Lab-3: Squirrel-Cage Induction Motor

Objectives and Overview

The goals for this laboratory experiment are:
- to fully characterize a small industrial ¼ HP 48V Induction Motor;
- to observe the start up transient when the motor is directly connected to the source and started from stall;
- to observe the load characteristics when the motor is supplied from a fixed frequency AC source;
- attempt to control the motor speed by adjusting the source voltage;
- demonstrate the motor control using Variable Frequency Drive (VFD).

By doing a set of measurements, the students will determine parameters of the induction motor per-phase equivalent circuit
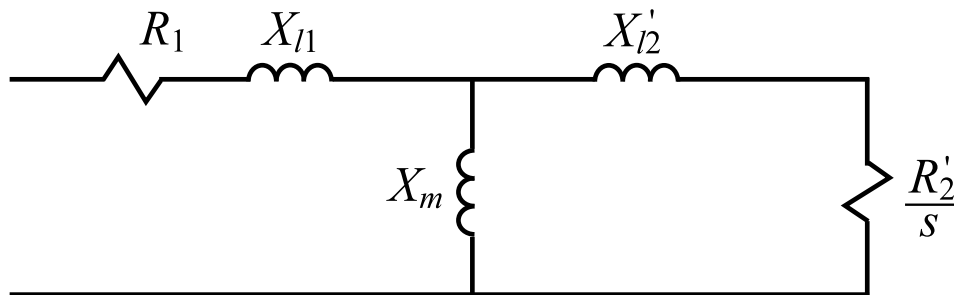

**Fig. 1: Induction motor per-phase equivalent circuit.**

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 motor, and then use the model to predict the torque-speed and load characteristics and compare them to the measured data.

Preparation

It is expected that the students have read and understood the textbook chapter and reviewed the lecture notes module corresponding to Induction Motors. In particular, the students should be familiar with the theory and principle of rotating magnetic field, principle of operation of induction machines, procedures to determine the equivalent circuit parameters, and basic torque-speed characteristics. In addition, the students should review the material on motor control using variable frequency inverter.
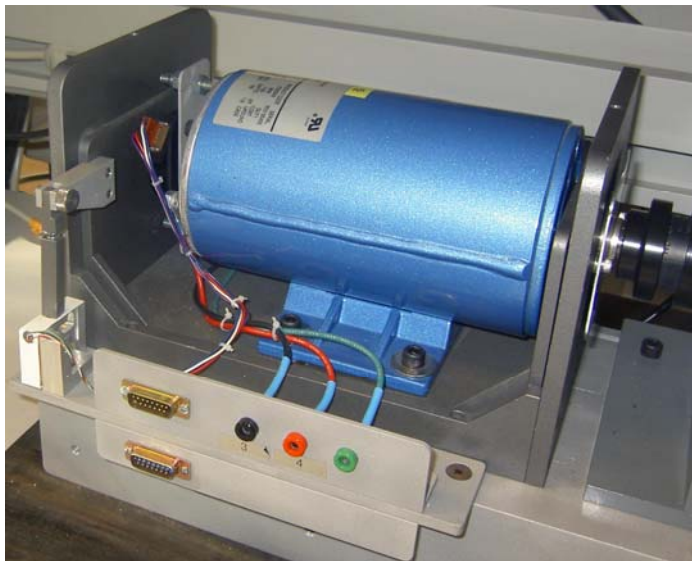
Apparatus

