Electric Power/Controls
Electrical Power Technology
Using Data Acquisition

Courseware Sample

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Lab-Volt®

ELECTRIC POWER/CONTROLS

ELECTRICAL POWER TECHNOLOGY USING DATA ACQUISITION

COURSEWARE SAMPLE

by
the Staff
of
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Introduction

The courseware for *Electrical Power Technology Using Data Acquisition* consists of two student manuals and an instructor guide. The 29 exercises in the first student manual, titled *Power Circuits and Transformers*, provide a foundation for further study in Electrical Power Technology, and their completion will allow students to readily continue with material contained in the second student manual, titled *AC/DC Motors and Generators*. The 18 exercises in this second manual provide the students with a solid foundation on rotating machines. The instructor guide gives the numerical results and the answers to all questions in the student manuals.

The hands-on exercises in the two student manuals can be performed using either the ElectroMechanical System (EMS system) or the ElectroMechanical System using Virtual Laboratory Equipment (LVSIM™-EMS).

The hands-on exercises guide students through circuit setup and operation, and explore many of the measurement and observation capabilities of the virtual instrumentation system. Much detailed information about circuit parameters (voltage and current levels, waveforms, phase angles, etc.) can be visualized with the virtual instruments, and students are encouraged to fully explore system capabilities.

Various symbols are used in many of the circuit diagrams given in the exercises. Each symbol is a functional representation of a device used in Electrical Power Technology. The use of these symbols greatly simplifies the circuit diagrams by reducing the number of interconnections shown, and makes it easier to understand circuit operation.

The exercises in the two student manuals can be carried out with ac network voltages of 120 V, 220 V, and 240 V. The component values used in the different circuits often depend on the ac line voltage. For this reason, components in the circuit diagrams are identified where necessary with letters and subscripts. A table accompanying the circuit diagram indicates the component value required for each ac network voltage (120 V, 220 V, 240 V).

Courseware Outline

POWER CIRCUITS AND TRANSFORMERS

Unit 1 Fundamentals for Electrical Power Technology

A review of basic electrical concepts and laws. Using the Virtual Instrumentation System to measure voltage, current and power.

Ex. 1-1 Voltage, Current, Ohm's Law

Definitions of voltage, current, resistance. Demonstration of Ohm's law using measurements of circuit parameters.

Ex. 1-2 Equivalent Resistance

Determining equivalent resistance for various combinations of series and parallel circuits. Confirming calculations with circuit measurements of voltage and current.

Ex. 1-3 Power in DC Circuits

Distinctions between energy, work and power. Determining power in dc circuits, power formula.

Ex. 1-4 Series and Parallel Circuits

Solving circuits using Kirchhoff's voltage and current laws. Using circuit measurements to confirm theoretical calculations.

Unit 2 Alternating Current

Introduction to the concepts associated with alternating current, ac waveforms, phase shift, instantaneous power.

Ex. 2-1 The Sine Wave

Definition of alternating current (ac), the amplitude (rms, average and peak values), frequency and phase of ac signals.

Ex. 2-2 Phase Angle

Definition of phase, measurement of phase difference. Leading and lagging phase shift.

Ex. 2-3 Instantaneous Power

The concept of instantaneous power. Average power dissipated in a resistive load supplied by an ac source. Viewing instantaneous power waveforms.

Courseware Outline

POWER CIRCUITS AND TRANSFORMERS

Unit 3 Capacitors in AC Circuits

The behaviour of capacitors in ac circuits. Capacitive reactance, parallel and series combinations of capacitors, capacitive phase shift. Introduction to the concepts of active, reactive, and apparent power.

Ex. 3-1 Capacitive Reactance

Definition of capacitive reactance. Using Ohm's law and measurements of circuit voltage and current to determine capacitive reactance.

Ex. 3-2 Equivalent Capacitance

Determining equivalent capacitance for various combinations of series and parallel circuits. Confirming calculations with circuit measurements of voltage and current.

Ex. 3-3 Capacitive Phase Shift and Reactive Power

Measuring and demonstrating the phase shift between voltage and current caused by capacitors. The phenomenon of "negative" reactive power.

Unit 4 Inductors in AC Circuits

The behaviour of inductors in ac circuits. Inductive reactance, parallel and series combinations of inductors, inductive phase shift. Active, reactive, and apparent power associated with inductors.

Ex. 4-1 Inductive Reactance

Definition of inductive reactance. Using Ohm's law and measurements of circuit voltage and current to determine inductive reactance.

Ex. 4-2 Equivalent Inductance

Determining equivalent inductance for various combinations of series and parallel circuits. Confirming calculations with circuit measurements of voltage and current.

Ex. 4-3 Inductive Phase Shift and Reactive Power

Measuring and demonstrating the phase shift between voltage and current caused by inductors. Differences between capacitive reactive power and inductive reactive power.

Courseware Outline

POWER CIRCUITS AND TRANSFORMERS

Unit 5 Power, Phasors and Impedance in AC Circuits

Measurement of active, reactive, and apparent power. Using phasors and impedance to analyze ac circuits.

Ex. 5-1 Power in AC Circuits

Active, reactive and apparent power measurements. Definition of power factor. Adding capacitance in parallel with an inductive load to improve a low power factor.

Ex. 5-2 Vectors & Phasors in Series AC Circuits

Definition of vectors and phasors. Using vectors and phasors to analyze the operation of series ac circuits. Viewing voltage phasors in RL, RC, and RLC series circuits.

Ex. 5-3 Vectors & Phasors in Parallel AC Circuits

Using vectors and phasors to analyze the operation of parallel ac circuits. Viewing current phasors in RL, RC, and RLC parallel circuits.

Ex. 5-4 Impedance

Definition of impedance, Ohm's law in ac circuits. Using impedance concepts to simplify the analysis of complex ac circuits.

Unit 6 Three-Phase Circuits

Concepts associated with three-phase circuits, balanced loads, wye and delta connections, phase sequence. Power factor, three-phase power measurement, wattmeters, varmeters.

Ex. 6-1 Balanced Three-Phase Circuits

Definitions of line and phase voltages, line and phase currents. Definition of a balanced three-phase load. Setting up wye and delta connections. The $\sqrt{3}$ factor between line and phase values.

Ex. 6-2 Three-Phase Power Measurement

Using the two-wattmeter method to measure the total power supplied to a three-phase load. Power factor in three-phase circuits.

Courseware Outline

POWER CIRCUITS AND TRANSFORMERS

Ex. 6-3 Phase Sequence

Definition of phase sequence, and its importance for certain types of three-phase loads. How to determine phase sequence.

Unit 7 Single-Phase Transformers

The principles of transformer operation. Magnetic induction, transformer loading, series-aiding and series-opposing configurations.

Ex. 7-1 Voltage and Current Ratios

Primary and secondary windings. Definition of the turns ratio, step-up and step-down operation. Transformer saturation, voltage and current characteristics.

Ex. 7-2 Transformer Polarity

Determining the polarity of transformer windings. Connecting windings in series-aiding so that winding voltages add, or in series-opposing so that winding voltages subtract.

Ex. 7-3 Transformer Regulation

Definition of transformer regulation. Determining the voltage regulation of a transformer with varying loads. Inductive and capacitive loading.

Unit 8 Special Transformer Connections

Connecting transformer windings in different ways to obtain special-use transformers. Volt-ampere ratings.

Ex. 8-1 The Autotransformer

Interconnecting primary and secondary windings of a standard transformer to obtain an autotransformer. Step-up and step-down connections.

Ex. 8-2 Transformers in Parallel

Connecting transformers in parallel to supply greater load power. Measuring the efficiency of parallel-connected transformers.

Courseware Outline

Courseware Outline

AC/DC MOTORS AND GENERATORS

Unit 1 Fundamentals for Rotating Machines

An introduction to rotating machines. Work, speed, torque, and power. Operation of the Prime Mover / Dynamometer module. Motor losses and efficiency.

Ex. 1-1 Prime Mover Operation

Familiarization with the Prime Mover / Dynamometer module operating in the Prime Mover mode. Prime mover speed versus voltage. Friction torque versus speed. Measurement of the opposition torque caused by the machine driven by the Prime Mover.

Ex. 1-2 Dynamometer Operation

Familiarization with the Prime Mover / Dynamometer module operating in the Dynamometer mode. Measurement of the speed and output torque of a motor using the Dynamometer.

Ex. 1-3 Motor Power, Losses, and Efficiency

Determining the mechanical output power of a motor from the speed and torque. Mechanical and electrical losses in motors. Determining the efficiency of a motor.

Unit 2 DC Motors and Generators

The operating principles of direct current (dc) motors and generators. The different types of dc motors and generators and their particularities.

Ex. 2-1 The Separately-Excited DC Motor

Operation of a separately-excited dc motor. Simplified equivalent circuit of a dc motor. Relationship between the no-load speed and the armature voltage. Relationship between the motor torque and the armature current. Armature resistance. Speed-torque characteristic.

Ex. 2-2 Separately-Excited, Series, Shunt, and Compound DC Motors

Effect of the field current on the speed-voltage and torque-current characteristics of a separately-excited dc motor. Description and operation of the series, shunt, and compound dc motors. Comparing the speed-torque characteristics of the separately-excited, series, shunt, and compound dc motors.

Courseware Outline

AC/DC MOTORS AND GENERATORS

Ex. 2-3 Separately-Excited, Shunt, and Compound DC Generators

Operation and characteristics of a separately-excited dc generator. Effect of the field current on the characteristics of a separately-excited dc generator. Simplified equivalent circuit of a dc generator. Operation and characteristics of self-excited dc generators. Comparing the voltage-current characteristics of the separately-excited, shunt, cumulative-compound, and differential-compound dc generators.

Unit 3 Special Characteristics of DC Motors

The behaviour of dc machines when the armature and field currents exceed the nominal values. Operation of the universal motor.

Ex. 3-1 Armature Reaction and Saturation Effect

Armature reaction. Effect of the armature reaction on the characteristics of dc machines. Armature inductance. Use of permanent-magnets to reduce armature reaction. Saturation. Effect of the saturation on the characteristics of dc machines.

Ex. 3-2 The Universal Motor

Direction of rotation versus the polarities of the armature and field currents. DC and AC operation of a universal motor. Improving ac operation by adding a compensating winding that reduces the armature inductance.

Unit 4 AC Induction Motors

The principles of electromagnetic induction. Rotating magnetic field and synchronous speed. Demonstrating the operation and characteristics of ac induction motors.

Ex. 4-1 The Three-Phase Squirrel-Cage Induction Motor

Creating a rotating magnetic field in a three-phase squirrel-cage induction motor. Synchronous speed. Description and operation of the three-phase squirrel-cage induction motor. Torque versus speed characteristic. Reactive power required for creating the rotating magnetic field.

