for synchronization test.

Task 4 A: Synchronization Procedure

1) Make sure that the **3-Phase Synchronization Switch** is **OFF**. Turn on both main **AC/DC Power Supplies** and adjust the speed to about 2000 rpm.
2) Adjust the field current of both Alternators to roughly the same value between 2 and 3 A. Record this value of the field current for future use. Due to rotational losses, the speed might drop a bit. So, you will have to re-adjust the speed back to 2000 rpm by increasing the DC voltage on the DC prime mover machines.
3) Check the voltages and frequencies on both **Machine Benches**. By adjusting the speed and field current on one of the **Motor Benches**, try to equalize the voltages and frequencies as close as possible. Check that the phase sequence is the same by verifying the voltage order **V1**, **V2**, and **V3** on both benches.
4) Observe the **Synchronization Lamps**. Are they slowly flashing or just steady on? If the Synchronization Lamps are steady on (or sequentially flashing), you may have a mismatch of sequences. If this is the case, turn OFF both main **AC/DC Power Supplies** and change the sequence on one of the Alternators. This can be achieved by flipping any two of the three phases, or by changing the direction of rotation that is determined by the DC Motor. After that, turn the power back on and repeat steps 3 and 4.

5) You must achieve the condition when the **Synchronization Lamps** are **slowly flashing**. If you cannot for some reason, ask your TA for help. Assuming this is achieved, record the measurements and observations in Table 5, Column 1. The voltages and speeds/frequencies on both benches should be very close. Record your observation/comments on the last page.
6) Assuming that the Synchronization Lamps are slowly flashing, select a moment when they are completely OFF and quickly close the **3-Phase Switch**. You may observe some electromechanical transients after which both machines will operate locked in synchronism. Record the measurements and observations in Table 5, Column 2. Did you notice any transients? Briefly record your observation/comments on the last page.
7) Adjust the field current of one of the Alternators in order to minimize the phase current flowing between the two synchronous machines.

Task 4 B: Power Flow in Synchronized Operation

1) With the system running in synchronism from Task 4 A part 7), slowly increase the field current of one of the machines such that one bench has about 0.5A more field current than the other one (0.5A difference). In this case, one of the Alternators is under-excited, while the other is over-excited relative to it. Record the measurements in Table 5, Column 3. What do you observe in terms of phase currents, real powers and speeds? Briefly record your observation/comments on the last page.
2) Increase the excitation of the Alternator that was under-excited in part 1 to minimize the phase currents again when both machines are running in synchronism.
3) Quickly turn OFF the **DC Motor** on the left **Motor Bench** by pushing the **Stop** button on the main **AC/DC Power Supply** and record the measurements in Table 5, Column 4. Briefly record your observation/comments on the last page. Which of the Alternators (M1 or M2) is motoring and which one is generating? Turn the power back ON and restore the condition of part 2) – Synchronous operation with minimum phase current between the machines.
4) Quickly turn OFF the **DC Motor** on the right **Motor Bench** by pushing the **Stop** button on the main **AC/DC Power Supply** and record the measurements in Table 5, Column 5. Your machines should continue rotating in synchronism. If you lose synchronization, you may need to restart the process, increase the field excitation a bit on both machines, and resynchronize the machines. After that, you can try to repeat this step from the beginning. Briefly record your observation/comments on the last page. Which of the Alternators (M1 or M2) is motoring and which one is generating?
5) Slowly reduce the speed of the DC Motor on the left Motor Bench and turn everything OFF. Parts 3 and 4 must be performed quickly to avoid overheating the Alternators.

Task 5: Calculations and Analysis

This part must be included with your Lab Report. You are strongly encouraged to use MATLAB (or an equivalent powerful tool) for your calculations.

Task 5 A: Determining Machine Parameters

1) Plot the following characteristics using measurements in Tables 2, 3, and 4:
    a. Open-circuit phase voltage vs. speed $V_{ph,oc,rms}(n)$ at field current 2A
    b. Open-circuit phase voltage vs. field current $V_{ph,oc,rms}(I_f)$ at speed 2000 rpm
    c. Short-circuit phase current vs. field current $I_{ph,sc,rms}(I_f)$ at speed 2000 rpm

2) Calculate the equivalent circuit parameters and write them down in Fig. A. The number of magnetic poles is determined by knowing the speed and the electrical frequency of the induced voltages. The rotational losses P_{loss} can be calculated from the mechanical torque and speed in Task 2. Calculate the value of an equivalent resistor R_{loss} that may be connected in parallel to the back emf voltage source in the equivalent circuit of Fig. A and will dissipate the power P_{loss}. Sketch this modified equivalent circuit in your report.