This lab includes the following components:
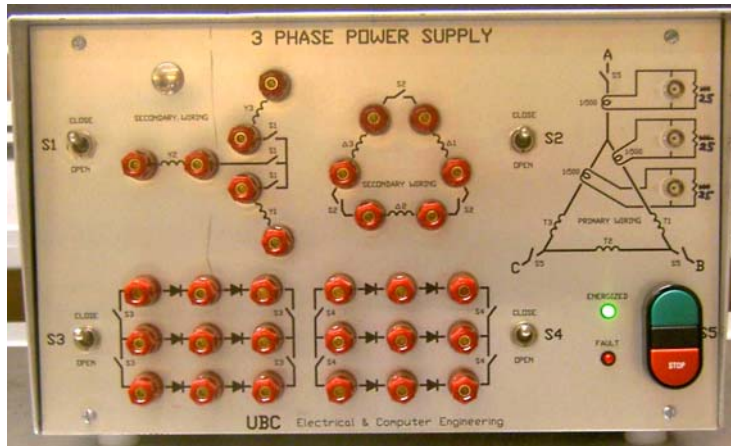
	3-Phase AC Power Supply: This flexible 3-phase AC/DC Power Supply has two 3-phase transformers inside, one that can readily be configured into a 'Y' (wye) connection and the other that can be configured into "Δ" (delta). Those transformers are fed from an internal 3-phase Variac that can be used to adjust the output voltage to the desired level. The Variac knob is on the right-side panel. 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.
	Induction Motor: This is a small industrial ¼ HP Squirrel-Cage Induction Motor which you have to parameterize. The Stator winding is assumed to be Y-connected with the access to the phase terminals. This motor should be mounted on the Motor Bench, wherein the motor shaft may be coupled to the Dynamometer for taking the measurements.
	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. Note though that friction and loss torque internal to the machine will not be coupled to the torque sensor. The Dynamometer also has an optical position encoder mounted on the back of its shaft (left side) for measurement of speed.
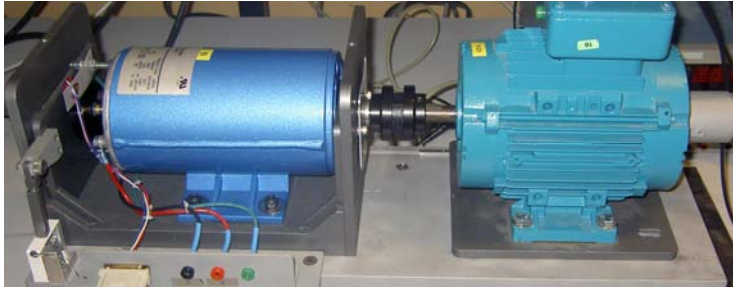
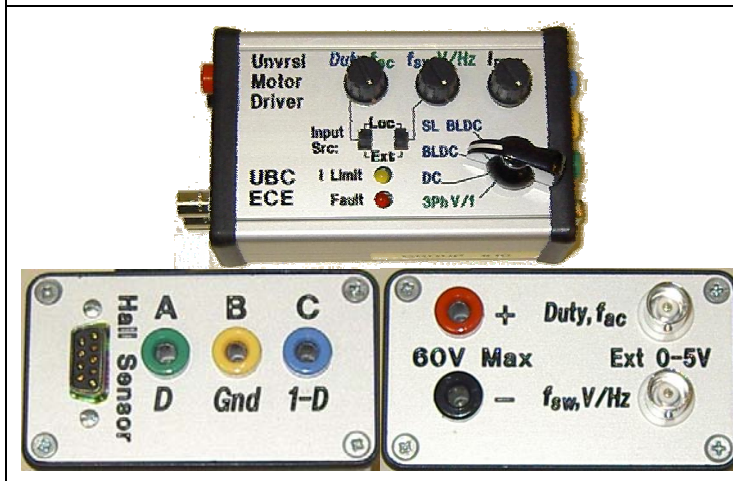|	
	Motor Bench: The Induction Motor under test should be mounted on the Motor Bench as shown on the left. A DC machine mounted on the Cradle is used to emulate the mechanical load. This machine can be coupled to the Induction Motor through the shaft.
	Measurement Box: This is a multi-functional unit 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 resistors from 500 to 25 ohms which can be switched on in parallel to each other. The box is equipped with a cooling fan to help dissipate the heat.

	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 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 **f$_{ac}$** (duty cycle) and the voltage/frequency ratio. The last knob on the right adjusts the current limit.

