Lab-4: AC Squirrel-Cage Induction Motor

Objectives and Overview

The objectives for this sequence of laboratory experiments are:

- Experiment and fully characterize a small industrial ¼ HP 34V Induction Motor (IM) by identifying its equivalent circuit parameters;
- Observe the start-up transient when the Motor is directly connected to the fixed 60 Hz AC source and started from the stall;
- Observe and measure the load characteristics when the Motor is supplied from a fixed frequency 3-phase AC source;
- Experimentally control the motor speed by adjusting the source voltage magnitude at a fixed 60 Hz frequency;
- Experiment and demonstrate the motor control using a Variable Frequency Drive (VFD) in a wide range of speeds, below and above the nominal speed;
- Evaluate the energy conversion efficiency of different stages when the Motor is driven by the VFD.

By doing a set of measurements, students will determine the parameters of the per-phase steady-state equivalent circuit for the conventional induction motor:

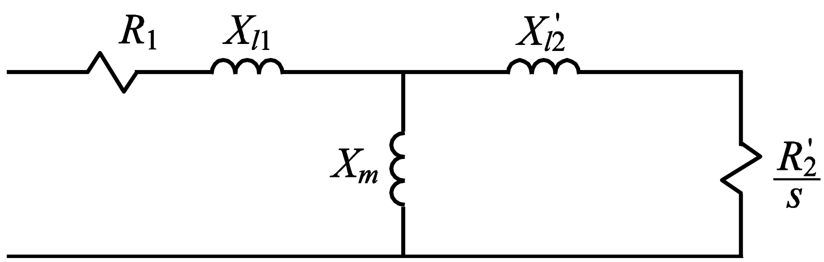

Fig. 1: Induction motor per-phase equivalent circuit.

This equivalent circuit and the equations discussed in class assume a symmetric Y-connected winding. The students will use this steady-state equivalent circuit as a model of the given Motor to predict the torque-speed and load characteristics and compare them to the measured data.

Preparation (Pre-Lab)

It is expected that the students have read and understood the textbook chapter and reviewed the lecture notes module corresponding to the AC Induction Machines. In particular, students should be familiar with the theory and principles of rotating magnetic fields, the principle of operation of induction machines, procedures for determining equivalent circuit parameters, and essential torque-speed characteristics. Additionally, students should review the material on motor control using a variable frequency 3-phase AC inverter. The students should read this Manual carefully and come prepared, knowing all the equipment and Tasks that they will be performing during this Lab. 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.
- Write down the expression for the torque-speed characteristic at 60 Hz fixed frequency and constant voltage magnitude.

- Assume an inductor (i.e. a magnetizing branch of the induction machine or a transformer) under sinusoidal AC excitation. Write down an expression for the magnitude of the flux in terms of voltage and frequency. Write a sentence to rationalize why the voltage and frequency should be adjusted **<u>together</u>** for the Variable Frequency Drive applications.
- **<u>Bring your Pre-Lab (either hard or soft copy) to your actual Lab and have TA to check it off. You will not be allowed to conduct any experiment without a reasonable Pre-Lab. Each student needs to complete Pre-Lab, and it cannot be shared between partners.</u>**

Apparatus & Equipment

This Lab includes the following components:

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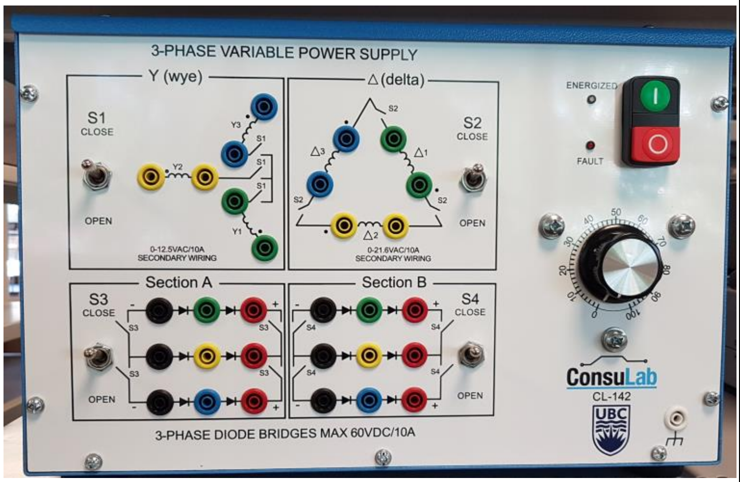

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<td>3-Phase AC Power Supply: This flexible 3-phase Power Supply has two 3-phase transformers inside. The secondary windings can readily be configured into ‘Y’ (wye) and “Δ” (delta) configurations. The front panel shows the transformer wiring and has several switches and connectors for configuring the output. It also has two 3-phase diode bridges for producing the DC output.
The Power Supply transformers are fed from an internal 3-phase Variac (variable autotransformer) that can be used to adjust the output voltage. The Variac knob is located on the right of the front panel. By varying the Variac knob from 0 to 100%, the output AC voltages may be changed in the range from 0 to about 25 V (rms) per phase.</td>
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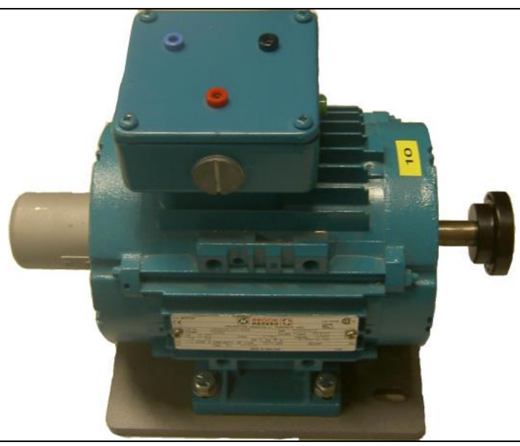
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<td>Induction Motor: This is a small industrial ¼ HP Squirrel-Cage Induction Motor, which you have to parameterize. The Stator winding is Y-connected with access to the phase terminals. This Motor should be mounted on the motor bench, wherein the motor shaft may be coupled to the Dynamometer to take measurements.</td>
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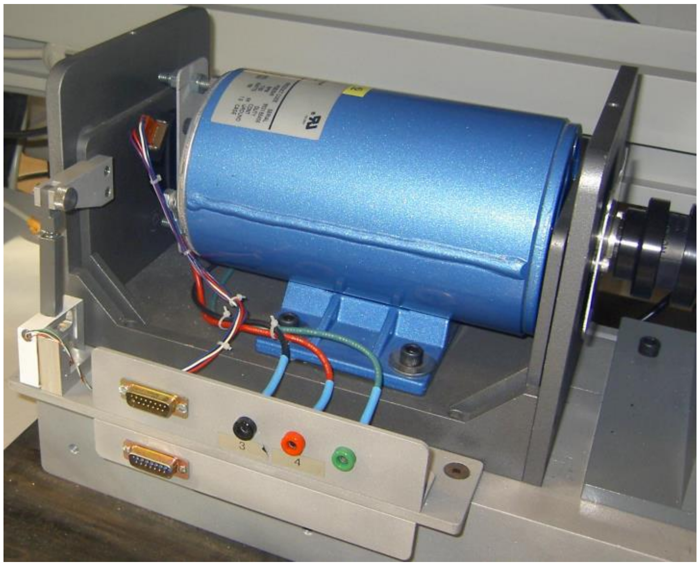
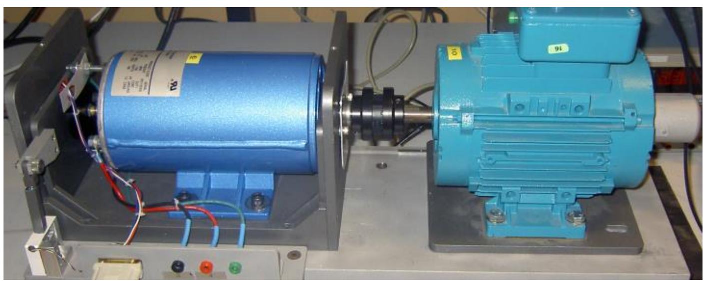
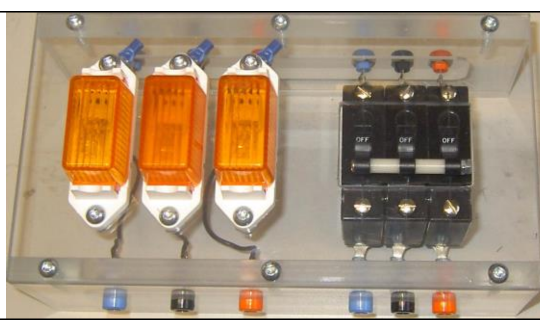