Courseware Outline

AC/DC MOTORS AND GENERATORS

Ex. 4-2 Eddy-Current Brake and Asynchronous Generator

Description and operation of the eddy-current brake. Operating a three-phase squirrel-cage induction motor as an asynchronous generator. Demonstrating that an asynchronous generator can supply active power to the ac power network. Demonstrating that asynchronous generator operation requires reactive power.

Ex. 4-3 Effect of Voltage on the Characteristics of Induction Motors

Saturation in induction motors. Nominal voltage of a squirrel-cage induction motor. Demonstrating the effect of the motor voltage on the torque versus speed characteristic of a squirrel-cage induction motor.

Ex. 4-4 Single-Phase Induction Motors

Description and operation of a simplified single-phase squirrel-cage induction motor. Torque-speed characteristic of the simplified single-phase induction motor. Adding an auxiliary winding (with or without a capacitor) to improve the starting torque of the simplified single-phase induction motor.

Unit 5 Synchronous Motors

Description and operation of the three-phase synchronous motor. Starting a synchronous motor. Speed of rotation versus the ac power source frequency.

Ex. 5-1 The Three-Phase Synchronous Motor

Interesting features of the three-phase synchronous motor. Effect of the field current on the reactive power exchanged between a three-phase synchronous motor and the ac power network. Using a synchronous motor running without load as a synchronous condenser.

Ex. 5-2 Synchronous Motor Pull-Out Torque

Effect of the field current on the pull-out torque of a three-phase synchronous motor.

Courseware Outline

AC/DC MOTORS AND GENERATORS

Sample Exercise

from

Power Circuits and Transformers

Exercise 1-4

Series and Parallel Circuits

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to solve series and parallel circuits and demonstrate Kirchhoff's voltage and current laws.

DISCUSSION

As you advance in your study of electric circuits, it will become obvious that even the most complex circuits can be solved using just a few fundamental rules. These rules are summarized in two groups as shown below - one for series circuits, and one for parallel circuits. They are directly related to Ohm's law, the formulas for equivalent resistance, and the Kirchhoff's voltage and current laws. The Kirchhoff's voltage law simply states that the sum of the voltages in a closed-circuit loop is equal to zero. Its counterpart, the Kirchhoff's current law, simply states that the sum of the currents entering a circuit node is equal to the sum of the currents leaving the node.

Rules for series circuits

1. The sum of the voltage drops across each resistor in a series circuit equals the applied voltage.
2. The same current flows in each series resistor.
3. The total series-circuit resistance is the sum of the individual resistor values.

Figure 1-16 will be used to illustrate the rules for series circuits. As shown, a dc source E_S is connected to the series combination of resistors R_1, R_2, and R_3. Current I_S flows around the circuit through the one path that is available. From Ohm's law we know that the voltage across each resistor equals I_SR, thus giving voltages I_SR_1, I_SR_2, and I_SR_3. Now, based on Rule 1 for this circuit, it can be seen that,

$$E_{R1} + E_{R2} + E_{R3} = E_S$$

and $$I_SR_1 + I_SR_2 + I_SR_3 = E_S.$$

Since I_S is common to all terms, the equation can be rewritten as follows:

$$I_S\,(R_1 + R_2 + R_3) = E_S$$

Using the equation for equivalent resistance R_{EQ} in a series circuit ($R_{EQ} = R_1+R_2+R_3$), or rule 3, we obtain:

$$I_S R_{EQ} = E_S$$

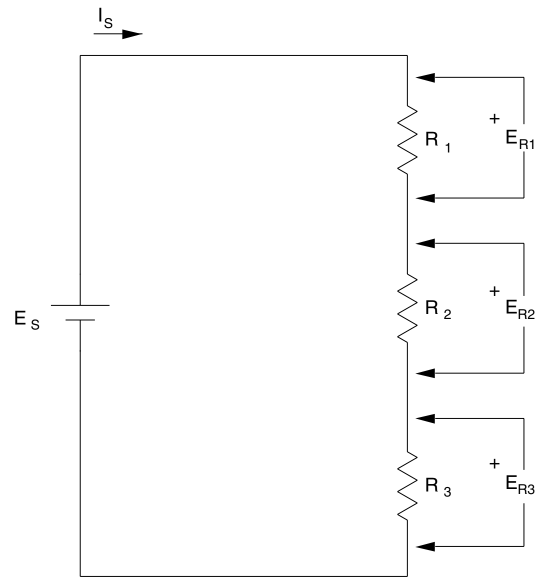


Figure 1-16. A Typical Series Circuit.

Rules for parallel circuits

1. The sum of the branch currents in a parallel circuit equals the total source current.
2. The voltage is the same across all parallel branches.
3. The reciprocal of the total parallel-circuit resistance is equal to the sum of the reciprocals of the individual resistor values.

Figure 1-17 will be used to illustrate the rules for parallel circuits. As shown, a dc source E_S is connected across the parallel combination of resistors R_1, R_2, and R_3. Current I_S divides and flows through three circuit branches. Also, Figure 1-17 shows that the voltage across each resistor is the same. Therefore, the three branch currents can be determined using Ohm's law. From Rule 1 for this circuit, we obtain:

$$I_{R1} + I_{R2} + I_{R3} = I_S$$

and $$\frac{E_S}{R_1} + \frac{E_S}{R_2} + \frac{E_S}{R_3} = I_S$$

Since E_S is common to all terms, the equation can be rewritten as follows:

$$E_S\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) = I_S$$

Using the equation for equivalent resistance R_{EQ} in a parallel circuit ($1/R_{EQ} = 1/R_1+1/R_2+1/R_3$), or rule 3, we obtain:

$$E_S \times \frac{1}{R_{EQ}} = I_S$$

and $$\frac{E_S}{R_{EQ}} = I_S$$

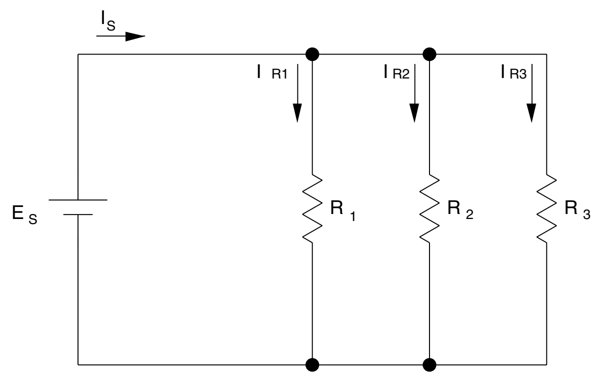


Figure 1-17. A Typical Parallel Circuit.

Two other fundamental principles used in solving electric circuits are the voltage divider principle and the current divider principle. Stated simply, the voltage divider principle says that a voltage E_S applied across two series resistors R_1 and R_2 will divide so as the ratio of the voltage drops across the resistors (E_{R1} and E_{R2}) is equal to the ratio of the resistors. This can be written as follows:

$$\frac{E_{R1}}{E_{R2}} = \frac{R_1}{R_2}$$

This then leads to the following two equations:

$$E_{R1} = \frac{E_S \times R_1}{R_1 + R_2}$$

and $$E_{R2} = \frac{E_S \times R_2}{R_1 + R_2}$$

The current divider principle says that the current I_S will split between two parallel resistors R_1 and R_2 so as the ratio of the currents in the resistors (I_{R1} and I_{R2}) is equal to the inverse ratio of the resistors. This can be written as follows:

$$\frac{I_{R1}}{I_{R2}} = \frac{R_2}{R_1}$$

This then leads to the following two equations:

$$I_{R1} = \frac{I_S \times R_2}{R_1 + R_2}$$

and $$I_{R2} = \frac{I_S \times R_1}{R_1 + R_2}$$

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart in Appendix C to obtain the list of equipment required for this exercise.

PROCEDURE

CAUTION!

High voltages are present in this laboratory exercise! Do not make or modify any banana jack connections with the power on unless otherwise specified!

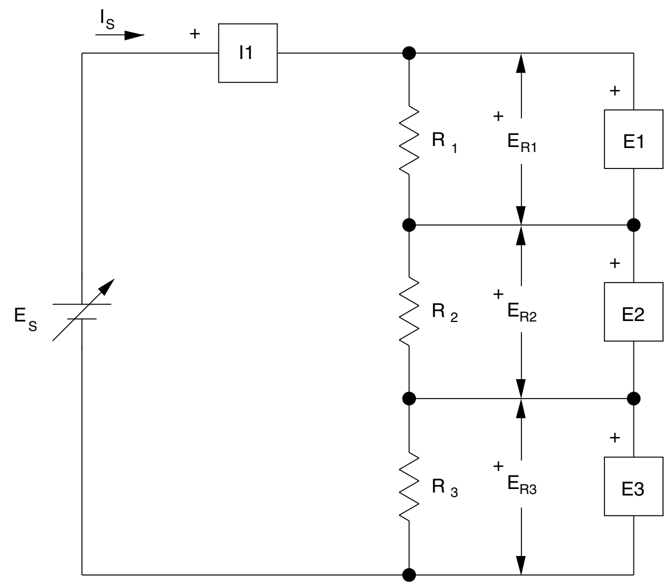
☐ 1. Install the Power Supply, Data Acquisition Interface, and Resistive Load modules in the EMS Workstation.

☐ 2. Make sure the main power switch of the Power Supply is set to the O (OFF) position and the voltage control knob is turned fully ccw. Set the voltmeter select switch on the Power Supply to the 7-N DC position. Ensure the Power Supply is connected to a three-phase wall receptacle.

☐ 3. Ensure the flat cable from the computer is connected to the DAI.

☐ 4. Set up the circuit shown in Figure 1-18. Select the appropriate resistor values for the given line voltage, and connect I1, E1, E2, and E3 as shown to measure the series-circuit current and voltages. Ensure the polarity of the connections, and that the DAI LOW POWER INPUT is connected to the main Power Supply.

☐ 5. Display the *Metering* application and select setup configuration file *ES11-6.dai*. Note that the metering setup configuration can be changed during the exercise if desired. This exercise was written using those given.



LINE VOLTAGE (V)	E_S (V)	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
120	120	171	200	240
220	220	629	733	880
240	240	686	800	960

Figure 1-18. Setup for a Typical Series Circuit.

☐ 6. Turn on the main Power Supply and set the 24 V - AC power switch to the I (ON) position. Adjust the voltage control for the value of E_S given in Figure 1-18.

☐ 7. Use the *Record Data* button to enter the voltage and current measurements in the *Data Table*. Turn off the Power Supply.