Task 5 B: Additional Analysis and Questions

1) Plot the saved voltage and current waveforms and show the frequency. How close are these waveforms to sinusoidal? Calculate and plot the spectrum of harmonics to support your answer.
2) Based on the equivalent circuit parameters (see Fig. A) and the induced excitation voltage E_f corresponding to a field current of 2A (see OCC in Table 3), calculate and plot the power-angle characteristic and the torque-angle (for the range of angles -180 to +180 electrical degrees) characteristic for this Synchronous Machine. Here, assume that $E_f = V_t$. What would be the maximum power and torque under this field current and given stator voltage? At what mechanical rotor angle will this be achieved?
3) Based on the equivalent circuit and losses presented in Fig. A, calculate and plot (using Matlab) the output voltage and efficiency of this Alternator vs. phase current at speed 2000 rpm and field current 2A when delivering power to a wye-connected resistive load. You can do this by varying the load resistor from a very large value, e.g. 100 Ohm, to a very small value, e.g. 0.1 Ohm per-phase, and taking approximately 20 to 30 points in this interval.
4) Assume the generator is loaded with 1 Ohm per phase resistors, when it operates at speed 2000 rpm and field current 2A. Plot a phasor diagram representing a voltage equation for the generator under this load condition.
5) When this Alternator is in the vehicle, explain what principle is used to regulate its output voltage when the engine speed is changing in a wide range?
6) Explain the causes of the rotational losses in this machine. Why are the losses so high for this Alternator? What is the impact of a low-efficiency alternator on the gas mileage? What recommendations can you provide to possibly improve the efficiency of such a generator?

Task 6: Reporting

Prepare the Lab Report that includes:

1) Title Page (all filled in, with electronic signatures).
2) Pre-lab pages.
3) Pages with the measured data and figures (pages 14 – 18).
4) Additional pages with Calculations and Analysis, discussions, and/or answers to questions 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 that you 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 #5

Section: ___

Bench #: ___

Partners	Student ID #:	% participation	Signatures

Date Performed:

Date Submitted:

Table 1: DC Resistance Measurement

<table>
<tr><td colspan="3">Stator phase resistance R_s, Ω</td><td colspan="3">Field winding resistance R_f, Ω</td></tr>
<tr><td colspan="2">Using DC source</td><td>Multimeter</td><td colspan="2">Using DC source</td><td>Multimeter</td></tr>
<tr><td>V_{dc}, V</td><td>I_{dc}, A</td><td rowspan="3"></td><td>V_{dc}, V</td><td>I_{dc}, A</td><td rowspan="3"></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Calculate R_s, Ω</td><td colspan="2">Calculate R_f, Ω</td></tr>
</table>

Explain and state which values you will be using for the equivalent circuit:

Table 2: Output Voltage vs. Speed Characteristic (keep field current constant at about 2 A)

Measurement #	1	2	3	4	5	6
Field Current I_f, A						
Phase Voltage $V_{s,ph}(ave, rms), V$						
T_m, Nm						
n, rpm					2000	
Frequency f, Hz						
Calculate rotational losses P_{loss}						

Table 3: Open-Circuit Characteristic (keep speed constant at about 2000 rpm)

Measurement #	1	2	3	4	5	6
Field Current I_f, A	0	0.5	1	1.5	2	3
Phase Voltage $V_{s,ph}(ave, rms), V$						
T_m, Nm						
n, rpm keep it constant						

Table 4: Short-Circuit Characteristic (keep speed constant at about 2000 rpm)

Measurement #	1	2	3	4	5	6
Field Current I_f, A	0					1
Phase Current $I_{s,ph}(ave, rms), A$						
T_m, Nm						
n, rpm keep it constant						