Dynamometer Cradle: A DC machine is mounted in a special cradle to permit torque and speed measurements on the shaft. The motor housing is supported along its axis by ball bearings, enabling it to move when the torque is developed on the shaft. The reaction torque is measured from the force acting on a load cell. This allows direct measurement of mechanical torque. The Dynamometer also has an optical position encoder mounted on the back of its shaft (left side) for speed measurement. To reduce the effect of EMIs, connect the ground of the **DC Power Supply** (**green terminal**) with the ground of the **Motor Bench** (**green terminal**).

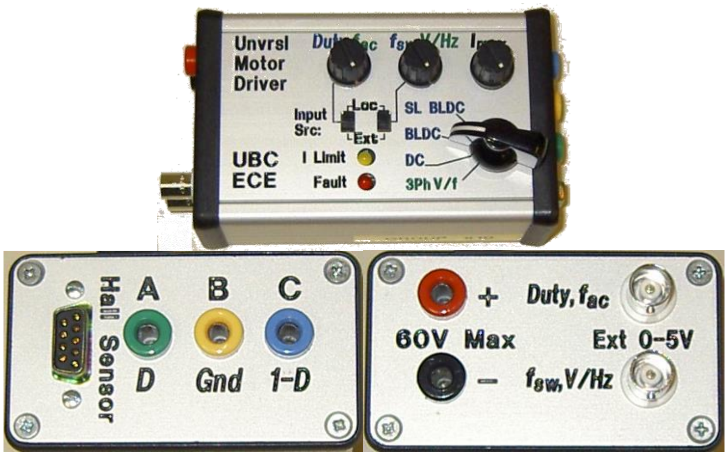


Motor Bench: The Induction Motor under test should be mounted on the Motor Bench as shown on the left. A DC machine mounted on the Cradle emulates the mechanical load. This machine can be coupled to the Induction Motor through the shaft.

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 significant power is delivered to the load. Be careful! This box may get very **hot**, especially its heat sink, which is on the bottom. When the box dissipates more than 50W, turn ON the internal fan.

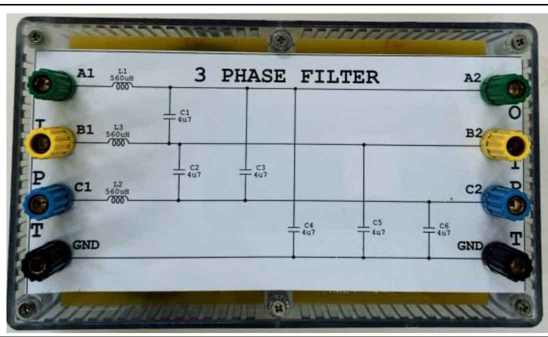


3-Phase Switch: A 3-phase switch is mounted in a box together with synchronization lamps. This box is used to switch ON and OFF the Induction Motor under test in order to observe the start-up transient and record the voltage sag in the system due to a very high start-up current.



Universal Inverter: A multi-purpose inverter is designed to drive various AC and DC motors. In this Lab, you will use this Inverter as the Variable Frequency Drive (VFD) to operate the Induction Motor. For this mode, the mode switch should be in **3Ph V/f** position (**green**) corresponding to the Pulse-Width-Modulation (PWM) Volts-per-Hertz control. The Inverter is also equipped with two **knobs** to control the frequency $\mathbf{f_{ac}}$ (duty cycle) and the voltage/frequency (**V/Hz**) ratio. The last knob on the right adjusts the current limit $\mathbf{I_{max}}$.

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 features an adjustable output voltage range of 0-60V and a current limit of 0-18A, which is sufficient for most experiments conducted in this laboratory.



3-Phase EMI Filter: A three-phase LC Filter will be used in the final Task of this Lab to filter out the high-frequency switching harmonics produced by the Inverter and thus reduce electromagnetic interference (EMI). The Filter has an inductive input (to be connected to the Inverter) and a capacitive output (to be connected to the Motor).

Measurement Box:

Each bench is equipped with a multi-functional **Measurement Box** that can measure up to 3 voltages and up to 3 currents simultaneously with 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 rescaled by a factor of 10, thus raising the measurement limit to 500 V (peak). The **Measurement Box** is connected to the PC's Data Acquisition (DAQ) card. The **Measurement Box** features a power switch on its back panel, located on the right side. The power switch should be normally turned ON, and the three LEDs on the front panel should also be ON, indicating its normal operation.