Experimental Part

Task 1: Setting-Up the Experiment

1) Induction Motor:

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 **de-coupled** 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 (as many entries as you can). Note that since this motor was specially re-wound for reduced voltage (34/68 V), not all of the standard information is provided. The motor has two identical windings that are internally connected in parallel to operate at 34 V line-to-line. However, 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:

For calculating the parameters of equivalent circuits 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 AC source. The simplest way to measure the winding resistance is to use the Multimeter that is available on your bench top. Alternately, you may apply a variable DC source and measure the current and voltage applied to the winding (similarly to the DC Machine Lab-2). Write your results in Table 3 of the Lab Report.

3) Dynamometer Cradle:

Use a special multi-pin cable to connect the **Dynamometer Cradle** tachometer and load cell output with the **Measurement Box** for displaying the torque and speed on PC screen.

4) Measurement Box and Data Acquisition:

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. A window 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 torque, speed, AC voltages, and AC currents in each phase. The program also computes and displays the average phase voltage, the average phase current, the average phase power factor angle, and the total real power.

Ask a TA to help you with the program if you have a problem locating and/or running it. Select all three voltages and currents to be measured on the **3-Phase Motor Analysis** program. The button "**Subtract Zero Sequence**" should be "**ON**." Remember to push buttons **ZERO** before each test to remove any offset when measuring currents, torque, and speed. The program can **PAUSE** and S**AVE** the measured data.
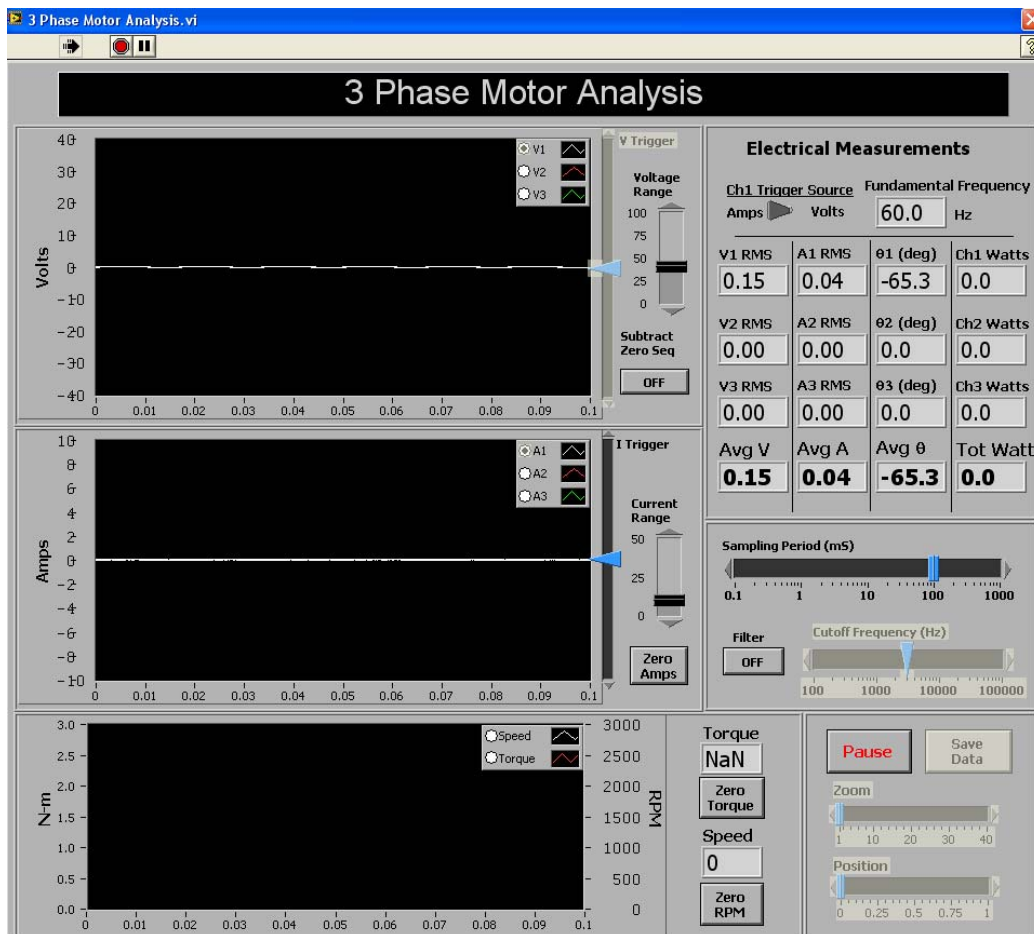

Fig. 2: LabView program interface 3-Phase Motor Analysis.