☐ 8. Calculate the circuit equivalent resistance R_{EQ} and the circuit current I_S using the values given in Figure 1-18.

$$R_{EQ} = R_1+R_2+R_3 = \_\_\_\_\_\_ \ \Omega$$

$$I_S = \frac{E_S}{R_{EQ}} = \_\_\_\_\_\_ \ A$$

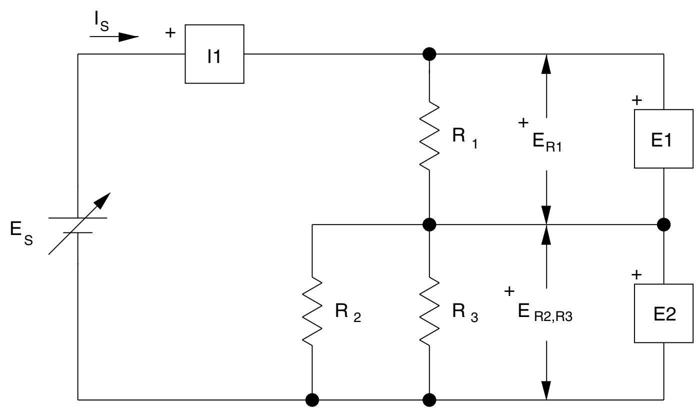
☐ 9. Calculate the voltage drops for each resistor using the current I_S calculated in the previous step and the resistor values given in Figure 1-18. Compare with the measured values.

E_{R1} = ______ V E_{R2} = ______ V E_{R3} = ______ V

☐ 10. Is there agreement between the values?

☐ Yes ☐ No

☐ 11. Set up the series combination circuit in Figure 1-19, and set the Resistive Load module for the given resistor values. Connect I1, E1, and E2 to measure the circuit parameters. Use setup configuration file *ES11-7.dai* for the circuit measurements.



LINE VOLTAGE (V)	E_S (V)	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
120	120	171	300	600
220	220	629	1100	2200
240	240	686	1200	2400

Figure 1-19. Setup for a Series Combination Circuit

☐ 12. Turn on the Power Supply, set E_S as required, and measure the circuit parameters.

☐ 13. Turn off the Power Supply and calculate E_{R1} and $E_{R2,R3}$ using the equivalent resistance of R_2 in parallel with R_3, $R_{R2,R3}$, R_1 and the value measured for I_S.

$R_{R2,R3}$ = _______ Ω E_{R1} = _______ V $E_{R2,R3}$ = _______ V

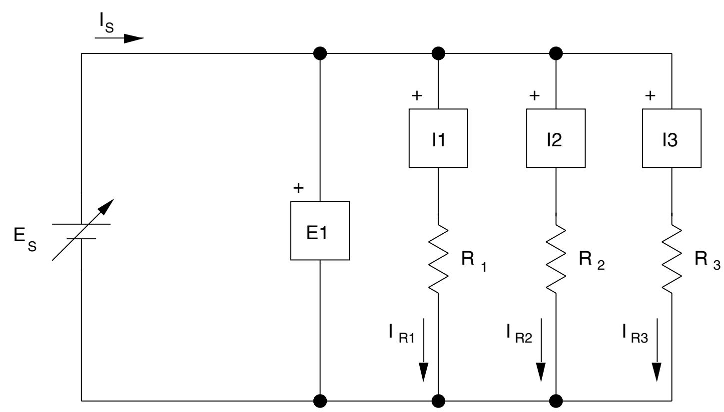
☐ 14. Calculate E_{R1} and $E_{R2,R3}$, using the voltage divider principle.

E_{R1} = _______ V $E_{R2,R3}$ = _______ V

☐ 15. Compare the values obtained in the previous steps. Do they agree?

☐ Yes ☐ No

☐ 16. Set up the parallel circuit shown in Figure 1-20, and set the Resistive Load module for the given resistor values. Connect I1, I2, I3, and E1 to measure the parallel-circuit voltage and currents.



LINE VOLTAGE (V)	E_S (V)	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
120	120	300	600	1200
220	220	1100	2200	4400
240	240	1200	2400	4800

Figure 1-20. Setup for a Typical Parallel Circuit.

☐ 17. Turn on the Power Supply and set E_S as required. Measure the circuit parameters, using *ES11-8.dai* configuration file for the measurements.

☐ 18. Turn off the Power Supply and calculate the values for R_{EQ}, I_S, and the branch currents, using the values given in Figure 1-20.

R_{EQ} = _______ Ω I_S = _______ A

I_{R1} = _______ A I_{R2} = _______ A I_{R3} = _______ A

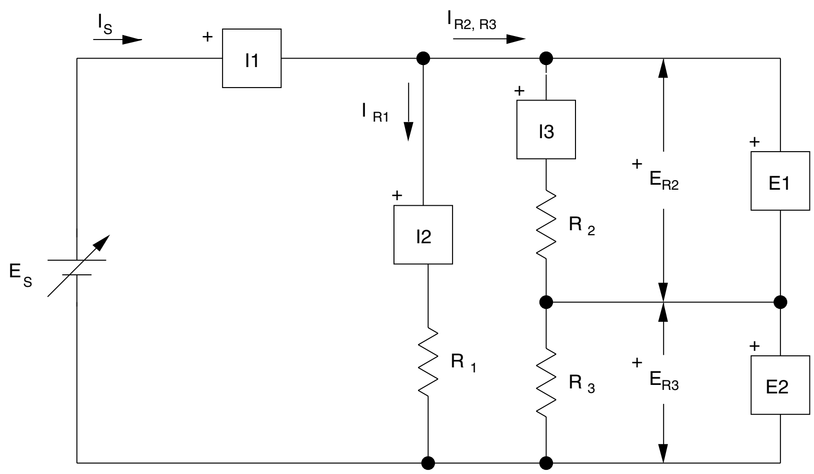
☐ 19. Determine the branch currents using the current divider principle.

I_{R1} = _______ A I_{R2} = _______ A I_{R3} = _______ A

☐ 20. Compare the calculated and measured values. Do they agree?

☐ Yes ☐ No

☐ 21. Set up the parallel combination circuit in Figure 1-21, and set the Resistive Load module for the given resistor values. Connect I1, I2, I3, E1, and E2 to measure the circuit parameters.



LINE VOLTAGE (V)	E_S (V)	R_1 (Ω)	R_2 (Ω)	R_3 (Ω)
120	120	300	171	200
220	220	1100	629	733
240	240	1200	686	800

Figure 1-21. Setup for a Parallel Combination Circuit

☐ 22. Turn on the Power Supply and set E_S as required. Measure the circuit parameters, using *ES11-9.dai* configuration file for the measurements.

☐ 23. Turn off the Power Supply and calculate the values for I_{R1} and $I_{R2,R3}$ using the values given in Figure 1-21.

I_{R1} = _______ A $I_{R2,R3}$ = _______ A

☐ 24. Compare the measured and calculated values. Do they agree?

☐ Yes ☐ No

☐ 25. Compare the source current I_S with the sum of the branch currents. Is there agreement between the results?

☐ Yes ☐ No

☐ 26. Calculate the values for E_{R2} and E_{R3} using the values given in Figure 1-21, and compare with the measured values.

E_{R2} = _______ V E_{R3} = _______ V

☐ 27. Is there agreement between the results?

☐ Yes ☐ No

☐ 28. Ensure that the Power Supply is turned off, the voltage control is fully ccw, and remove all leads and cables.

CONCLUSION

You demonstrated that different combinations of series and parallel circuits can be solved using rules and principles based on Ohm's law and Kirchhoff's laws. You also had the opportunity to practice the techniques presented in the previous exercises.

REVIEW QUESTIONS

1. The main rules and principles for solving electric circuits are related to

   a. the conservation of energy law.
   b. combinations of different circuits.
   c. Kirchhoff's law, Ohm's law, and rules for equivalent resistance.
   d. the random operation of a circuit.

2. The source voltage in the circuit of Figure 1-19 is doubled. What effect does this have on the circuit current and voltages?

   a. Both will double.
   b. Both will decrease by half.
   c. Both will increase by half.
   d. There will be no change.

3. The value of resistor R_3 in figure 1-19 is reduced by half. Will the current through R_2 increase or decrease?

   a. Increase.
   b. Decrease.
   c. It will not change.
   d. None of the above.

4. What will be the effect of removing one of the resistors in Figure 1-20?

   a. The source voltage will drop.
   b. The source current will increase.
   c. The source current will decrease.
   d. There will be no effect.

5. How can current I_S be reduced by half in the circuit of Figure 1-21?

   a. By reducing the source voltage by half, or doubling R_1.
   b. By increasing the source voltage by half, or doubling R_{EQ}.
   c. By reducing the source voltage by half, or doubling R_{EQ}.
   d. By increasing the source voltage by half and doubling R_{EQ}.

Sample Exercise

from

AC/DC Motors and Generators

Exercise 2-1

The Separately-Excited DC Motor

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the main operating characteristics of a separately-excited dc motor using the DC Motor / Generator module.

DISCUSSION

Previously, you saw that a dc motor is made up basically of a fixed magnet (stator) and a rotating magnet (rotor). Many dc motors use an electromagnet for the stator, as illustrated in Figure 2-7.

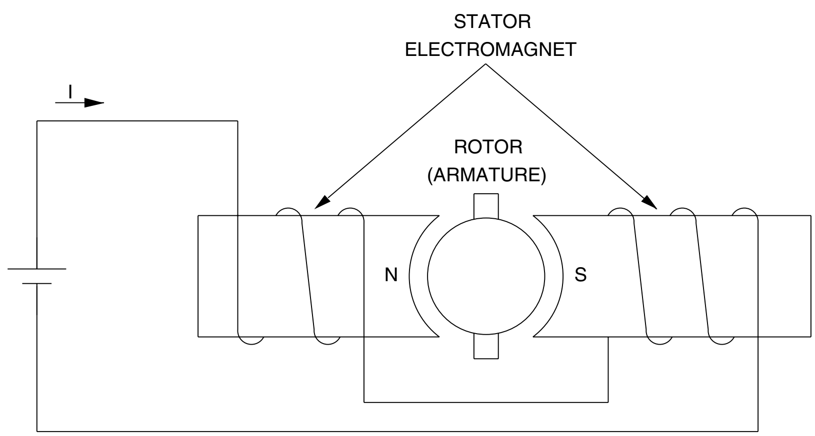


Figure 2-7. Simplified DC Motor with an Electromagnet as Stator.

When power for the stator electromagnet is supplied by a separate dc source, either fixed or variable, the motor is known as a separately-excited dc motor. Sometimes the term independent-field dc motor is also used. The current flowing in the stator electromagnet is often called **field current** because it is used to create a fixed magnetic field. The electrical and mechanical behaviour of the dc motor can be understood by examining its simplified equivalent electric circuit shown in Figure 2-8.