The channels are colour-coded. It is strongly recommended that you use appropriate and consistent colour wires for each 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

Log in to your local PC and locate the **3-Phase Motor Analysis** program. Double-click on the icon and start the program. A window, as shown in Fig. 2, 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 three voltages (channels **V1, V2,** and **V3**) and three currents (channels **A1, A2,** and **A3**), as well as **Speed** and **Torque**, as will be needed in this Lab. The measurement window can be triggered using either the voltage or current signal of the first measuring channel (either **V1** or **A1**). The point of triggering also defines the relative angle of the measured signals. The user can select or un-select the measurement of voltages and currents, but the first channels V1 and A1 are always selected. For this Lab, select all the voltages and currents, as well as the 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 shown as **real-time instantaneous waveforms** – just like in an oscilloscope (or as **Phasors**). The RMS values of the voltages (in Volts) and currents (in Amps), along with their corresponding average values over the three phases, are displayed on the right side of the panel. All three Channels also display the calculated average real power in Watts. The **Phasor View** panel may be selected to display the voltages and currents as phasors relative to each other.

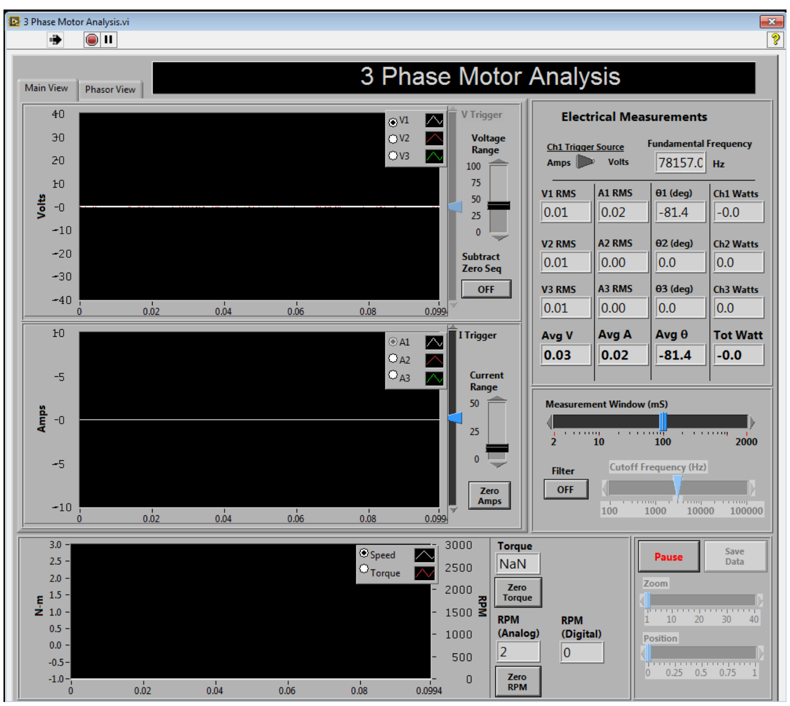


Fig. 2: LabVIEW program interface 3-Phase Motor Analysis.

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.

Measuring Speed and Torque: The dynamometer DC machine in the Cradle is equipped with a tachometer for measuring speed and a load cell for measuring the reaction torque. The measured speed is displayed from two calculations: one digital (achieved by counting the tachometer pulses) and one analog (achieved by converting pulses to voltage). Depending on the condition of your setup (e.g. with or without switching converters that may contribute to the noise in electrical measurements), one of the methods may be more accurate. 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.

Measurement Window: The measurement window period (in ms) can be adjusted when taking measurements in the range of 0.1ms to 2s to capture the desired waveforms more accurately and to reveal details. The button "**Subtract Zero Sequence**" should be "**ON**."

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.**

Setting up Trigger Point: Similar to a conventional Oscilloscope, the program allows the beginning of the measurement window to be triggered based on Channel 1 signals, either current or voltage. The user can toggle the **Ch1 Trigger Source** switch to **Amps** or **Volts**, respectively, as well as slide the **blue** vertical slider on the voltage or current display window.

Displaying Phasors: The program can display all measured voltages and currents as the actual captured Instantaneous Waveforms (default mode), as well as display the corresponding phasors that are computed based on the measured RMS values and angles of each recorded voltage and current. To display the phasors, just switch the tab to **Phasor View**. In each Task, you can use the **Phasor View** tab in the LabVIEW program to observe the phasor diagram of three-phase voltages and currents.

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** at the bottom of the panel. Pushing the bottom **SAVE** brings up the window for saving the data file. The user should name the file and save it in the appropriate location/folder for future analysis.

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

Setting Up the Experimental Part

Mandatory comments: As you are performing the experiments and taking measurements, based on your observations and understanding, provide brief answers to the questions listed in your report below each Table of measurements.

Use of Coloured Wires: When wiring your circuits, it is generally recommended to connect all current-carrying wires and components (including the current measurement channels) first and then connect the voltmeter channels afterward. Use colour wires consistently with phases and parts of the circuit to minimize the chances of any mistakes!

1) Induction Motor Nameplate Information:

The **Induction Motor** must be mounted on the right side of the **Motor Bench**. For the first part of the experiment, the **Induction Motor** shaft should be **decoupled** from the Dynamometer so that the motor shaft is free to rotate. Look carefully at the **Induction Motor** and read the information that is written on its **Nameplate**. Using the Nameplate information, fill in Table 1 of your Lab Report. Note that since this Motor was specially re-wound for reduced voltage (34/68 V), not all standard information is provided. So, complete as many entries of Table 1 as you can. The Motor has two identical windings that are internally connected in parallel to operate at a 34 V line-to-line. You will be able to complete Table 1 after you have completed this Lab Experiment. Calculate the nominal/rated values and write them down in Table 2 of your report.

2) Measuring Stator Winding Resistance:

To calculate the parameters of the equivalent circuit, you will also need to measure the resistance of the stator winding at DC. It is convenient to take this measurement before the Motor is connected to the AC source. 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 a low current. You may apply a variable DC source and measure the current and voltage applied to the winding (similarly to the DC Machine Lab). Use long wires and the bench **DC Power Supply**. Ensure that you apply a very low voltage and a current between 2 and 3 A. **Do not exceed 5 A** for the DC measurement. Write your results in Table 3 of the Lab Report.