5) 3-Phase AC Power Supply:

In this part, the students will set up the multi-purpose **Power Supply** in such a way that it will provide a variable 3-phase AC voltage to drive the motor under study. The **Power Supply** has two sets of 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. In order to get the required output voltage, you will need to connect these windings as shown in Fig. 3.
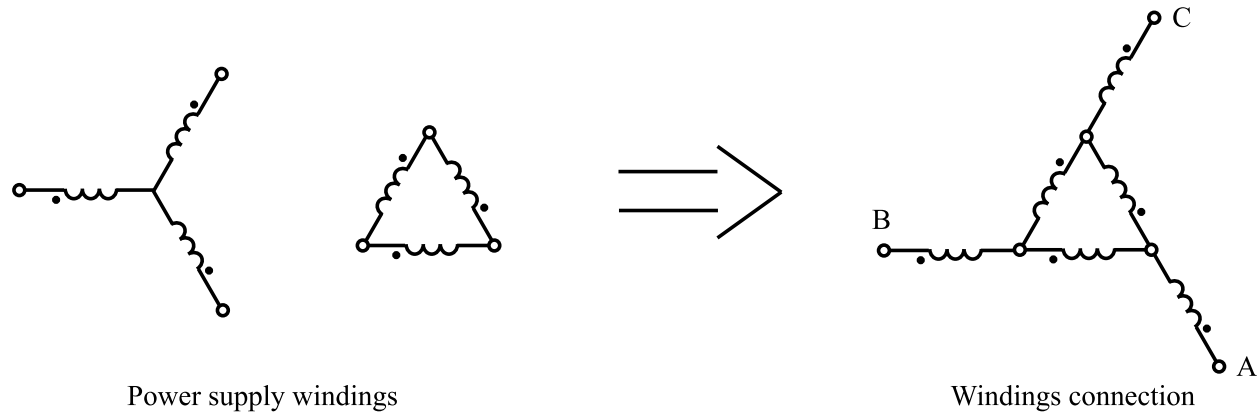

Power supply windings   Windings connection

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

Please pay a particular attention to the windings polarity, which is required to properly add up the voltages. This arrangement will give about 18 V (line-to-neutral) and 31V (line-to-line) at the output terminals A-B-C. **Switch S1 must be open and S2 must be closed.** The terminals A-B-C are then used to provide the variable AC voltages to supply the **Induction Motor**.

6) Wiring the Induction Motor:

In your experiment you will be monitoring the phase voltages and currents. Wire up the circuit as shown in Fig. 4 so that you can measure current and voltage in each phase. **Make sure that the polarity of each current and voltage channel are connected as shown in Fig. 4 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). Mismatching the channels will result in incorrect measurements.

Note that in Fig. 4 the Voltmeter Channels form a floating neutral point. This neutral point is used to measure the phase voltages. Although the motor winding is Y-connected, its actual neutral point is not available at the motor terminals. The rest of the wiring is described in each Task.
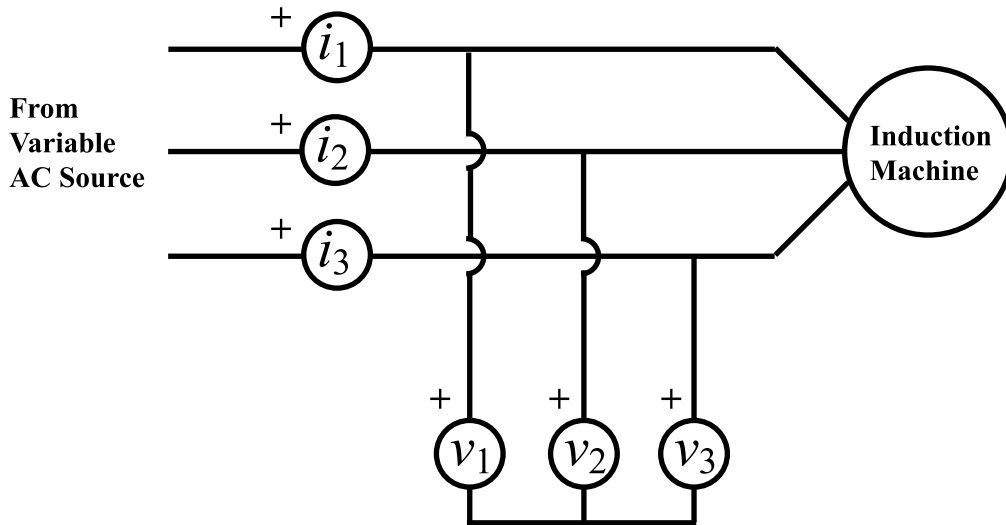
Fig. 4: Wiring diagram for taking the phase voltage and current measurements.

Task 2: No-Load Motor Characteristics

Verify your circuit according to Fig. 4 and make sure that 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 2 A: Measuring No-Load Rotational Losses

1) Turn on the 3-Phase AC Power Supply and slowly increase the applied voltage from 0V to its maximum (17 to 18V rms line-to-neutral). Note that the maximum voltage (even for unloaded motor) is less then the nominal value recorded in Table 2. The software program should display the voltage and current measurements for each phase individually as well as averaged 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 less the power dissipated on the stator resistance. That is $P_{rot-loss} = P_{nl} - 3R_1 I^2_{s,average}$.

2) Turn off the Power Supply by pushing the red **Stop** button. The Variac knob should remain in the maximum voltage position.

Task 2 B: Recording the No-Load Start-Up Transient

1) Make sure that 3-Phase AC Power Supply is off and the Variac knob is in the position corresponding to the **maximum** output voltage.

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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 (about 1 sec). Your screen will be updated at a larger time intervals.
3) Hold your computer Mouse on the **PAUSE** button and be prepared to click on it. Then, press the green button **Start** on the Power Supply to start the Induction Motor. As soon as the transient appear on the screen click on the **PAUSE** button on the program interface. Once the transient is captured on the PC screen you may be able to zoom into the representative part of the transient that includes only few cycles (before) after the steady-state is reached. Then save the data file by clicking on the **SAVE** button. The saved file is in the text format and can be used for plotting the data in the software of your preference (Matlab, Excel, etc.)
4) Turn off the Power Supply by pushing the red **Stop** button.

Task 2 C: Recording the Start-Up Transient under Mechanical Load

5) Now couple the Induction Motor shaft to the Dynamometer (DC Machine). Make sure that the robber coupling is in place and that the Induction Motor is tightly fixed using the finger skews (at least one of them).
6) Repeat part 3) of Task 2 B and record the start-up transient. Note that now your motor is loaded with additional inertia as well as the friction from the Dynamometer DC Machine. The observed transient will be somewhat different - longer. Save the captured data for the future comparison.
7) Reduce the voltage to zero and turn off the Power Supply.

Task 3: 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 2.

1) Make sure that 3-Phase AC Power Supply is off and the Variac knob is in the position corresponding to the **minimum** output voltage.
2) Turn on the Power Supply and 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. The developed starting torque is quite small and the friction of the Dynamometer Machine is sufficient to prevent it from rotating. Record the measurements in Table 5.

Task 4: Measuring Load Characteristics of the Motor

Connect the Load Resistor Box to the Dynamometer DC Machine as shown in the 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. Making sure that the resistor box fan is spinning. Otherwise the box may get very hot. By adjusting the load of the DC Machine you will be changing the mechanical torque applied to the **Induction Motor** under test.
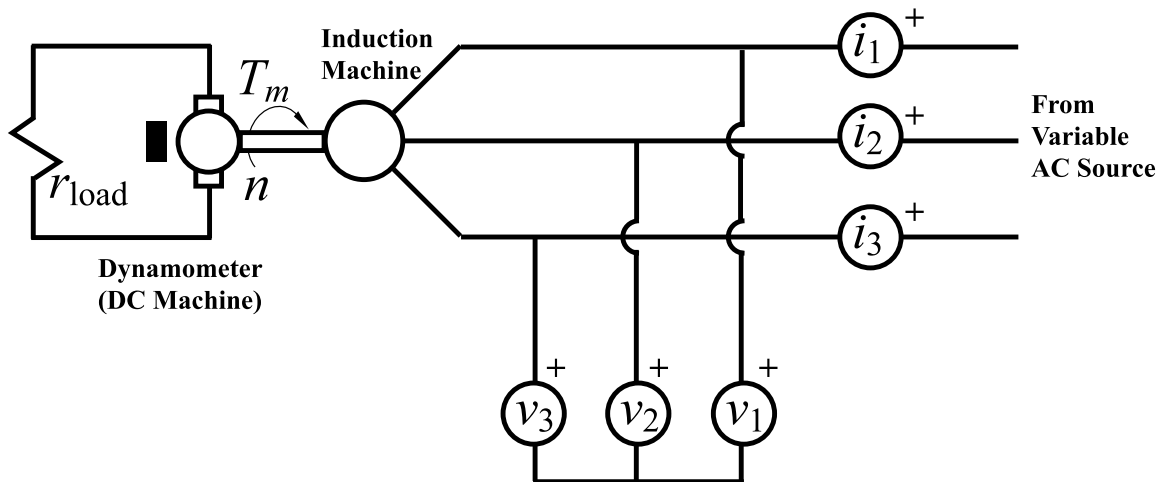
Fig. 5: Wiring diagram for the measuring the Load Characteristics.

Task 4 A: Load Characteristic – Speed Regulation (at 16 – 17 V)

1) Switch off all load resistors in the **Load Resistor Box** and turn on the **Power Supply**.
2) Aadjust the **Power Supply** to output about 16 - 17V rms per-phase. Record this value in Table 6. Because the supply is unregulated, it will be necessary to adjust the output to the same value when the voltage drops under load. Record the first measurement in Table 6.
3) Then, switch the **Load Resistor Box** in small steps (from high to minimum low) thus increasing the load torque. Take about 6 measurements to span the range from no- to full-load and record the values in Table 6. Monitor the real power so that it does not significantly exceeds the rated power of the motor. The last measurement should be taken when the real power is in the range 190 – 250W.

Task 4 B: Speed Control by Adjusting Voltage

1) Continue from the previous test Task 4 A part 3) when the real power is in the range 190 – 250W and the voltage is about 16 – 17 V rms per-phase. Do not change the switches of the **Load Resistor Box**. Record the first measurement in Table 7.
2) Slowly decrease the voltage in 1 to 2 volt increments. Record each measurement in Table 7. After taking several measurements the Induction Motor might/will stall. When it happens, turn off the Power Supply. You will have to explain why it happened in your Lab Report.

Task 5: Demonstration of 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 previous task as depicted in Fig. 5. However, for this task, remove the three wires from the 3-Phase AC Power Supply and connect them to the **Universal Inverter** output terminals A-B-C as shown in Fig. 6. The **Universal Inverter** mode switch should be in **3Ph V/f** position (green) corresponding to the Volts-per-

Hertz control Pulse-Width-Modulation (PWM). The Inverter is also equipped with knobs to control the frequency $\mathbf{f_{ac}}$ (duty cycle) and the voltage/frequency $\mathbf{V/Hz}$ ratio. Initially, the left-most knob should be turned to minimum position corresponding to minimum frequency and output voltage. The second knob controlling the $\mathbf{V/Hz}$ ratio should be turned to approximately 1/3. 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**.
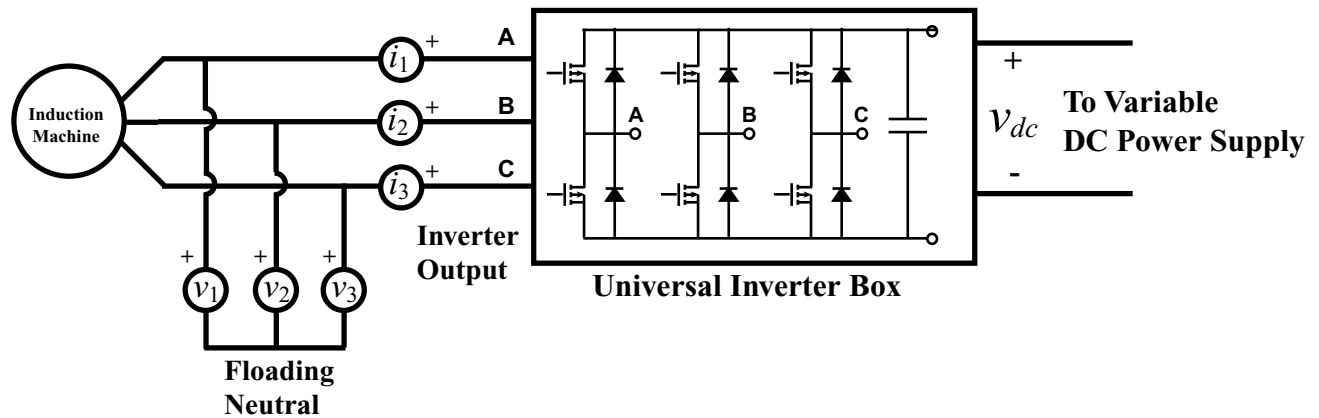

Fig. 6: Wiring diagram for Induction Motor Variable Frequency Drive demonstration.

Task 5 A: Speed Control by Varying the Frequency

1) Turn on the **DC Power Supply** and adjust the DC voltage to 45 V. Increase the current limit, if needed, so that the supply is not current limited. Initially, the motor should not be spinning.
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** button on the **3-Phase Motor Analysis** LabView interface and observe the difference between the filtered and unfiltered voltages.
3) Adjust the **Load Resistor Box** so that you have about 150 to 200 W coming into 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 up to 95 Hz and record several measurements in Table 8. You should observe that you can readily control the motor speed and easily exceed the 1800 rpm limit. You may need to adjust the V/Hz ratio in order to keep the current waveforms close to sinusoidal.
5) Complete the calculations of power and efficiency in Table 8.

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Task 6: Calculations and Comparisons

This part must be included with your Lab Report. You are very strongly encouraged to use the **Matlab** or Excel (or equivalently powerful tool) for performing the calculations.

Task 6 A: Determining Motor Parameters

1) Calculate the equivalent circuit parameters and write them down in Fig. A. Complete the Table 1 for the condition when the motor was loaded to the nominal output power defined by the mechanical speed and torque.

Task 6 B: Equivalent Circuit vs. Measured Comparison

1) Use the per-phase equivalent circuit of the Induction Machine (Fig. A) and calculate the torque-speed characteristics $T(n)$ using the voltage from Table 6. Use about 10 to 15 equally-spaced (from 0 to 1800 rpm) points and superimpose on the same plot both calculated (theoretical) characteristics as well as the measured characteristics from Table 6. Provide two plots: one with the scale from 0 to 1800 rpm, and the second one where you zoom-in to show all the measured points. Comment on the results and speed regulation.
2) Using the data in Table 6, calculate and plot the motor efficiency vs. torque $\eta(T)$. Show two curves: one calculated using measured data, and one calculated using the equivalent circuit. Comment on the result.

Task 6 C: Starting Transient

1) On one graph, plot the voltage and current (only for one of the phases) saved in Task 2 C or B step 3). Analyze the transients and write your conclusion as to why this may represent a problem for the remaining power network? Extrapolate your conclusions to large induction motors.

Task 6 D: Questions

1) What are the advantages and disadvantages of controlling the Induction Motor speed using the method of Task 4 B? Briefly explain.
2) What are the advantages and disadvantages of controlling the Induction Motor using the VFDs based on your experience in Task 5? How efficient is the Inverter Box that you used in this lab?