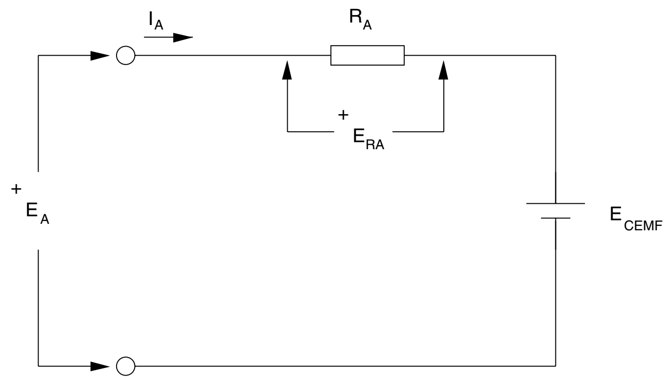


Figure 2-8. Simplified Equivalent Circuit of a DC Motor.

In the circuit, E_A is the voltage applied to the motor brushes, I_A is the current flowing through the brushes, and R_A is the resistance between the brushes. Note that E_A, I_A, and R_A are usually referred to as the armature voltage, current, and resistance, respectively. E_{RA} is the voltage drop across the armature resistor. When the motor turns, an induced voltage E_{CEMF} proportional to the speed of the motor is produced. This induced voltage is represented by a dc source in the simplified equivalent circuit of Figure 2-8. The motor also develops a torque T proportional to the armature current I_A flowing in the motor. The motor behaviour is based on the two equations given below. The first relates motor speed n and the induced voltage E_{CEMF}, and the second relates the motor torque T and the armature current I_A.

$$n = K_1 \times E_{CEMF} \quad \text{and} \quad T = K_2 \times I_A$$

where K_1 is a constant expressed in units of r/min/V,
K_2 is a constant expressed in units of N·m/A or lbf·in/A.

When a voltage E_A is applied to the armature of a dc motor with no mechanical load, the armature current I_A flowing in the equivalent circuit of Figure 2-8 is constant and has a very low value. As a result, the voltage drop E_{RA} across the armature resistor is so low that it can be neglected, and E_{CEMF} can be considered to be equal to the armature voltage E_A. Therefore, the relationship between the motor speed n and the armature voltage E_A is a straight line because E_{CEMF} is proportional to the motor speed n. This linear relationship is illustrated in Figure 2-9, and the slope of the straight line equals constant K_1.

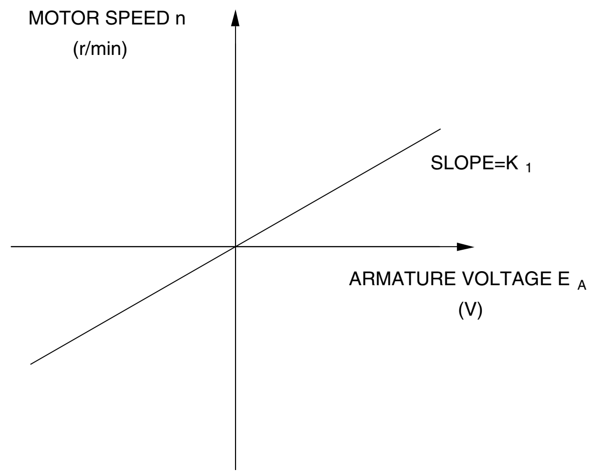


Figure 2-9. Linear Relationship Between the Motor Speed and the Armature Voltage.

Since the relationship between voltage E_A and speed n is linear, a dc motor can be considered to be a linear voltage-to-speed converter as shown in Figure 2-10.

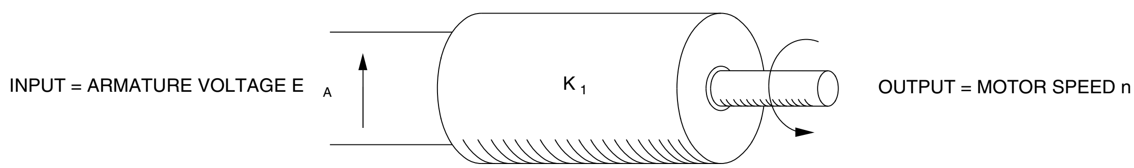


Figure 2-10. DC Motor as a Voltage-to-Speed Converter.

The same type of relationship exists between the motor torque T and the armature current I_A, so that a dc motor can also be considered as a linear current-to-torque converter. Figure 2-11 illustrates the linear relationship between the motor torque T and the armature current I_A. Constant K_2 is the slope of the line relating the two. In Figure 2-12, the linear current-to-torque converter is illustrated.

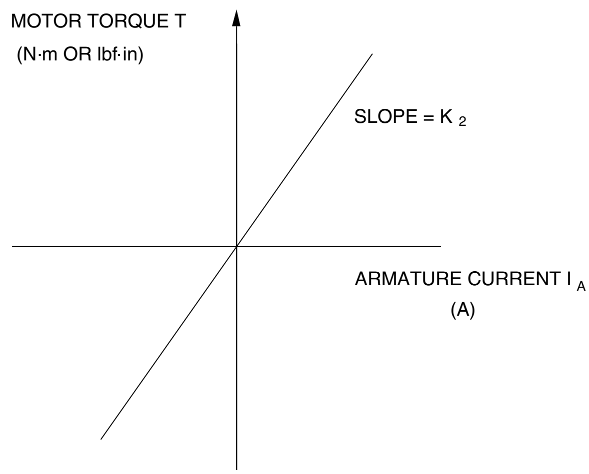


Figure 2-11. Linear Relationship Between the Motor Torque and the Armature Current.

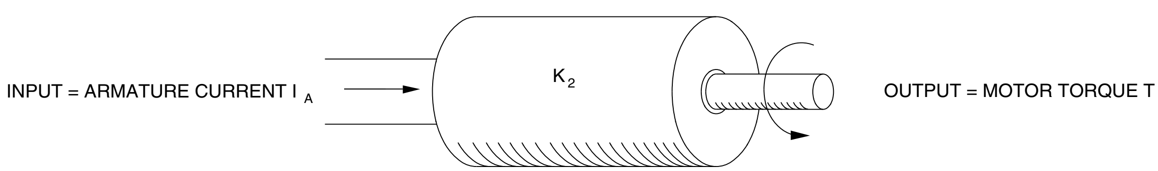


Figure 2-12. DC Motor as a Current-to-Torque Converter.

When the armature current I_A increases, the voltage drop E_{RA} (R_A x I_A) across the armature resistor also increases and can no longer be neglected. As a result, the armature voltage E_A can no longer be considered to be equal to E_{CEMF}, but rather the sum of E_{CEMF} and E_{RA} as indicated in the following equation:

$$E_A = E_{CEMF} + E_{RA}$$

Therefore, when a fixed armature voltage E_A is applied to a dc motor, the voltage drop E_{RA} across the armature resistor increases as the armature current I_A increases, and thereby, causes E_{CEMF} to decrease. This also causes the motor speed n to decrease because it is proportional to E_{CEMF}. This is shown in Figure 2-13 which is a graph of the motor speed n versus the armature current I_A for a fixed armature voltage E_A.

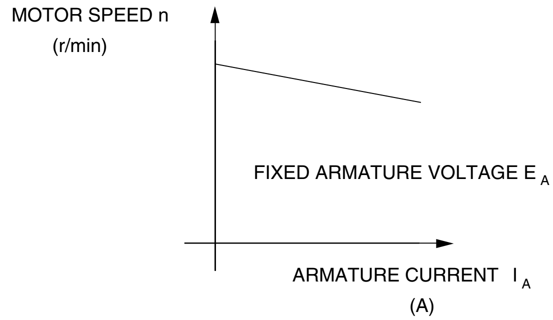


Figure 2-13. Motor Speed Drop as the Armature Current Increases (Fixed Armature Voltage E_A).

Procedure Summary

In the first part of the exercise, you will set up the equipment in the Workstation, connect the equipment as shown in Figure 2-14, and make the appropriate settings on the Prime Mover / Dynamometer.

In the second part of the exercise, you will measure the armature resistance R_A of the DC Motor / Generator. It is not possible to measure the armature resistance R_A directly with a conventional ohmmeter because the non-linear characteristic of the motor brushes causes incorrect results when I_A is too small. The general method used to determine the armature resistance R_A consists in connecting a dc power source to the motor armature and measuring the voltage required to produce nominal current flow in the armature windings. Power is not connected to the stator electromagnet to ensure that the motor does not turn, thus E_{CEMF} equals zero. The ratio of the armature voltage E_A to the armature current I_A yields the armature resistance R_A directly.

Note: *The motor will not start to rotate because it is mechanically loaded.*

In the third part of the exercise, you will measure data and plot a graph of the motor speed n versus the armature voltage E_A to demonstrate that the speed of the separately-excited dc motor is proportional to the armature voltage E_A under no-load conditions.

In the fourth part of the exercise, you will measure data and plot a graph of the motor torque T versus the armature current I_A to demonstrate that the torque of the separately-excited dc motor is proportional to the armature current I_A.

In the fifth part of the exercise, you will demonstrate that when the armature voltage E_A is set to a fixed value, the speed of the separately-excited dc motor decreases with increasing armature current or torque because of the increasing voltage drop across the armature resistor.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart in Appendix C to obtain the list of equipment required for this exercise.

PROCEDURE

CAUTION!

High voltages are present in this laboratory exercise! Do not make or modify any banana jack connections with the power on unless otherwise specified!

Setting up the Equipment

☐ 1. Install the Power Supply, Prime Mover / Dynamometer, DC Motor / Generator, and Data Acquisition Interface modules in the EMS workstation.

Note: *If you are performing the exercise using the EMS system, ensure that the brushes of the DC Motor/Generator are adjusted to the neutral point. To do so, connect an ac power source (terminals 4 and N of the Power Supply) to the armature of the DC Motor/Generator (terminals 1 and 2) through CURRENT INPUT I1 of the Data Acquisition Interface module. Connect the shunt winding of the DC Motor/Generator (terminals 5 and 6) to VOLTAGE INPUT E1 of the Data Acquisition Interface module. Start the Metering application and open setup configuration file ACMOTOR1.DAI. Turn on the Power Supply and set the voltage control knob so that an ac current (indicated by meter I1) equal to half the nominal value of the armature current flows in the armature of the DC Motor/Generator. Adjust the brushes adjustment lever on the DC Motor/Generator so that the voltage across the shunt winding (indicated by meter E1) is minimum. Turn off the Power Supply, exit the Metering application, and disconnect all leads and cable.*

Mechanically couple the Prime Mover / Dynamometer to the DC Motor / Generator using a timing belt.

☐ 2. On the Power Supply, make sure the main power switch is set to the O (off) position, and the voltage control knob is turned fully counterclockwise. Ensure the Power Supply is connected to a three-phase power source.

☐ 3. Ensure that the flat cable from the computer is connected to the DAI module.

Connect the LOW POWER INPUTs of the DAI and Prime Mover / Dynamometer modules to the 24 V - AC output of the Power Supply.

On the Power Supply, set the 24 V - AC power switch to the I (on) position.

☐ 4. Start the Metering application.