3) Wiring the 3-Phase AC Power Supply:

In this part, the students will set up the multi-purpose **3-Phase AC Power Supply** in such a way that it will provide a variable 3-phase AC voltage to drive the Motor under study. The **3-Phase AC Power Supply** has two sets of windings 'Y' (wye) and "Δ" (delta). For this test, you will need to reconfigure the "Δ" (delta) winding, which is on the right side, into the 'Y' (wye) configuration in order to provide sufficient voltage to supply the Motor. **The switch S2 must be open.** Use three **short red wires** to make the neutral point, as shown in Fig. 3. **Please pay particular attention to the winding's polarity**, which is required to correctly add up the voltages. The arrangement in Fig. 3 will give up to about 21 V (phase voltage) and 37V (line-to-line voltage) at the output terminals A-B-C. This should be sufficient to supply the Induction Motor under test. The terminals A-B-C are then used to provide the variable AC voltages to supply the **Induction Motor**. The Variac knob on the front panel of the Power Supply is used to adjust the output voltage. **By varying the Variac knob from 0 to 100%, the output AC voltages may be changed in the range from 0 to about 21 V (rms) per phase.**

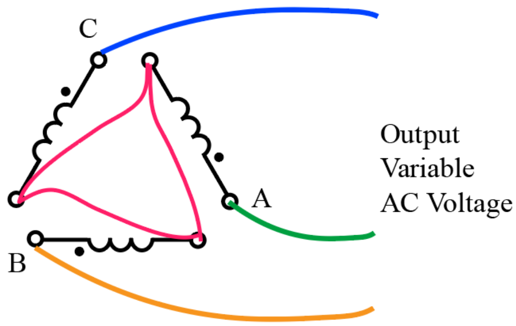


Fig. 3: 3-Phase AC Power Supply wiring diagram.

4) Wiring the Induction Motor:

In your experiment, you will monitor the phase voltages and currents. Wire up the circuit as shown in Fig. 4 to measure current and voltage in each phase. First, connect the current-carrying circuit to the **3-Phase Switch**. Then, connect the voltmeter wires directly to the AC Power Supply panel. Use **colour wires** to distinguish among the phases (For example, Green, Yellow, and Blue). Ensure that the polarities of each current and voltage channel are connected as shown in Fig. 4 and that the channels are ordered consistently. For example, **Ch. 1** current and **Ch. 1** voltage are connected to the same phase (the same applies to the other channels). Mismatching the channels will result in incorrect measurements. Note that in Fig. 4, the Voltmeter Channels form a neutral point. This neutral point is used to measure the phase voltages that will be supplied to the Motor. Although the motor winding is Y-connected, its actual neutral point is unavailable at the motor terminals! The rest of the wiring is described in each Task.

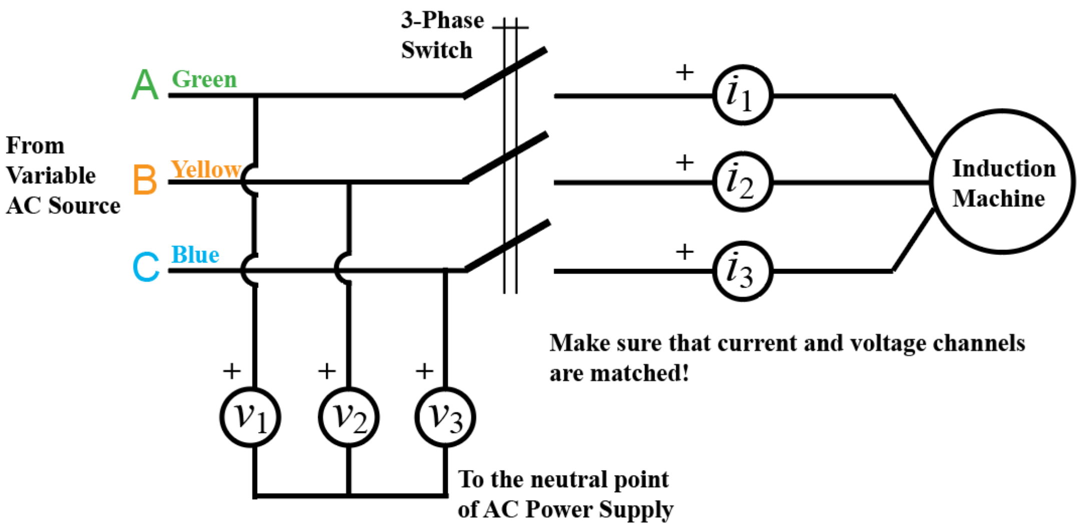


Fig. 4: Wiring diagram for taking the no-load phase voltage and current measurements.

Task 1: No-Load Motor Characteristics

Verify your circuit according to Fig. 4 and ensure the **Induction Motor** is decoupled from the Dynamometer Cradle (Load-Motor). Use the **Measurement Box** to display the voltages, currents, and power of the Motor under test.

Task 1 A: Measuring No-Load Rotational Losses

1) Turn ON the 3-Phase AC Power Supply and slowly increase the applied voltage from 0V to the nominal value of the line-to-neutral voltage recorded in Table 2 (about 19 to 21 V rms for phase voltages). Turn ON the **3-Phase Switch** to power up the Motor. The software program should display the voltage and current measurements for each phase individually, as well as average them among the three phases. The readings should be roughly balanced among the phases with pronounced lagging current. Record the average phase voltage, phase current, average angle, and the total real power in Table 4. You will have to calculate the combined rotational losses as the total input electrical power minus the power dissipated on the stator resistances. That is $P_{rot-loss} = P_{nl} - 3R_1 I_{s,average}^2$.
2) Turn **OFF** the Power Supply by pushing the red **Stop** button. The Variac knob should remain in the same position, corresponding to the nominal voltage, approximately 20 V RMS.

Task 1 B: Recording the No-Load Start-Up Transient

A typical induction motor may draw a substantial current when starting from a fixed-frequency AC line source. This transient starting current may be **5 to 8** times larger than its nominal operating stator current, which causes a voltage sag (drop) and may represent a problem, especially for large motors. The starting torque is not very high (compared with the very high starting current). Therefore, adding mechanical inertia (mechanical load) may significantly prolong the transient period of starting. In this Task, you will observe this phenomenon.

1) Make sure that the **3-Phase Switch** is OFF and the Motor is not spinning. Turn ON the 3-Phase AC Power Supply and check the Variac knob to supply the **nominal** output voltage.
2) The program should be prepared to SAVE the measurements. For that, you will need to increase the measurement window size to its maximum time length (2 seconds). Your screen will be updated at longer time intervals (2 seconds).
3) Move your computer Mouse to the **PAUSE** button and be prepared to click on it. Then, turn ON the **3-Phase Switch** to start the Induction Motor. As soon as the transient appears on the screen, click on the **PAUSE** button on the program interface. Once the transient is captured on the PC screen, you can **ZOOM** in on the representative part of the transient, which includes only a few cycles before the transient and after the steady state is reached. Then, save the data file by clicking on the **SAVE** button. The saved file is in text format and can be used to plot the data in the software of your choice (e.g., MATLAB, Excel).
4) Turn off the Power Supply by pushing the red **Stop** button.