Task 7: Reporting

Prepare the Lab Report that includes:
1) Title Page (all filled-in, with signatures)
2) Pages with the measured data and figures (pages 12 – 15),
3) Additional pages with calculations, discussions, and/or answers to questions in Task 6,
4) 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: Motor Nameplate Information

Info/Parameter	Nominal/Rated Value	Comments
NEMA Class		
Horse Power , HP		
Speed		
Current		
Voltage		
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 (use DC source)

V_{dc}, V (line-to-line)	I_{dc}, A	**Calculate** R_1, Ω $R_{1,dc} = 0.5 V_{dc}/I_{dc}$

Table 4: No-load measurement (motor is free 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

Table 6: Load test measurement: (up to 6 measurement points at high voltage, 16-17 V)

Measurement #	1	2	3	4	5	6
$V_1(ave, rms), V$ keep it constant						
$I_1(ave, rms), A$						
$\varphi_1(ave, deg)$						
$P_1(total), W$						
n, rpm						
T_m, Nm						
Calculate Slip S						
$SR = (n_1 - n_{6,load})/n_{6,load}$						

Table 7: Motor speed control by varying voltage

Measurement #	1	2	3	4	5	6
$V_1(ave, rms), V$						
$I_1(ave, rms), A$						
$\varphi_1(ave, deg)$						
$P_1(total), W$						
n, rpm						
T_m, Nm						
Calculate Slip S						
$SR = (n_1 - n_{6,load})/n_{6,load}$						

Table 8: Motor speed control by varying frequency at Vdc =45 V

Measurement #	1	2	3	4	5	6
f_{ac}, Hz	10	20	40	60	80	95
Inverter input DC current $I_{inv,dc}, A$						
$V_1(ave, rms), V$						
$I_1(ave, rms), A$						
$\varphi_1(ave, \deg)$						
$P_1(total), W$						
n, rpm						
T_m, Nm						
Calculate Slip S						

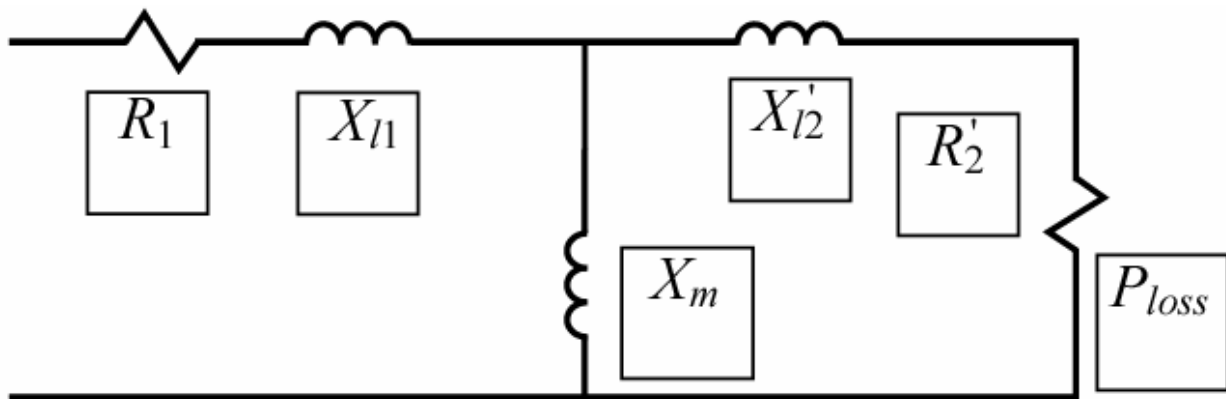| Calculate these values corresponding to different frequencies	Inverter input power P_{in-dc}, W	Input power at the Induction Motor terminals P_{e-ac}, W	Output mechanical power P_m, W	Efficiency of the Inverter, % P_{e-ac}/P_{in-dc}	Efficiency of the Motor, % P_m/P_{e-ac}
$f_{ac} = 60Hz$					
$f_{ac}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

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