In the Metering window, open setup configuration file DCMOTOR1.DAI then select custom view 2.

☐ 5. Set up the separately-excited dc motor circuit shown in Figure 2-14. Leave the circuit open at points A and B shown in the figure.

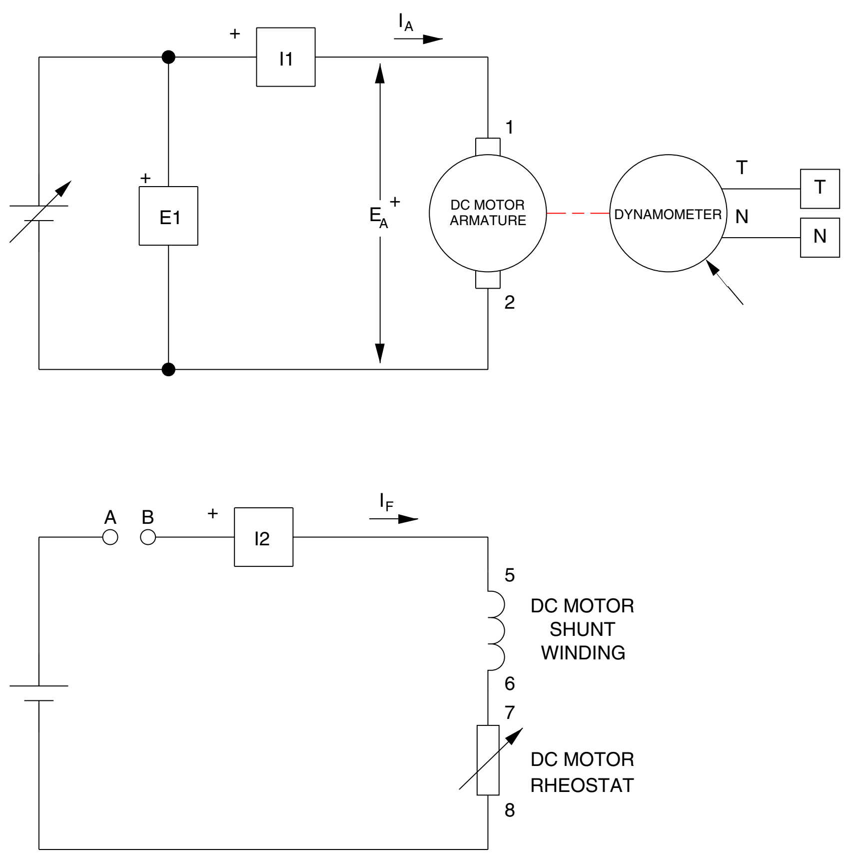


Figure 2-14. Separately-Excited DC Motor Coupled to a Dynamometer.

☐ 6. Set the Prime Mover / Dynamometer controls as follows:

MODE switch . . . . DYN.
LOAD CONTROL MODE switch . . . . MAN.
LOAD CONTROL knob . . . . MAX. (fully CW)
DISPLAY switch . . . . SPEED (N)

> **Note:** *If you are performing the exercise using EMS VLE, you can zoom in the Prime Mover / Dynamometer module before setting the controls in order to see additional front panel markings related to these controls.*

Determining the Armature Resistance

☐ 7. Turn on the Power Supply by setting its main power switch to the **I** (on) position, and set the voltage control knob so that the rated armature current flows in the DC Motor / Generator. The armature current is indicated by meter **I**1 in the Metering window.

> **Note:** *The rating of any of the Lab-Volt machines is indicated in the lower left corner of the module front panel. If you are performing the exercise using EMS VLE, you can obtain the rating of any machine by leaving the mouse pointer on the rotor of the machine of interest. Pop-up help indicating the machine rating will appear after a few seconds.*

Record the value of armature resistance R_A indicated by programmable meter B.

R_A = _______ Ω

☐ 8. Turn the voltage control knob fully counterclockwise and turn off the Power Supply by setting its main power switch to the O (off) position.

Interconnect points A and B shown in the circuit of Figure 2-14.

Motor Speed Versus Armature Voltage

☐ 9. Turn on the Power Supply.

On the Prime Mover / Dynamometer, set the LOAD CONTROL knob to the MIN. position (fully CCW).

On the DC Motor / Generator, set the FIELD RHEOSTAT so that the current indicated by meter **I**2 in the Metering window is equal to the value given in the following table:

LINE VOLTAGE	FIELD CURRENT I_F
V ac	**mA**
120	300
220	190
240	210

Table 2-1. DC Motor Field Current.

☐ 10. In the Metering window, select the torque correction function for meter T. Meter T now indicates the dc motor output torque. Record the dc motor speed n, armature voltage E_A, armature current I_A, field current I_F, and output torque T (indicated by meters N, E1, I1, I2, and T, respectively) in the Data Table.

On the Power Supply, set the voltage control knob to 10%, 20%, 30% etc. up to 100% in order to increase the armature voltage E_A by steps. For each voltage setting, wait until the motor speed stabilizes, and then record the data in the Data Table.

> **Note:** *If you are performing the exercise using EMS VLE, click the button located beside the Power Supply display until the % inscription appears in this button. This will cause the Power Supply display to indicate the position of the voltage control knob in percentage values.*

☐ 11. When all data has been recorded, turn the voltage control knob fully counterclockwise and turn off the Power Supply.

In the Data Table window, confirm that the data has been stored, edit the data table so as to keep only the values of the dc motor speed n, armature voltage E_A, armature current I_A, field current I_F, and output torque T (data in columns N, E1, I1, I2, and T, respectively), entitle the data table as DT211, and print the data table.

> **Note:** *Refer to Appendix E of this manual to know how to edit, entitle, and print a data table.*

☐ 12. In the Graph window, make the appropriate settings to obtain a graph of the dc motor speed n (obtained from meter N) as a function of the armature voltage E_A (obtained from meter E1). Entitle the graph as G211, name the x-axis as Armature Voltage, name the y-axis as DC Motor Speed, and print the graph.

> **Note:** *Refer to Appendix E of this manual to know how to use the Graph window of the Metering application to obtain a graph, entitle a graph, name the axes of a graph, and print a graph.*

What kind of relationship exists between the armature voltage E_A and the dc motor speed n?

____

Does this graph confirm that the separately-excited dc motor is equivalent to a linear voltage-to-speed converter, with higher voltage producing greater speed?

☐ Yes ☐ No

☐ 13. Use the two end points to calculate the slope K_1 of the relationship obtained in graph G211. The values of these points are indicated in data table DT211.

$$K_1 = \frac{n_2 - n_1}{E_2 - E_1} = \frac{\_\_\_\_\_ - \_\_\_\_\_}{\_\_\_\_\_ - \_\_\_\_\_} = \_\_\_\_\_\_ \frac{\text{r/min}}{\text{V}}$$

In the Data Table window, clear the recorded data.

Motor Torque Versus Armature Current

☐ 14. Turn on the Power Supply.

On the DC Motor / Generator, slightly readjust the FIELD RHEOSTAT so that the current indicated by meter I2 in the Metering window still equals the value given in Table 2-1 (if necessary).

On the Power Supply, set the voltage control knob so that the dc motor speed is 1500 r/min. Note the value of the armature voltage E_A in the following blank space.

E_A = ______ V (n = 1500 r/min)

☐ 15. In the Metering window, record the dc motor output torque T, armature voltage E_A, armature current I_A, field current I_F, and speed n (indicated by meters T, E1, I1, I2, and n, respectively) in the Data Table.

On the Prime Mover / Dynamometer, set the DISPLAY switch to the TORQUE (T) position then adjust the LOAD CONTROL knob so that the torque indicated on the module display increases by 0.2 N·m (2.0 lbf·in) increments up to 2.0 N·m (18.0 lbf·in). For each torque setting, readjust the voltage control knob of the Power Supply so that the armature voltage E_A remains equal to the value recorded in the previous step, then record the data in the Data Table.

Note: *The armature current may exceed the rated value while performing this manipulation. It is, therefore, suggested to complete the manipulation within a time interval of 5 minutes or less.*

☐ 16. When all data has been recorded, set the LOAD CONTROL knob on the Prime Mover / Dynamometer to the MIN. position (fully CCW), turn the voltage control knob fully counterclockwise, and turn off the Power Supply.

In the Data Table window, confirm that the data has been stored, edit the table so as to keep only the values of the dc motor torque T, armature voltage E_A, armature current I_A, field current I_F, and speed n (data in columns T, E1, I1, I2, and N respectively), entitle the data table as DT212, and print the data table.

☐ 17. In the Graph window, make the appropriate settings to obtain a graph of the dc motor torque (obtained from meter T) as a function of the armature current I_A (obtained from meter I1). Entitle the graph as G212, name the x-axis as Armature Current, name the y-axis as DC Motor Torque, and print the graph.

What kind of relationship exists between the armature current I_A and the dc motor torque T as long as the armature current does not exceed the nominal value?

____

Does this graph confirm that the separately-excited dc motor is equivalent to a linear current-to-torque converter (when the armature current does not exceed the nominal value), with higher current producing greater torque?

☐ Yes ☐ No

Note: *The torque versus current relationship is no longer linear when the armature current exceeds the nominal value because of a phenomenon called armature reaction. This phenomenon is described in the next unit of this manual.*

☐ 18. Use the two end points of the linear portion of the relationship obtained in graph G212 to calculate the slope K_2. The values of these points are indicated in data table DT212.

$$K_2 = \frac{T_2 - T_1}{I_2 - I_1} = \frac{\_\_\_\_ - \_\_\_\_}{\_\_\_\_ - \_\_\_\_} = \_\_\_\_\_\_ \frac{\text{N·m (lbf·in)}}{\text{A}}$$

Speed Decrease Versus Armature Current

☐ 19. Using the armature resistance R_A and the constant K_1 determined previously in this exercise, the armature voltage E_A measured in step 14, and the set of equations given below, determine the dc motor speed n for each of the three armature currents I_A given in Table 2-2.

$E_{RA} = I_A \times R_A$

$E_{CEMF} = E_A - E_{RA}$

$n = E_{CEMF} \times K_1$

LINE VOLTAGE	ARMATURE CURRENT I_A	ARMATURE CURRENT I_A	ARMATURE CURRENT I_A
V ac	**A**	**A**	**A**
120	1.0	2.0	3.0
220	0.5	1.0	1.5
240	0.5	1.0	1.5

Table 2-2. DC Motor Armature Currents.

When I_A equals ____ A:

E_{RA} = _____ V
E_{CEMF} = _____ V
n = _____ r/min

When I_A equals ____ A:

E_{RA} = _____ V
E_{CEMF} = _____ V
n = _____ r/min

When I_A equals ____ A:

E_{RA} = _____ V
E_{CEMF} = _____ V
n = _____ r/min

Based on your calculations, how should E_{CEMF} and the dc motor speed n vary as the armature current is increased?