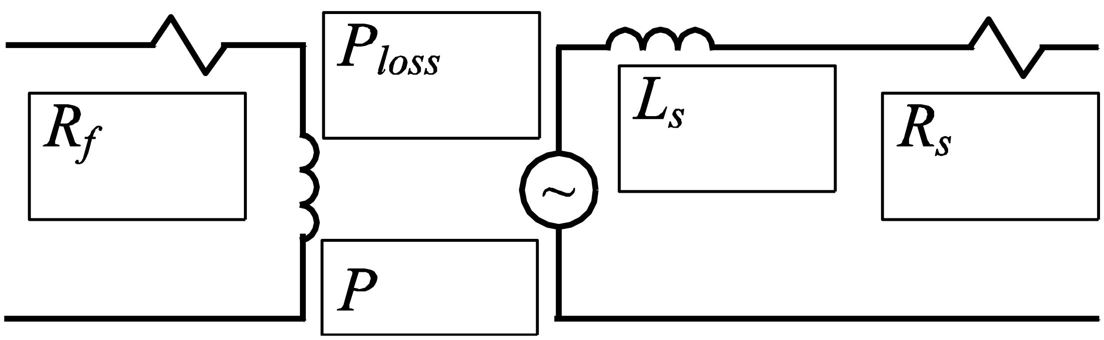


Fig. A. Synchronous Machine Equivalent Circuit. Fill in the corresponding boxes with machine parameters, including the number of magnetic poles and the rotational losses P_{loss} (at speed 2000 rpm and field current 2 A). Include the units.

Synchronization of Two Machines

Identify your bench with respect to Fig. B by circling the appropriate words and writing your and your partners' bench numbers below. You should perform this experiment with the group closest to you, on the left or the right.

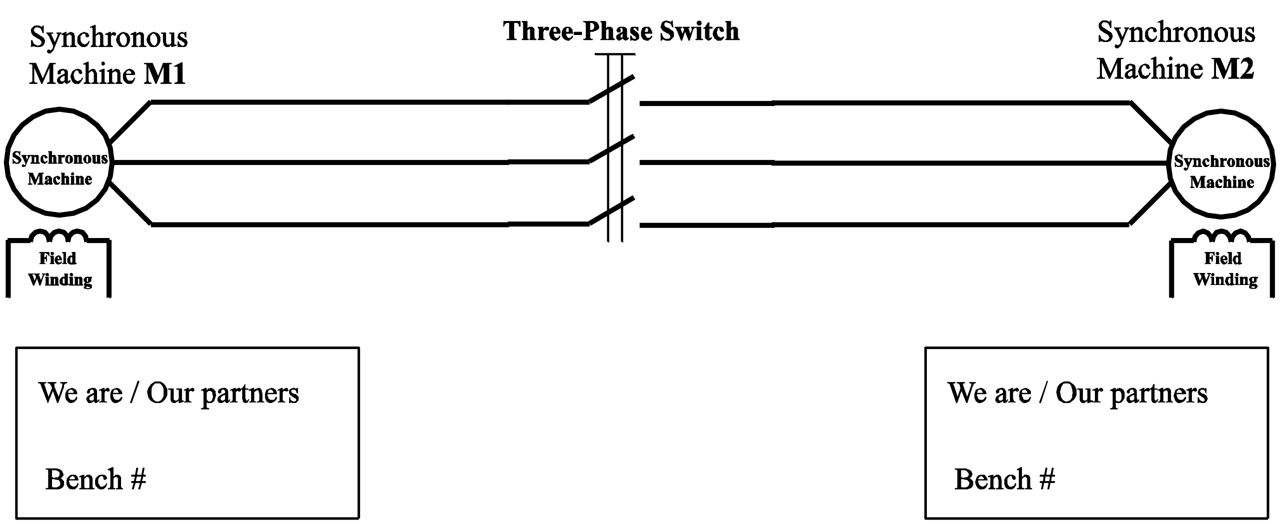


Fig. B. Synchronization test of left and right benches.

Table 5: Synchronization and Synchronous Operation

Measurement #	**Column 1** Before Synchronizing	**Column 2** When Synchronized	**Column 3** Increased/ Reduced Excitation	**Column 4** Left Bench DC Motor Off	**Column 5** Right Bench DC Motor Off
Machine M1 (circle we/partners)					
Field Current I_f, A					
Phase Current $I_{s,ph}(ave, rms), A$					
Phase Voltage $V_{s,ph}(ave, rms), V$					
Angle ϕ, deg					
Total Real Power P_{tot}, W					
Calculated Total Reactive Power Q_{tot}, VAR					
T_m, Nm					
n, rpm					
Frequency f, Hz					
Machine M2 (circle we/partners)					
Field Current I_f, A					
Phase Current $I_{s,ph}(ave, rms), A$					
Phase Voltage $V_{s,ph}(ave, rms), V$					
Angle ϕ, deg					
Total Real Power P_{tot}, W					
Calculated Total Reactive Power Q_{tot}, VAR					
T_m, Nm					
n, rpm					
Frequency f, Hz					

Briefly record your observation/comments corresponding to each measurement test:

Column 1: Observations and/or Comments:

Column 2: Observations and/or Comments:

Column 3: Observations and/or Comments:

Column 4: Observations and/or Comments:

Column 5: Observations and/or Comments: