Experiment 7
ET 332b
No-load and Starting Characteristics of Squirrel-Cage Induction Motors

Purpose:

Determine the electrical and mechanical characteristics of a squirrel-cage induction motor during no-load and start-up operation through lab measurements and calculations.

Theoretical Background

A squirrel-cage induction motor consists of two parts: the stator and the rotor. There is no electrical connection between the rotor and stator. The magnetic flux produced by the stator provides power transfer across the air gap without any electrical connection. This makes the squirrel-cage induction motor a rugged machine for industrial applications

Applying three phase voltages to the motor stator produces a rotating magnetic field. The field's rotational speed depends on the voltage frequency and the number of magnetic poles in the motor design. The variable, n_s, synchronous speed, defines the speed of the rotating magnetic field. The rotating magnetic field induces a voltage in the squirrel-cage rotor bars. The induced voltage produces a current in the rotor bars since the squirrel-cage forms a complete circuit.

At startup, the induced rotor voltage has maximum frequency since the slip speed is equal to the synchronous speed. The induced voltage has maximum magnitude also since the relative speed between the rotor and the rotating field is greatest. Equation (1) gives the relationship between rotor frequency and slip.

$$f_r = f_s \cdot s \tag{1}$$

Where: f_r = rotor frequency (Hz)
f_s = synchronous frequency (Hz)
s = motor slip (per unit)

The motor slip is nearly zero when the squirrel-cage motor operates without mechanical load connected to the shaft. This produces a very low rotor frequency. The rotor leakage reactance magnitude varies with the rotor frequency based on equation (2)

$$x_r = 2\pi f_r L_r \tag{2}$$

This equation shows that the rotor leakage reactance is maximum when the motor starts since $f_r = f_s$.

Figure 1 shows a schematic per-phase circuit representation of the rotor-stator circuit. The rotor resistance is a function of the motor slip, which relates to the mechanical load on the motor. The motor slip changes from 1 at start up to nearly zero for no-load. This causes the rotor resistance

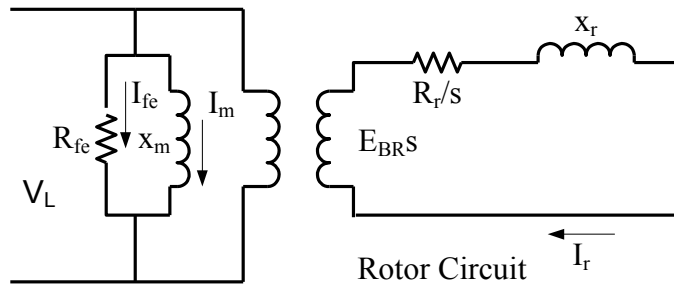to change from a maximum value at no-load to a minimum value during the transition from start-up to no-load.

Figure 1: Induction Motor Rotor Circuit Per Phase Representation

At no-load, the current flowing in the rotor, I_r, is small since the induced voltage is very low and rotor resistance is high. Most of the current entering the motor goes to the stator circuit to produce the magnetization current that forces flux across the air gap. The value of x_m in Figure 1 represents the magnetization reactance that draws the current I_m. Active power losses in the iron cores of the motor draw core loss current, I_{fe}. The resistor, R_{fe}, represents the power losses in the core in the motor model.

Squirrel-cage induction motors draw a large lagging current at no-load since the magnetic circuit includes an air gap. Most of the current goes to I_m, since x_m is much smaller than R_{fe}. The resulting power factor of the unloaded induction motor is very low (0.2-.5) due to the large magnetization current component.

The induced rotor voltage E_{BR} is at a maximum when the motor starts. The rotor resistance is minimum, and the inductive reactance is maximum because slip is 1 at start-up. This combination of factors produces rotor impedance that is highly inductive and low in value relative to the no-load rotor impedance. This produces a high rotor current that is reflected to the stator due to transformer action. This current is seven to ten times the motor rated current typically. The large inductive component of the rotor impedances gives the rotor a low power factor during start-up.

The rotor current is directly proportional to stator voltage and inversely proportional to rotor impedance. The stator voltage also affects the motor torque. Motor torque is proportional to the strength of the stator magnetic field, which depends on stator voltage. Equation 3 gives the relationship between the rotor current, power factor, field flux and torque. Increasing the rotor resistance increases motor torque.

$$T = K\phi I_r \cos(\theta) \tag{3}$$

Where: ϕ = field flux
I_r = rotor current
$\cos(\theta)$ = rotor power factor
T = motor torque
K = proportionality constant

Even though starting current is high; the starting power factor is low so the starting torque is not the maximum torque produced by the motor.

Since current and flux are both proportional to the applied voltage, V_L, in Figure 1, the following equation shows that the starting torque is proportional to the square of the applied voltage.

$$T_{st} = K_1 V_L^2 \tag{4}$$

A motor starting torque test utilizing reduced terminal voltage can use Equation 4 to find the value of starting torque for rated terminal voltage. Reducing the terminal voltage by half reduces the starting torque by a factor of four. Reducing the terminal voltage lowers the motor line current during the test allowing measurement to be made before circuit breakers trip due to high starting currents.

Three Phase Power Measurement

Testing three-phase induction motors requires three-phase power measurement. The two-wattmeter method can measure total three-phase power by using two single-phase wattmeters. Figure 2 shows the connects for this method using an ABC phase sequence.
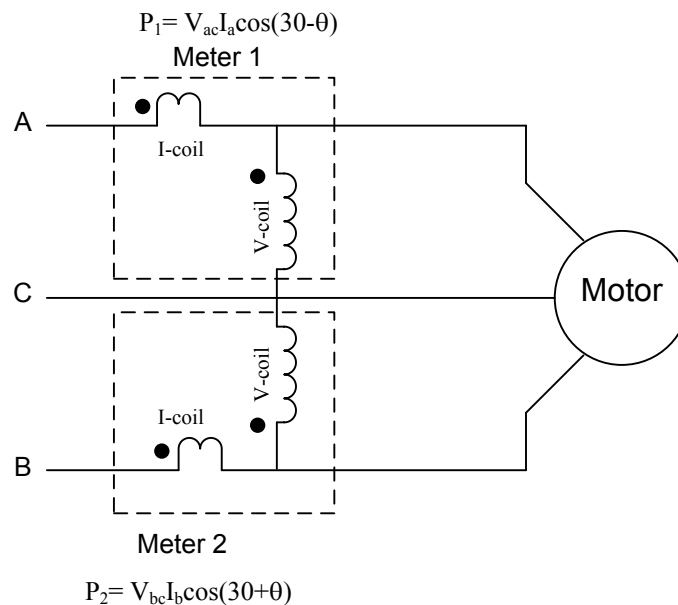

Figure 2. Two-Wattmeter Connections for Measuring Three-Phase Power.

The total motor power is the algebraic sum of the meter readings. The meter readings also give the total reactive power consumed and the load power factor by using Equations 5-7 below. These equations are correct for ABC phase sequence.

Total active power: $\qquad P_T = P_1 + P_2$ (5)

Total reactive power (VARS): $\quad Q_T = \sqrt{3}\left(P_1 - P_2\right)$ (6)

Load power factor: $$\theta = \tan^{-1}\left[\frac{\sqrt{3}(P_1 - P_2)}{P_1 + P_2}\right] \qquad (7)$$

For a BAC phase rotation with the same meter connections, equations (6) and (7) become:

Total reactive power (VARS): $Q_T = \sqrt{3}(P_2 - P_1)$

Load power factor: $\theta = \tan^{-1}\left[\dfrac{\sqrt{3}(P_2 - P_1)}{P_1 + P_2}\right]$

The equations above show variables P_1 and P_2 exchanged in the differences of the two equations when using BAC phase sequence.

Performance Objectives

After successfully completing this lab, the student will be able to:

1.) Perform a locked rotor test on an induction motor.
2.) Use the two-wattmeter method to measure three-phase load power.
3.) Explain how motor terminal voltage affects starting torque.
4.) Measure motor no-load power factor.

Required Equipment

Required Machines:	IM-100 Three Phase Squirrel-Cage Induction Motor
	Pony Brake
Power Source:	0-240 V Variable 3-phase ac
Meters:	1, 0-8 A ac Ammeter
	1, 0-300 V ac Voltmeter
	2, 0-600 W wattmeters
Other Equipment:	MGB-100 DG bedplate, banana leads, tachometer, rubber coupling, shaft guards.

Program Plan

Part 1: No load testing of the induction motor

Step 1: Place the IM-100 induction machine on the bedplate and clamp the machine securely.