____

____

____

☐ 20. In the Graph window, make the appropriate settings to obtain a graph of the dc motor speed (obtained from meter N) as a function of the armature current I_A (obtained from meter I1) using the data recorded previously in the data table (DT212). Entitle the graph as G212-1, name the x-axis as Armature Current, name the y-axis as DC Motor Speed, and print the graph.

Does graph G212-1 confirm the prediction you made in the previous step about the variation of the dc motor speed as a function of the armature current I_A?

☐ Yes ☐ No

Briefly explain what causes the dc motor speed to decrease when the armature voltage E_A is fixed and the armature current I_A increases.

____

____

____

____

☐ 21. In the Graph window, make the appropriate settings to obtain a graph of the dc motor speed (obtained from meter N) as a function of the dc motor torque T (obtained from meter T) using the data recorded previously in the data table (DT212). Entitle the graph as G212-2, name the x-axis as Separately-Excited DC Motor Torque, name the y-axis as Separately-Excited DC Motor Speed, and print the graph. This graph will be used in the next exercise of this unit.

☐ 22. Set the 24 V - AC power switch to the O (off) position, and remove all leads and cables.

ADDITIONAL EXPERIMENTS

Speed-Voltage and Torque-Current Graphs for Reversed Armature Connections

You can obtain graphs of the dc motor speed n versus the armature voltage E_A, and dc motor torque T versus the armature current I_A, with reversed armature connections. To do so, make sure the Power Supply is turned off and reverse the connection of the leads at terminals 7 and N of the Power Supply. Refer to steps 6 to 17 of this exercise to record the necessary data and obtain the graphs. This will allow you to verify that the linear relationships between the speed and armature voltage, and the torque and armature current, are valid regardless the polarity of the armature voltage. Recalculating constants K_1 and K_2 will show you that their values are independent of the armature voltage polarity.

CONCLUSION

In this exercise, you have learned how to measure the armature resistance of a dc motor. You have seen that the speed of a separately-excited dc motor is proportional to the armature voltage applied to the motor. You saw that the torque produced by a dc motor is proportional to the armature current. You observed that the dc motor speed decreases with increasing armature current when the armature voltage is fixed. You demonstrated that this speed decrease is caused by the increasing voltage drop across the armature resistor as the armature current increases.

If you have performed the additional experiments, you observed that the speed versus voltage and torque versus current relationships are not affected by the polarity of the armature voltage. You also observed that the direction of rotation is reversed when the polarity of the armature voltage is reversed.

REVIEW QUESTIONS

1. What kind of relationship exists between the speed and armature voltage of a separately-excited dc motor?

   a. A linear relationship.
   b. A parabolic relationship.
   c. An exponential relationship.
   d. The speed of the motor is independent of the applied voltage.

2. What kind of relationship exists between the torque and armature current of a separately-excited dc motor as long as the armature current does not exceed the nominal value?

   a. A linear relationship.
   b. A parabolic relationship.
   c. An exponential relationship.
   d. The motor torque is independent of the current.

3. Connecting a dc source to the armature of a dc motor that operates without field current and measuring the voltage that produces nominal current flow in the armature allows which parameter of the dc motor to be determined.

   a. The nominal armature current.
   b. The nominal armature voltage.
   c. The armature resistance.
   d. The resistance of the field winding.

4. Does the speed of a separately-excited dc motor increase or decrease when the armature current increases?

   a. It increases.
   b. It decreases.
   c. It stays the same because speed is independent of motor current.
   d. The speed will oscillate around the previous value.

5. The armature resistance R_A and constant K_1 of a dc motor are 0.5 Ω and 5 r/min/V, respectively. A voltage of 200 V is applied to this motor. The no-load armature current is 2 A. At full load, the armature current increases to 50 A. What are the no-load and full-load speeds of the motor?

   a. $n_{NO\ LOAD}$ = 1005 r/min, $n_{FULL\ LOAD}$ = 880 r/min
   b. $n_{NO\ LOAD}$ = 995 r/min, $n_{FULL\ LOAD}$ = 875 r/min
   c. $n_{NO\ LOAD}$ = 1000 r/min, $n_{FULL\ LOAD}$ = 875 r/min
   d. The speeds cannot be calculated without constant K_2.

Other Sample Extracted

from

AC/DC Motors and Generators

Unit Test

1. A synchronous motor with a permanent-magnet rotor

    a. is started the same way as a synchronous motor with an electromagnet rotor.
    b. starts like a squirrel-cage induction motor.
    c. can be started using a variable-frequency ac power source.
    d. starts when dc power is applied to the rotor.

2. A three-phase synchronous motor draws reactive power from an ac power source. Decreasing the field current

    a. will increase the reactive power which the motor draws from the ac power source.
    b. will decrease the reactive power which the motor draws from the ac power source.
    c. will decrease the power factor of the motor.
    d. both a and c.

3. A three-phase synchronous motor supplies reactive power to an ac power source. Decreasing the field current

    a. will increase the reactive power which the motor supplies to the ac power source.
    b. will decrease the reactive power which the motor supplies to the ac power source.
    c. will decrease the power factor of the motor.
    d. both a and c.

4. A three-phase synchronous motor operates as a synchronous condenser. It is adjusted so that the power factor of the load connected to an ac power source is unity. One of the many inductive loads connected to the ac power source is removed. Therefore,

    a. the synchronous motor draws more reactive power from the ac power source.
    b. the synchronous motor supplies more reactive power to the ac power source.
    c. the field current of the synchronous motor should be decreased to readjust the power factor so that it is unity.
    d. the field current of the synchronous motor should be increased to readjust the power factor so that it is unity.

5. It is desirable to turn off the rotor electromagnet of a synchronous motor to

    a. obtain a higher starting torque.
    b. improve the power factor.
    c. increase the starting line current.
    d. increase the pull-out torque.

6. When the line current of a three-phase synchronous motor is minimized, the

   a. motor is used as a synchronous condenser.
   b. motor neither draws or supplies reactive power.
   c. field current is minimum.
   d. None of the above.

7. The pull-out torque of a synchronous motor depends on

   a. the power factor.
   b. the motor line current.
   c. the field current.
   d. None of the above.

8. The most interesting features of the three-phase synchronous motor are

   a. its ability to run at exactly the synchronous speed and to be able to operate as an asynchronous generator.
   b. its ability to run at exactly the synchronous speed and to be able to supply reactive power to an ac power source.
   c. the capability of running at unity power factor and to be able to draw reactive power from an ac power source.
   d. both b and c.

9. A three-phase synchronous motor operating without load acts as

   a. a resistive load whose value depends on the field current.
   b. an asynchronous generator operating without load.
   c. three independent single-phase power sources.
   d. a reactive load whose nature (inductive or capacitive) and value depend on the field current.

10. A three-phase synchronous motor

    a. can operate with either ac or dc power.
    b. does not start easily.
    c. is another type of ac induction motor.
    d. with a permanent-magnet rotor is often used as a synchronous condenser to adjust the power factor of an ac power source.

Sample Extract from

the Instructor Guide

EXERCISE 4-1 THE THREE-PHASE SQUIRREL-CAGE INDUCTION MOTOR

ANSWERS TO PROCEDURE QUESTIONS

☐ 7. The motor rotates clockwise.

n = 1768 r/min

Yes.

☐ 8. $n_{NOM.}$ = 1712 r/min

$T_{NOM.}$ = 0.98 N·m

$I_{NOM.}$ = 0.97 A

☐ 10.

LINE VOLTAGE (E1)	LINE CURRENT (I1)	REACTIVE POWER (A)	ACTIVE POWER (C)	TORQUE (T)	SPEED (N)
V	A	var	W	N·m	r/min
208.0	0.751	244	111	0.33	1768
207.6	0.843	244	168	0.63	1745
207.1	0.954	247	235	0.94	1716
206.7	1.106	252	303	1.23	1684
206.0	1.293	264	379	1.53	1645
205.4	1.519	279	463	1.83	1597
204.5	1.803	310	568	2.13	1498
204.5	2.018	317	598	2.22	1468
204.0	2.095	329	673	2.33	1421
203.6	2.292	346	718	2.42	1368
203.3	2.510	382	793	2.52	1275
200.6	3.921	671	1182	1.94	172

Table 4-1. Motor line voltage, line current, active power, reactive power, speed, and torque (DT411).

Yes.

☐ 11.

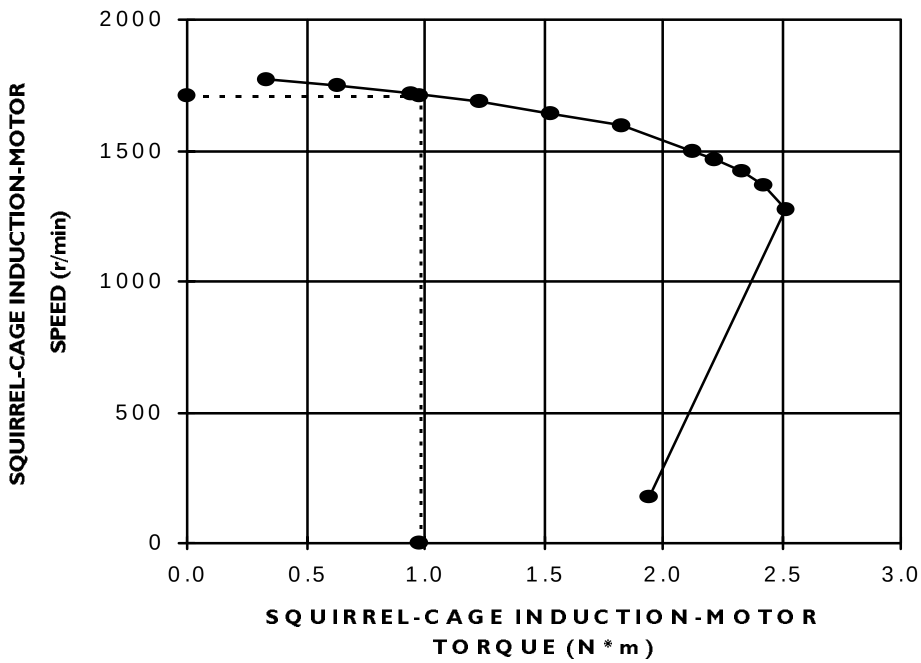


Figure 4-1. Squirrel-cage induction-motor speed versus torque (G411).

The speed decreases when the mechanical load applied to the squirrel-cage induction motor increases.

☐ 12. $T_{BREAKDOWN}$ = 2.52 N·m

$T_{LOCKED\ ROTOR} \cong$ 1.94 N·m

The breakdown and locked-rotor torques of the squirrel-cage induction motor are approximately 2 and 2.5 times the nominal torque, respectively.

☐ 13.

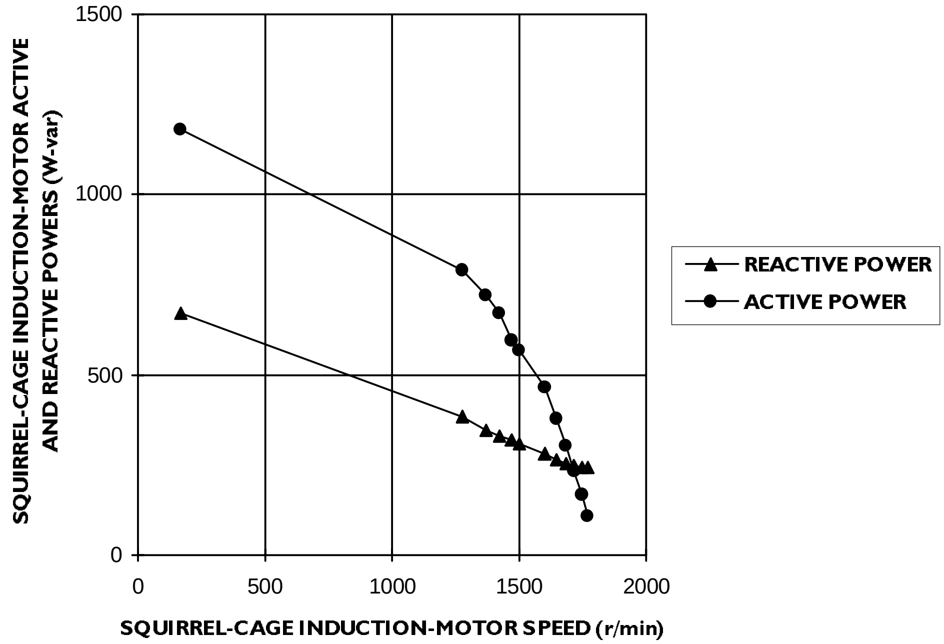


Figure 4-2. Squirrel-cage induction-motor active and reactive powers versus speed (G411-1).

Yes.

Yes.

This indicates that a squirrel-cage induction motor without load is similar to a reactive load (an inductor).

☐ 14.

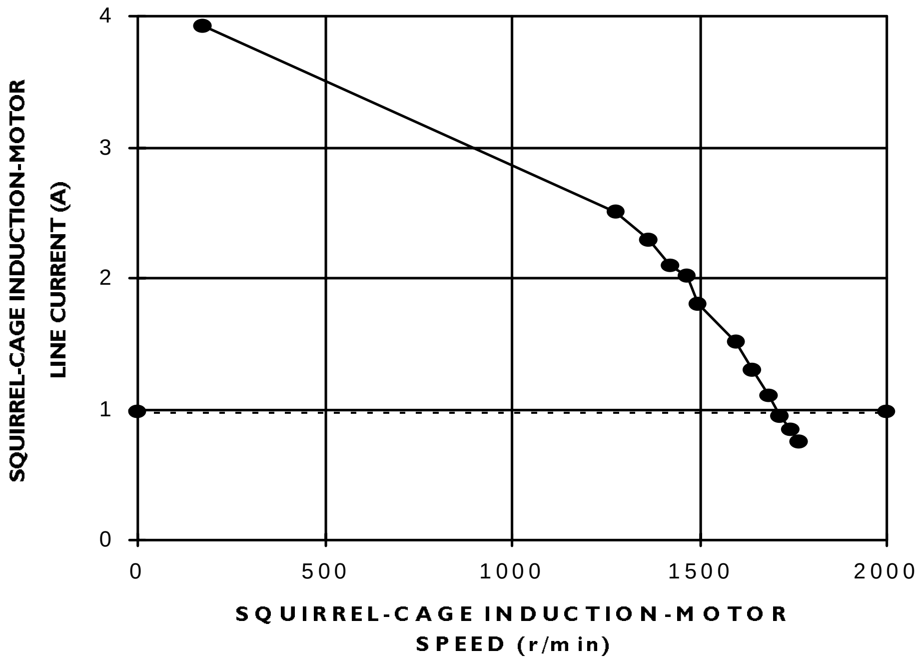


Figure 4-3. Squirrel-cage induction-motor line current versus speed (G411-2).

The line current increases when the motor speed decreases.

☐ 15. The starting line current is approximately four times greater than the nominal current.

☐ 16. The motor rotates counterclockwise.

Yes.

ANSWERS TO REVIEW QUESTIONS

1. b; 2. a; 3. c; 4. b; 5. c.

EXERCISE 4-2 EDDY-CURRENT BRAKES AND ASYNCHRONOUS GENERATORS

ANSWERS TO PROCEDURE QUESTIONS

☐ 7. n = 150 r/min
I_{EM} = 0 A
$T_{BRAKING}$ = −0.09 N·m

Direction of Rotation : CW

☐ 8. n = 50 r/min
I_{EM} = 1.79 A
$T_{BRAKING}$ = − 0.87 N·m
Direction of Rotation : CW

The braking torque increases when the electromagnet current is increased.

Yes.

☐ 9. n = −150 r/min
I_{EM} = 0 A
$T_{BRAKING}$ = 0.09 N·m
Direction of Rotation : CCW

☐ 10. n = −47 r/min
I_{EM} = 1.80 A
$T_{BRAKING}$ = 0.87 N·m
Direction of Rotation : CCW

The braking torque increases when the electromagnet current is increased.

No.

☐ 14. P = 333 W Q = 278 vars
P_m = 237 W n = 1688 r/min
T = 1.34 N·m

Yes.

The squirrel-cage induction machine acts as an induction motor.

☐ 15. P = 26 W Q = 274 vars
P_m = −27 W n = 1800 r/min
T = −0.14 N·m

No.

☐ 16. P = −244 W Q = 384 vars
P_m = −361 W n = 1890 r/min
T = −1.82 N·m

Yes.

The squirrel-cage induction machine acts as an asynchronous generator.

☐ 17. E_{LINE} = 1.1 V

Yes.

RESULTS OF THE ADDITIONAL EXPERIMENTS

Speed Versus Torque Characteristic of a Squirrel-Cage Induction Motor for Both the Motor and Generator Modes of Operation

LINE VOLTAGE (E1)	LINE CURRENT (I1)	REACTIVE POWER (A)	ACTIVE POWER (C)	TORQUE (T)	SPEED (N)
V	A	var	W	N·m	r/min
215.5	1.644	467	-364	-2.66	1933
215.4	1.518	439	-321	-2.40	1918
215.4	1.396	414	-281	-2.10	1906
215.6	1.272	388	-238	-1.80	1891
215.7	1.153	363	-194	-1.50	1876
215.5	1.044	342	-150	-1.20	1861
215.6	0.936	319	-103	-0.90	1844
215.6	0.842	300	-54.7	-0.60	1827
215.6	0.764	281	-4.1	-0.30	1809
215.9	0.738	270	48.4	0.00	1792
216.1	0.779	268	109	0.33	1776
216.1	0.855	268	169	0.63	1753
216.1	0.950	271	230	0.93	1729
215.9	1.092	276	300	1.23	1702
215.9	1.244	284	368	1.52	1671
215.9	1.426	296	446	1.83	1634
215.8	1.651	313	533	2.13	1590
215.8	1.728	322	561	2.23	1573
215.9	1.857	326	602	2.33	1540
215.8	2.050	313	638	2.43	1517
215.7	2.100	356	686	2.53	1489
215.5	2.220	394	724	2.62	1458
215.4	2.449	392	750	2.73	1413
215.9	2.644	421	750	2.81	1370
215.4	2.734	436	750	2.93	1321
215.4	3.041	509	750	3.02	1217
214.8	4.340	795	750	2.31	195

Table 4-2. Squirrel-cage induction-motor line voltage, line current, active power, reactive power, speed, and torque (DT421).

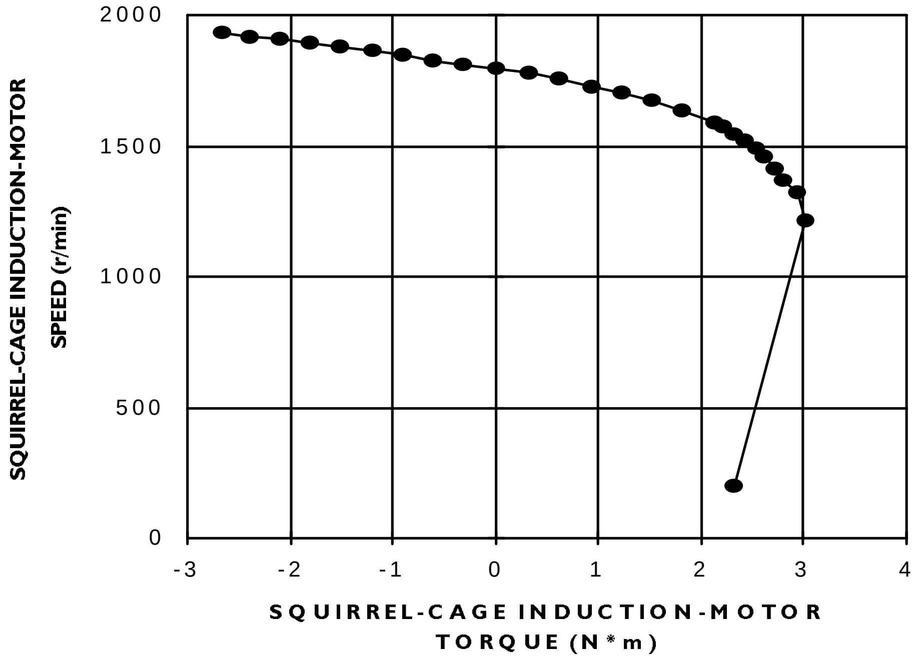


Figure 4-4. Squirrel-cage induction-motor speed versus torque (G421).

ANSWERS TO REVIEW QUESTIONS

1. c; 2. d; 3. a; 4. c; 5. a.

EXERCISE 4-3 EFFECT OF VOLTAGE ON THE CHARACTERISTICS OF INDUCTION MOTORS

ANSWERS TO PROCEDURE QUESTIONS

☐ 8.

WINDING VOLTAGE (E1)	WINDING CURRENT (I1)
V	A
60.01	0.343
64.18	0.359
74.65	0.412
85.14	0.474
96.27	0.540
106.9	0.611
117.5	0.694
127.7	0.776
138.5	0.878
148.8	0.992
159.4	1.129
170.8	1.313
180.4	1.488
191.3	1.734
202.5	2.022
213.0	2.405

Table 4-3. Squirrel-cage induction-motor winding voltage and current (DT431).

☐ 9.