Task 1 C: Recording the Start-Up Transient under Mechanical Load

1) Now couple the **Induction Motor** shaft to the Dynamometer (DC Machine). Ensure that the metal coupling is in place and that the Induction Motor is securely fastened using the finger screws (at least one of them).
2) Repeat Step 3) of Task 1 B, record and **SAVE** the start-up transient. Note that your Motor is now loaded with additional inertia and friction from the Dynamometer DC Machine. The observed transient will be somewhat different – it should be longer. Save the captured data for future comparison.
3) Reduce the voltage to zero and turn off the Power Supply. You will then need to plot and compare the results from Tasks 1 B and C.

Task 2: Blocked-Rotor Test

The Induction Motor shaft should be coupled to the Dynamometer (DC Machine). The wiring remains the same as it was in Task 1. For this measurement only, you will need to lock the Machine shaft. Ask your Lab TA and/or technician for a metal lock that can be inserted in a special slot on the top of the Motor carve to lock the shaft. Slide the **Metal Lock** plate in and manually rotate the shaft to ensure that the lock clicks into place and locks properly.

1) Make sure that the 3-Phase AC Power Supply is OFF and the Variac knob is in the position corresponding to the **minimum** output voltage. Also, ensure that you zero the torque measurement before closing the **3-Phase Switch**.
2) Turn ON the 3-Phase Switch and the AC Power Supply. **Slowly increase the voltage until you reach the rated/nominal phase current** recorded in Table 2. Observe that the motor shaft is not (or should not be) spinning. Note that the developed starting torque is relatively small. Recall that you can change the direction of rotation by swapping any two phases on the motor terminals. If your torque measurement is in the negative direction, you can simply swap any two phases on the motor terminals to get the correct direction of rotation! Record the measurements in Table 5.

Task 3: Measuring Load Characteristics of the Motor

For this Task, you can simplify the circuit by removing the **3-Phase Switch**, as shown in Fig. 5. Reconnect the voltmeter wires directly to the Induction Motor terminals; the neutral point can now be left floating. Connect the **Load Resistor Box** to the Dynamometer DC Machine as shown in Fig. 5. The loaded Dynamometer will be used to emulate a mechanical load torque for the **Induction Motor**. There is no need to measure any electrical variable on the DC side since we are only interested in the resulting mechanical torque. By adjusting the load of the DC Machine, you will be changing the mechanical torque applied to the **Induction Motor** under test.

Ensure the **Resistor Box** fan switch is turned **ON** to allow the fan to operate and cool the resistors. Otherwise, the box will get very **hot**!

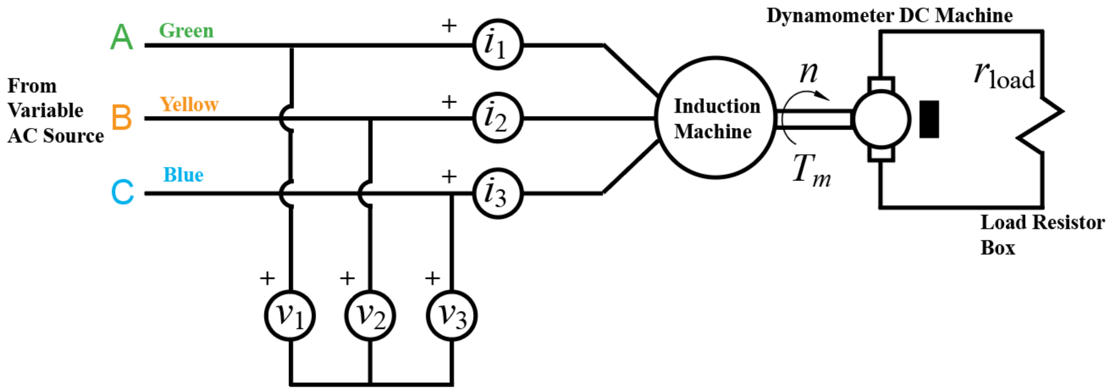


Fig. 5: Wiring diagram for measuring the Load Characteristics.

Task 3 A: Load Characteristic – Speed Regulation under Nominal Voltage

1) Switch OFF all load resistors in the **Load Resistor Box** and turn ON the **Power Supply**.
2) Once the machine is rotating, adjust the voltage of the **Power Supply** to output approximately **20 V** rms per phase. Because the supply is unregulated, it will be necessary to continually adjust the output to maintain the same value when the voltage drops under load. Record this measurement in the first column of Table 6.
3) Then, one at a time, start switching ON the resistors in the **Load Resistor Box** and record the measurements in Table 6. Your last measurement should be taken at the maximum mechanical load achieved when all resistors in the **Load Resistor Box** are turned ON. The last measurement should be in the range of 200 –290W.

Task 3 B: Speed Control by Adjusting Voltage

1) Continue from the previous test in Task 3 A. Verify that the phase voltage is **20 V** rms per phase. The dissipated real power should be high, corresponding to the last point in Task 3 A, step 3). Do not change the switches of the **Load Resistor Box**. Record this measurement in the first column of Table 7.
2) Slowly decrease the voltage by 3 volts at a time and record the values in Table 7. The machine speed should reduce, but not as smoothly as you experienced with DC machines. After taking several measurements, the **Induction Motor** will slowly stall! When it happens, turn OFF the AC Power Supply. You will have to explain why it happened in your Lab Report. Note that when the voltage decreases, the current rapidly increases!

Task 4: Operation with Variable Frequency Drive (VFD)

In this Task, you will operate the **Induction Motor** under test using the **Universal Inverter Box** that is capable of producing/modulating output voltages with variable frequency and amplitude. Most of the AC circuit remains the same as in the previous Task, as depicted in Fig. 5; however, the AC source used in the earlier tasks will be replaced by the **Inverter Box**. Therefore, remove the three wires from the **3-Phase AC Power Supply** and connect them to the **Universal Inverter Box** output terminals **A**, **B**, and **C**, as shown in Fig. 6.

Configure the Universal Inverter:

Attention: Since the **Inverter** switches operate at high frequency (20kHz), they emit electromagnetic waves that could cause electromagnetic interference (EMI). To minimize the impact of EMIs on measurement accuracy, you will also need to connect the ground terminal of the DC Power Supply (**green** terminal) to the ground terminal of the **Motor Bench** (**also green terminal**).

a) The **Universal Inverter** mode switch should be set to the **3Ph V/f** position (**green**) corresponding to the Volts-per-Hertz control Pulse-Width-Modulation (PWM) mode.
b) The Inverter is also equipped with knobs to control the frequency $\mathbf{f_{ac}}$ (duty cycle) and the voltage/frequency **V/Hz** ratio. **Initially, the leftmost knob should be turned to its minimum position, corresponding to the minimum frequency and output voltage**. The second knob, which controls the V/Hz ratio, should be turned to approximately 1/3.
c) The third knob is for setting the current limit, and it should be set to maximum (which corresponds to about 30A). The DC terminals should be connected to the Xantrex **DC Power Supply**.

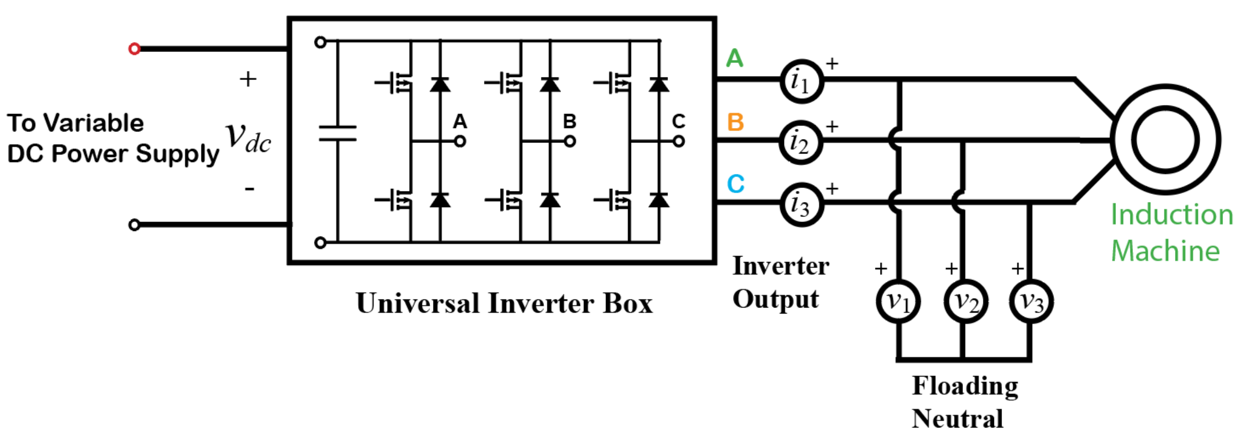


Fig. 6: Wiring diagram for the operation of an Induction Motor with the Variable Frequency Drive using the Universal Inverter Box.

Task 4 A: Speed Control by Varying the Frequency

1) Double-check to ensure that the $\mathbf{f_{ac}}$ knob of the **Inverter** has been turned to a minimum position corresponding to the minimum frequency and output voltage. Then, turn on the **DC Power Supply** and adjust the DC voltage to 48 V. Initially, the Motor should not spin.
2) Slowly turn on the $\mathbf{f_{ac}}$ knob on the Inverter and increase the frequency. You should observe that the Motor is now starting to rotate and that you can easily control its speed by changing the electrical frequency $\mathbf{f_{ac}}$. Observe the frequency on the **3-Phase Motor Analysis** LabVIEW interface (make sure that the triggering is set on current!). Set the frequency to about 60 Hz and observe the waveforms of currents and voltages. Turn on the **Filter** located in the middle of the **3-Phase Motor Analysis** LabVIEW interface and observe the difference between the filtered and unfiltered voltages. Adjust the **V/Hz** ratio knob so that the output voltage is approximately 20 V rms per phase at a frequency of 60 Hz. This should result in the current and voltage waveforms that are very close to ideal sinusoids.
3) Adjust the **Load Resistor Box** so that approximately 150 W of power is supplied to the **Induction Motor**.
4) Decrease the frequency to 10 Hz and do not change the **Load Resistor Box**. Then, start increasing the frequency from 10 to 95 Hz and record several measurements in Table 8. You should observe that you can readily control the motor speed, which can easily exceed the 1800 rpm limit for 60 Hz! You may need to **adjust the V/Hz ratio** in order to keep the **current waveforms close to sinusoidal**!
5) After the last measurement at 95 Hz, slowly decrease the frequency back to zero, and turn OFF the **DC Power Supply**.

Task 4 B: Efficiency of Energy Conversion (without EMI Filter)

6) Complete the calculations of power and efficiency in the bottom section of Table 8, for the low, nominal, and high frequencies.

Task 4 C: Operation of Inverter with LC Filter to Reduce the EMI

In some applications, to reduce the electromagnetic interference (EMI), a special filter may be inserted between the Inverter terminals and the Motor. Locate and connect the **3-Phase LC Filter** box, as shown in Fig. 7, by inserting the **Filter** between the Inverter terminals and the Motor. The easiest way to do it is to unplug the three **coloured** wires from the Inverter and connect them to the **Filter** output (where the **capacitors** are). Then, use the three short **red** wires to connect the **Filter** input (where the **inductors** are) to the Inverter output terminals **A**, **B**, and **C**. Ensure that the **Filter inductors** are correctly connected to the Inverter output! Connecting the **capacitors** to the Inverter output terminals will result in destroying all its internal transistors! Remember that the **Inverter** outputs switched PWM voltages, but the capacitor does not allow for a fast change in voltage, which will result in extremely high current and **instant damage** to the **Inverter**. You will also need to connect the neutral point of the **Filter** to the bench ground for better results.

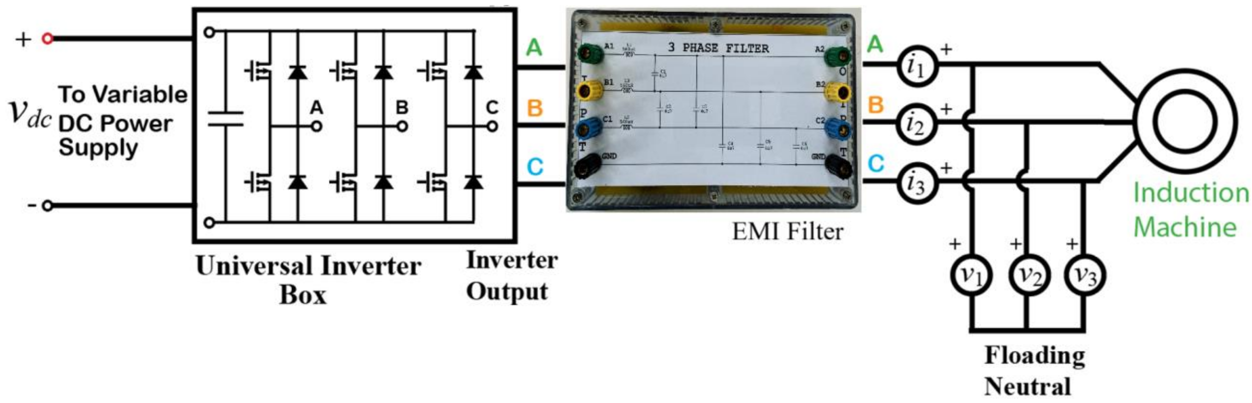


Fig. 7: Wiring diagram for the operation of an Induction Motor from Universal Inverter using EMI Filter. (Use short red wires to connect the EMI Filter to the Inverter. The Filter's neutral point should be connected to the bench ground for best results.)