Step 2: Connect the induction machine as shown in Figure 3. Note the polarity of the current and voltage coils of the wattmeters. The dotted ends indicate positive instantaneous polarity. Set the range to 600 watts when using the analog meters. The digital meters are auto-ranging and need no additional adjustment. Figure 4 gives the details of the power meter connections.
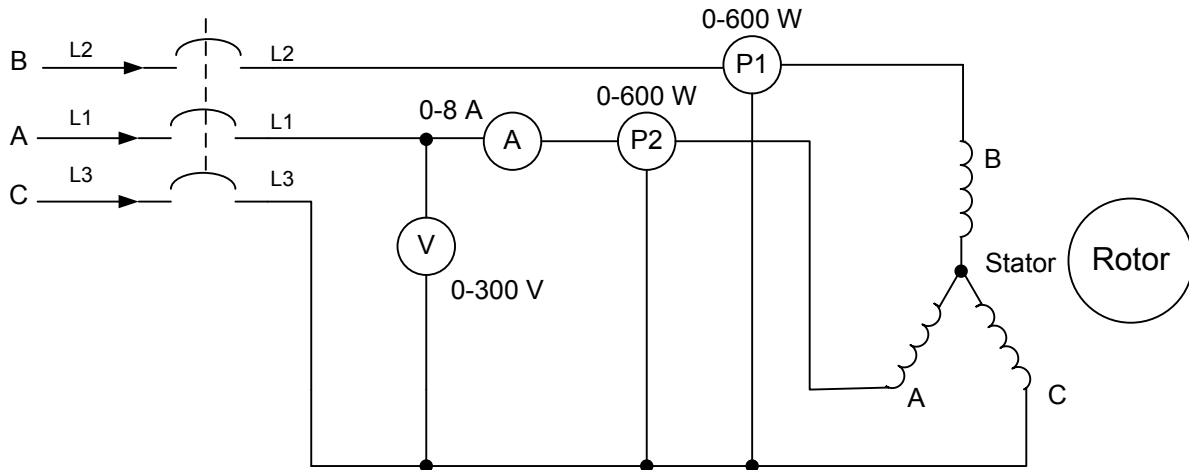

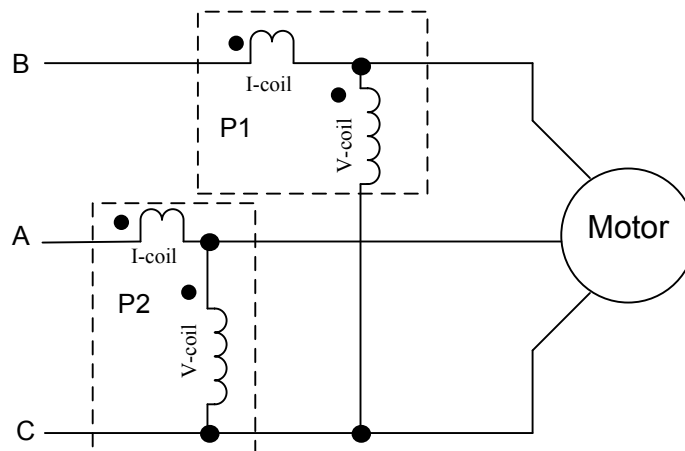Figure 3. Induction Motor Electrical Connections- No-Load Testing

Figure 4. Power meter connection details. Dotted end of coils indicates positive terminals.

Step 3: Find the induction motor nameplate and record the rated speed, voltage, current and horsepower in Table 1 on the Data Tables and Calculations Summary sheet.

Step 4: Move the voltmeter connections to the terminals of the bench supply. Turn on the bench power supply and adjust the output voltage to rated motor voltage. Replace the voltmeter leads to the position in Figure 3.

Step 5: Turn the motor on by placing the motor circuit breaker in to ON position. Record the motor line current, line voltage and wattmeter P1 and P2 readings in Table 2. (Note: one of the meters should read negative. Turn off the power and reverse the voltage leads on analog meters to get proper indication and enter the value as a negative in the table. Digital meter automatically change polarity.)

Step 6: Measure the no-load motor speed using the strobe tachometer. Record the measurement in Table 3.

Step 7: Turn the motor off. Turn the bench power off.

Part 2: Locked Rotor Testing of an Induction motor

Step 1: Install the pony brake on the bedplate and couple it to the motor using the rubber coupling. Clamp the pony brake securely and place shaft guards on all rotating shafts.

Step 2: Move the voltmeter leads from the motor to the bench power supply. Turn on the supply and adjust the supply voltage to 104 V. Turn off the supply and replace the leads in the position shown in Figure 3.

Step 3: Loosen the pony brake tension strap by adjusting the knob located on top of the device (See photo). Loosen the brake until the shaft turns freely.
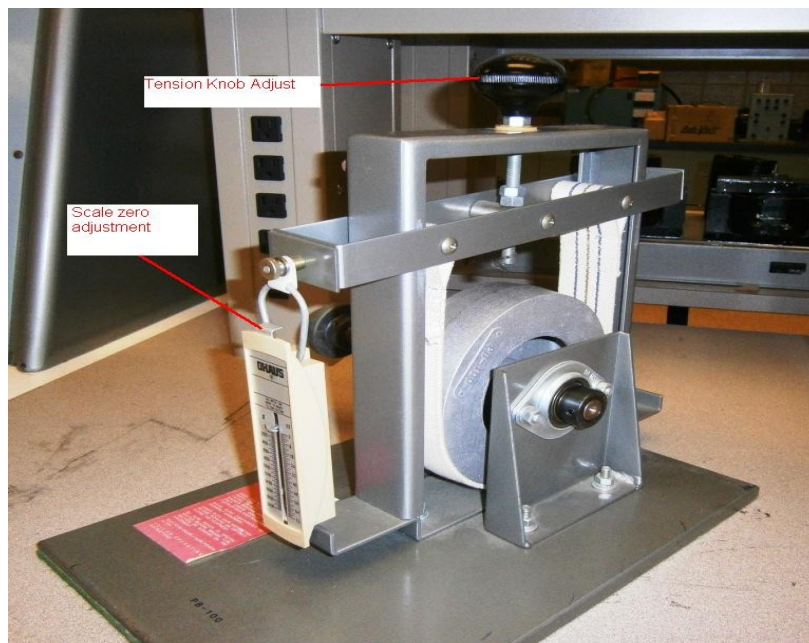
Step 4: Find the force scale and check the zero position. Adjust the zero position as necessary by pulling the metal tab located on the top of the scale.

Step 5: Turn on the bench power supply and the motor.

Step 6: Complete this step as quickly as possible because the motor will draw a large current at locked rotor and will eventually trip the breaker on the motor front panel. Tighten the pony brake until the motor shaft stops. Record the motor current, voltage and power readings. Record the scale force value in grams. Enter all these values in Table 4. Power the motor down using the breaker switch. (Note: Allow the motor to cool and reset it if it trips before all measurements are taken again.

Step 7: Wait 2-5 minutes for the motor and breaker to cool and repeat step 6 two more times to complete Table 4.

Step 8: Turn off the motor and the bench power supply. Remove all wiring and return test items to storage.

De-briefing and Calculations

Part 1: No load testing of the induction motor

1.   The total three phase power is the algebraic sum of the P1 and P2 measurements. Add any negative value to find the net power. Record the value below.

$$P_T = \underline{\hspace{3cm}}$$

2.   Compute the total apparent power entering the motor using the following formula and record the result below.

$$S_T = \sqrt{3} \cdot V_L \cdot I_L \tag{8}$$

Where: V_L = the line voltage measurement from Table 2
                I_L = the line current measurement from Table 2

$$S_T = \underline{\hspace{3cm}}$$

3.   The ratio of motor active power to apparent power gives the no-load motor power factor. This value should be low since the motor draws a large reactive current to establish the flux in the air gap with little active power transfer. Compute the value and enter it below.

$$F_p = \frac{P_T}{S_T} = \underline{\hspace{3cm}} \quad \text{Lagging}$$

4. Compute the per unit motor slip at using the measured no-load speed. The synchronous speed is 1800 RPM.

$$s = \frac{n_s - n_r}{n_s} = \underline{\hspace{2cm}} \text{ p.u.}$$

Part 2: Locked Rotor Testing of an Induction motor

1. Compute the average line current values using the measurement in Table 4 and enter it in the last row of the table.

2. The experiment uses half the rated terminal voltage when conducting the starting torque test. Full voltage starting current will be twice the average test value from Table 4. Compute this value and enter it in the first row of Table 5.

3. Compute the torque values for each test measurements in Table 4 using the following equation:

$$T\,(\text{N-m}) = \left(\frac{F}{101.972 \text{ gm/N}} \right) \cdot d$$

Where: T = torque in Newton-meters
            F = force in grams (gm)
            d = distance to center of rotation (m)

Compute the average of the three tests and enter in Table 4.

4. Motor torque is proportional to the square of the applied voltage. Stated as proportions this becomes:

$$\frac{T_1}{T_2} = \frac{V_1^2}{V_2^2}$$

Where: T_1 = reduced voltage starting torque
            T_2 = full voltage starting torque
            V_1 = test voltage (104 V)
            V_2 = rated line voltage (208 V)

The experimental measurements are made using half voltage so starting torque at rated voltage is 4 times the average from Table 4.

$$T_2 = 4 \cdot T_1$$

Compute this value and enter it into the first row of Table 5.

5. Find the full load running amps from the rated motor current in Table 1. Enter this value in the second row of Table 5. Compute the rated motor torque from the motor rated shaft horsepower and the rated speed using the following formula:

$$T\,(N\text{-}m) = \frac{7124 \cdot HP}{n_r}$$

Where: n_r = rated motor shaft speed (RPM) from Table 1
         HP = rated motor shaft torque (HP) from Table 1.

Enter this value in row 2 of Table 5.

6. Compute the ratio of starting current to full load (rated) current and multiply it by 100% to determine the percentage of rated current. (Typical 400-700%). Compute the ratio of starting torque to full load (rated) torque and multiply by 100% to determine percentage of rated torque. (Typical 200-250%) Enter both these values in row 3 of Table 5.

7. Compute the reduced voltage starting apparent power using Equation (8) from step 2 of this section. Use the average current and voltage values from Table 4. Enter the computed result below.

$$S_{TR} = \underline{\hspace{3cm}} \ VA$$

8. Compute the average total power and enter it in Table 4. Compute the rotor power factor by dividing the average total power by S_{TR} from step 7. Enter the result below.

$$F_p = \underline{\hspace{2.5cm}}$$

9. Find the power factor angle of the rotor using the following formula and enter the result below.

$$\theta = \cos^{-1}(F_p)$$

$$\theta = \underline{\hspace{2cm}}$$

Quick Quiz

1. Motor starting current is:

   a) greater than full load current.

   b) less than full load current.

   c) the same a full load current.

2. Full load running torque is:

    a) greater than starting torque.

    b) less than starting torque.

    c) the same as starting torque.

3. Each amp of starting current provides:

    a) the same torque as each amp of running current.

    b) more torque than each amp of running current.

    c) less torque than each amp of running current.

4. You would get more N-m of starting torque from each amp of starting current if:

    a) there were more inductive reactance in the rotor.

    b) there were more resistance in the rotor.

    c) the rotor bars did not form a complete circuit.

5. At the instant of start, an induction motor has:

    a) a leading phase angle.

    b) a good power factor, small lagging phase angle.

    c) a poor power factor, large lagging phase angle.

Experiment 7 Data Tables and Calculation Summary

Table 1-Motor Ratings

Rated Speed (RPM)	
Rated Terminal Voltage	
Rated Current (A)	
Rated Horsepower (HP)	

Table 2-Motor No-Load Electrical Readings

Line Current (A)	
Line Voltage (V)	
Wattmeter 1 P1 (W)	
Wattmeter 2 P2 (W)	

Table 3-Motor N-Load Mechanical Readings

Shaft Speed (RPM)	

Table 4- Lock-Rotor Test Readings

	Line V	Line I	P1	P2	Force (gm)	Total P	Lever Arm d (m)	Torque N-m
Test 1	104						0.1588	
Test 2	104						0.1588	
Test 3	104						0.1588	
Average	104						0.1588	

Table 5- Starting Torque Test Calculations

	Volts	Amps	Torque (N-m)
Full Voltage Starting	208 V		
Full Load Running			
(Starting/Running)x100%			

Discussion Points for Lab 7

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20 pts

Write a 1-2 page double spaced discussion that answers the following questions. Do not repeat the question. Write paragraphs that address these topics using correct grammar and spelling.

1.) Explain how the induced voltage in the rotor of an induction motor changes as the rotor speed changes.

2.) Show the per-phase schematic model of an induction motor and explain why the rotor current stays almost constant while the rotor power factor changes.

3.) Explain the relationship between stator terminal voltage and motor torque.

4.) Draw the connections for the two-wattmeter method of measuring active power. How is power factor found from the power measurements? Use both words and formulas to explain the process.