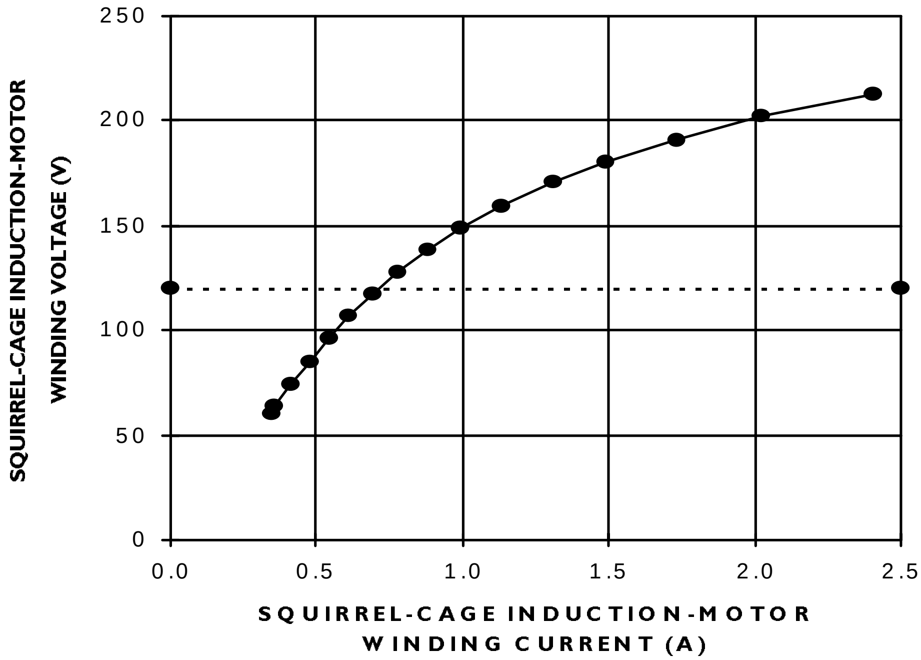


Figure 4-5. Squirrel-cage induction-motor winding voltage versus current (G431).

☐ 10. Yes.

Yes.

☐ 11. $E_{WINDING} \cong 180$ V (at nominal winding current and with no load)

☐ 14. n = 1742 r/min (at 75% of the nominal motor line voltage)

Yes.

Yes.

☐ 16.

LINE VOLTAGE (E1)	LINE CURRENT (I1)	REACTIVE POWER (A)	ACTIVE POWER (C)	TORQUE (T)	SPEED (N)
V	A	var	W	N·m	r/min
156.1	0.605	133	98.5	0.33	1744
155.3	0.789	139	163	0.63	1694
154.7	1.050	154	238	0.93	1626
153.5	1.411	184	329	1.22	1524
153.2	1.592	202	372	1.32	1461
152.6	1.815	230	423	1.42	1375
151.8	2.245	288	515	1.51	1184
149.7	3.264	480	691	1.06	102

Table 4-4. Squirrel-cage induction-motor line voltage, line current, active power, reactive power, speed, and torque (DT432).

Yes.

☐ 17.

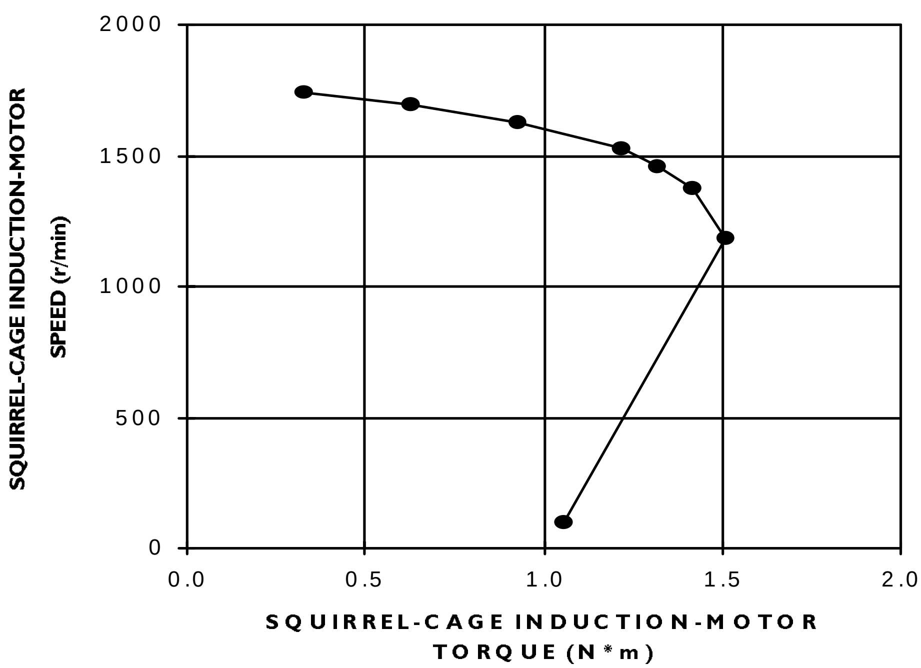


Figure 4-6. Squirrel-cage induction-motor speed versus torque (G432).

$T_{BREAKDOWN}$ = 1.51 N·m (with motor voltage reduced to 75% of the nominal value)

$T_{LOCKED\ ROTOR} \cong 1.06$ N·m (with motor voltage reduced to 75% of the nominal value)

The breakdown and locked-rotor torques obtained when the motor voltage is set to 75% of the nominal value are approximately 1 N·m less than those obtained when the motor voltage equals the nominal value.

Yes.

☐ 18.

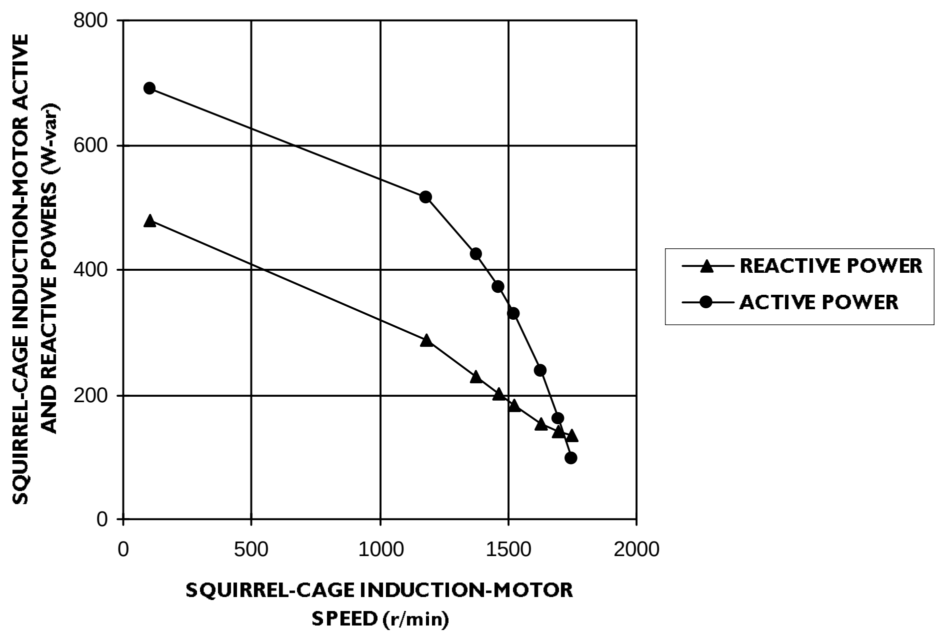


Figure 4-7. Squirrel-cage induction-motor active and reactive powers versus speed (G432-1).

The active and reactive powers obtained when the motor voltage is set to 75% of the nominal value are lower than those obtained when the motor voltage equals the nominal value. However, they vary in the same way for both motor voltages.

☐ 19.

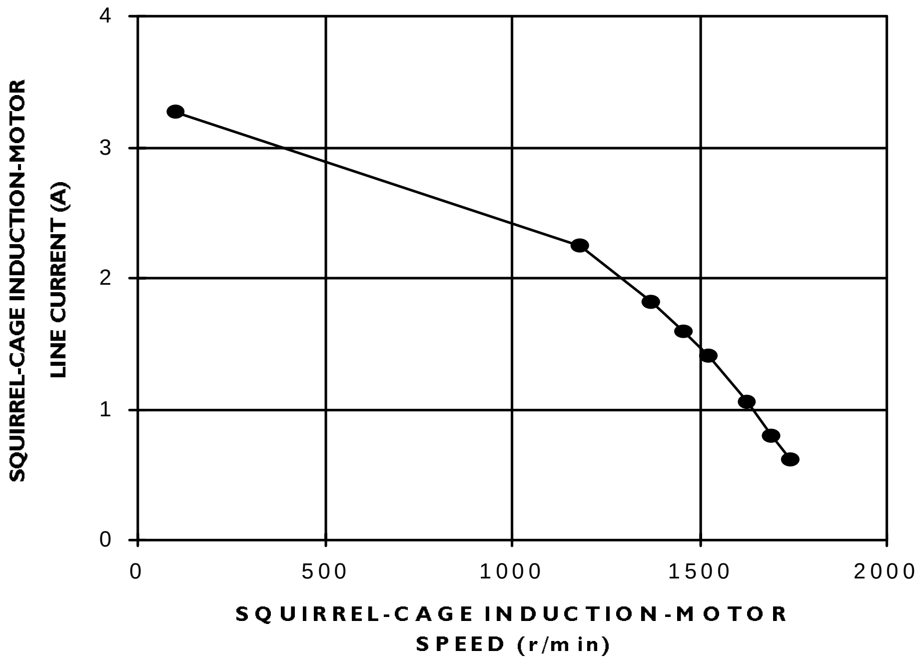


Figure 4-8. Squirrel-cage induction-motor line current versus speed (G432-2).

The starting current obtained when the motor voltage is set to 75% of the nominal value is slightly less than that obtained when the motor voltage equals the nominal value.

Yes.

ANSWERS TO REVIEW QUESTIONS

1. a; 2. c; 3. c; 4. b; 5. a.

EXERCISE 4-4 SINGLE-PHASE INDUCTION MOTORS

ANSWERS TO PROCEDURE QUESTIONS

☐ 6. Yes.

☐ 7. Yes.

☐ 9. Yes.

Yes.

☐ 11. No.

☐ 13. Yes, because there is a phase shift between the currents in the windings. This creates a rotating magnetic field in the induction motor.

☐ 14. Yes.

☐ 16. No.

☐ 18. Yes.

Yes.

Yes.

☐ 20. Yes.

Yes.

The circuit breaker on the Capacitor-Start Motor trips and the auxiliary winding is disconnected.

☐ 22. Yes.

This is because the centrifugal switch opens, thereby disconnecting the auxiliary winding from the power source.

ANSWERS TO REVIEW QUESTIONS

1. a; 2. c; 3. d; 4. b; 5. d.

ANSWERS TO UNIT TEST

1. b; 2. c; 3. a; 4. c; 5. d; 6. c; 7. c; 8. a; 9. b; 10. b.

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