1) You can start taking measurements from the previous setting. Double-check to ensure that the **f_{ac}** knob of the **Inverter** has been turned to a minimum position. Then, turn on the **DC Power Supply** and adjust the DC voltage to 48 V. Initially, the Motor should not spin. The **Load Resistor Box** should remain unchanged from the last test, corresponding to approximately 150 W of power at a 60 Hz output frequency. The digital **Filter** in the **3-Phase Motor Analysis** LabVIEW program should be turned OFF.
2) Slowly turn on the **f_{ac}** knob on the Inverter and increase the frequency in the range from 10 to 95 Hz. You should see that the measured voltage waveforms are now filtered by the **LC Filter** and are very close to pure sine waves. Adjust the **V/Hz** ratio knob so that the output voltage is approximately 20 V rms per phase at a frequency of 60 Hz. You can also disconnect and connect again the **Filter's** neutral point from the ground and see how it impacts the EMI and visible harmonics in measured voltages and currents. Make a note of the observed results for your report.
3) Then, start increasing the frequency and take just three measurements at 10, 60, and 95 Hz, recording them in Table 9. You may need to **adjust the V/Hz ratio** in order to keep the **current waveforms close to sinusoidal**!
4) After the last measurement at 95 Hz, slowly decrease the frequency back to zero, and turn OFF the **DC Power Supply**.

Task 4 D: Efficiency of Energy Conversion (with EMI Filter)

7) Complete the calculations of power and efficiency in the bottom section of Table 9, for the low, nominal, and high frequencies. You will need to compare these results with Table 8 and draw conclusions about the impact of the EMI Filter on efficiency.

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) to perform the calculations.

Task 5 A: Determining Motor Parameters

1) Calculate the equivalent circuit parameters based on **No-Load** and **Blocked-Rotor** tests. Write them down in Fig. A, all except the rotor resistance R_2'. Note this value of R_2', which corresponds to the measurement at 60 Hz. Complete Table 1 for the condition when the Motor was loaded to the nominal output power defined by the mechanical speed and torque.
2) The equivalent rotor resistance (at around nominal slip) can also be estimated from the measured load torque-speed characteristic. In particular, using the equation $T_e = 3\frac{P}{2}\frac{V_{1,th}^2}{\omega_e}\cdot\frac{\left(R_2'/s\right)}{\left(R_{1,th}+R_2'/s\right)^2+\left(X_{1,th}+X_2'\right)^2}$, it can be noted that at very small values of slip, the torque is almost linearly/proportional to slip and may be approximated as $T_e \approx 3\frac{P}{2}\frac{V_{1,th}^2}{\omega_e}\cdot\frac{\left(R_2'/s\right)}{\left(R_2'/s\right)^2} = 3\frac{P}{2}\frac{V_{1,th}^2}{\omega_e}\cdot\frac{s}{R_2'}$. Based on this approximation, a new value for R_2' can be calculated using several points from the measured load torque-speed characteristic. Calculate this value of R_2' and compare it to the value found in Step 1) corresponding to 60 Hz. Choose one that, in your opinion, is more accurate at the considered range of speed, state and justify your choice, and write it in Fig. A as your final value.

Task 5 B: Equivalent Circuit vs. Measured Comparison

1) Use the per-phase equivalent circuit of the Induction Machine (Fig. A) and calculate the torque-speed characteristic $T_e(n)$ using the voltage from Table 6. Use about 15 to 25 equally-spaced (from 0 to 1800 rpm) points and superimpose on the same plot both the calculated (theoretical) characteristic, as well as the measured characteristic from Table 6. Provide two plots: one with the scale from 0 to 1800 rpm, and the second plot where you zoom in to show all the measured points. Comment on the accuracy of "theoretical" vs. measured results.
2) Using the data in Table 6, calculate the motor efficiency as a function of the torque $\eta(T_m)$. Then, calculate the same characteristic using the equivalent circuit. Plot/superimpose the two curves: one calculated using the measured data, and one calculated using the equivalent circuit. Comment on the results.
3) Using the data in Table 6, plot the motor power factor as a function of the torque $PF(T_m)$. Show two curves: one calculated using the measured data, and one calculated using the equivalent circuit. Comment on the results.
4) Find the maximum and the minimum voltages for which you took measurements in Table 7. For these two voltages, plot two theoretical torque-speed characteristics using the equation $T_e = 3\frac{P}{2}\frac{V_{1,th}^2}{\omega_e}\cdot\frac{\left(R_2'/s\right)}{\left(R_{1,th}+R_2'/s\right)^2+\left(X_{1,th}+X_2'\right)^2}$ and the equivalent circuit parameters. Use about 15 to 25 equally spaced (from 0 to 1800 rpm) points and superimpose both plots on the same graph. Also, superimpose the data points corresponding to the measured speed and torque in Table 7 on the same plot. Make comments on the speed regulation.

5) What can you say and conclude about the accuracy of the equivalent circuit compared to your measurements?

Task 5 C: Starting Transients

1) First, on one graph (using two subplots), plot the voltage and current (only for one of the phases) saved in Task 1 B. Then, plot the phase voltage and current recorder in Task 1C on another graph. In both cases, select the time interval that clearly shows the duration of the start-up transient and then use the same relative time scale for both cases.
2) Show how long the transient lasts in each case. Write your conclusion as to why this may represent a problem for the remaining power network. Extrapolate your conclusions to large induction motors on industrial sites.

Task 5 D: Variable Speed Operation

1) What are the advantages and disadvantages of controlling the Induction Motor speed using the method of Task 3B? Briefly explain.
2) What are the advantages and disadvantages of controlling the Induction Motor using the VFDs based on your experience in Task 4?
3) Consider the chain of components that you had in Task 4, including the following:

AC Source, VFD Inverter (without and with EMI Filter), Induction Machine, Mechanical Coupling, Mechanical Load.

Based on measurements in Task 4, calculate/assign the energy conversion efficiency at each stage in the above chain and complete Tables 8 and 9. Comment on where most energy is lost and how the efficiency changes with motor speed and frequency. Comment on the effect and result of the EMI **Filter** on the observed voltages and the overall VFD efficiency. What was the effect of disconnecting or connecting the **Filter's** neutral point to the bench's ground? Explain why it is not a good idea to connect the EMI Filter capacitors (or any capacitors) directly to the VFD Inverter output.

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 figures (pages 17 – 22).
4) 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 or Windows of Simulink models 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 # 4

Section: ___

Bench #: ___

Partners	Student ID #:	% participation	Signatures

Date Performed:

Date Submitted:

Table 1: Motor Nameplate Information and Nominal Characteristics

Info/Parameter	Nominal/Rated Value	Comments
NEMA Class		
Horse Power		
Speed		
Number of Poles		
Line Current		
Line Voltage		
Calculations corresponding to full load		
Efficiency		
Power Factor		

How can you explain the voltage and current information? Briefly explain why the Motor has two sets of values.

Table 2: Nominal/rated phase voltage and current assuming Y-connected winding

$V_1(rms), V$	$I_1(rms), A$

Table 3: Stator winding DC resistance measurement (Do not exceed 5 A dc current!)

	Measurements (line-to-line)		**Calculation**
Using DC Source	V_{dc}, V	I_{dc}, A	$R_{1,dc} = 0.5V_{dc}/I_{dc}, \Omega$
Using Multimeter	R_{total}, Ω		$R_{1,dc} = 0.5R_{total}, \Omega$

Table 4: No-load measurement (Motor is freely spinning)

Average phase voltage $V_{nl}(rms),V$	Average phase current $I_{nl}(rms), A$	Average phase power-factor angle $\varphi_{nl}(\deg)$	Total real power P_{nl},W	**Calculate** rotational losses P_{rot},W

Table 5: Blocked-rotor measurement (Motor is not spinning)

Average phase voltage $V_{br}(rms),V$	Average phase current $I_{br}(rms), A$	Average phase power-factor angle $\varphi_{br}(\deg)$	Total real power P_{br},W	Stall Torque T_{br}, Nm

Table 6: Load test measurement: (under nominal phase voltage, 20 V)

Measurement #	1	2	3	4	5	6	7
$V_{ph}(ave, rms),V$ Keep it constant							
$I_{ph}(ave, rms), A$							
$\varphi_{pf}(ave, \deg)$							
$P_{in}(total),W$							
n, rpm							
T_m, Nm							
Calculation							
P_m,W							
Slip s							
Using the last measurement, calculate SR $SR = \left(n_1 - n_{7,load}\right) / n_{7,load}$							
Using the last measurement, calculate efficiency of the Motor, % P_m / P_{in}							

Table 7: Motor speed control by varying voltage (Motor may stall at low voltages)

Measurement #	1	2	3	4	5	6
$V_{ph}(ave, rms), V$						
$I_{ph}(ave, rms), A$						
$\varphi_{pf}\,(ave, \deg)$						
$P_{in}(total), W$						
n, rpm						
T_m, Nm						
Calculation						
P_m, W						
Slip s						
Using last measurement, calculate SR $SR = \left(n_1 - n_{last,load}\right) / n_{last,load}$						

Table 8: VFD: Motor speed control by varying frequency at Vdc =48 V

Measurement #	1	2	3	4	5	6
f_{ac}, Hz	10	20	40	60	80	95
Inverter input DC current $I_{inv,dc}, A$						
$V_{ph}(ave, rms), V$						
$I_{ph}(ave, rms), A$						
$\varphi_{pf}\,(ave, \deg)$						
$P_{in-ac}(total), W$						
n, rpm						
T_m, Nm						
Calculate Slip s						

Calculate these values corresponding to different frequencies	Inverter input power P_{in-dc}, W	Input power at the Induction Motor terminals P_{in-ac}, W	Output mechanical power P_m, W	Efficiency of the Inverter, % P_{in-ac}/P_{in-dc}	Efficiency of the Motor, % P_m/P_{in-ac}
$f_{ac} = 10\,Hz$					
$f_{ac} = 60\,Hz$					
$f_{ac} = 95\,Hz$					

Table 9: VFD: Motor speed control by varying frequency at Vdc =48 V, with EMI filter

Measurement #	**1**	2	3	**4**	5	**6**
You can take just three measurements, at 10, 60, and 95 Hz						
f_{ac}, Hz	**10**	20	40	**60**	80	**95**
Inverter input DC current $I_{inv,dc}, A$						
$V_{ph}(ave, rms), V$						
$I_{ph}(ave, rms), A$						
$\varphi_{pf}\,(ave, \deg)$						
$P_{in-ac}(total), W$						
n, rpm						
T_m, Nm						
Calculate Slip S						

Calculate these values corresponding to different frequencies	Inverter input power P_{in-dc}, W	Input power at the Induction Motor terminals P_{in-ac}, W	Output mechanical power P_m, W	Efficiency of the Inverter + EMI Filter, % P_{in-ac}/P_{in-dc}	Efficiency of the Motor, % P_m/P_{in-ac}
$f_{ac} = 10\,Hz$					
$f_{ac} = 60\,Hz$					
$f_{ac} = 95\,Hz$					

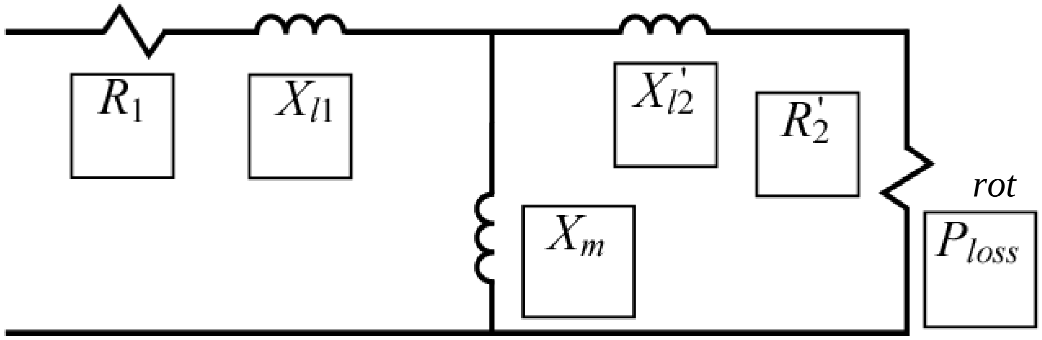


Fig. A. Per-phase steady state equivalent circuit of the induction Motor under test. Fill in the corresponding boxes with machine parameters that you have determined in this Lab. Make sure to include the units.