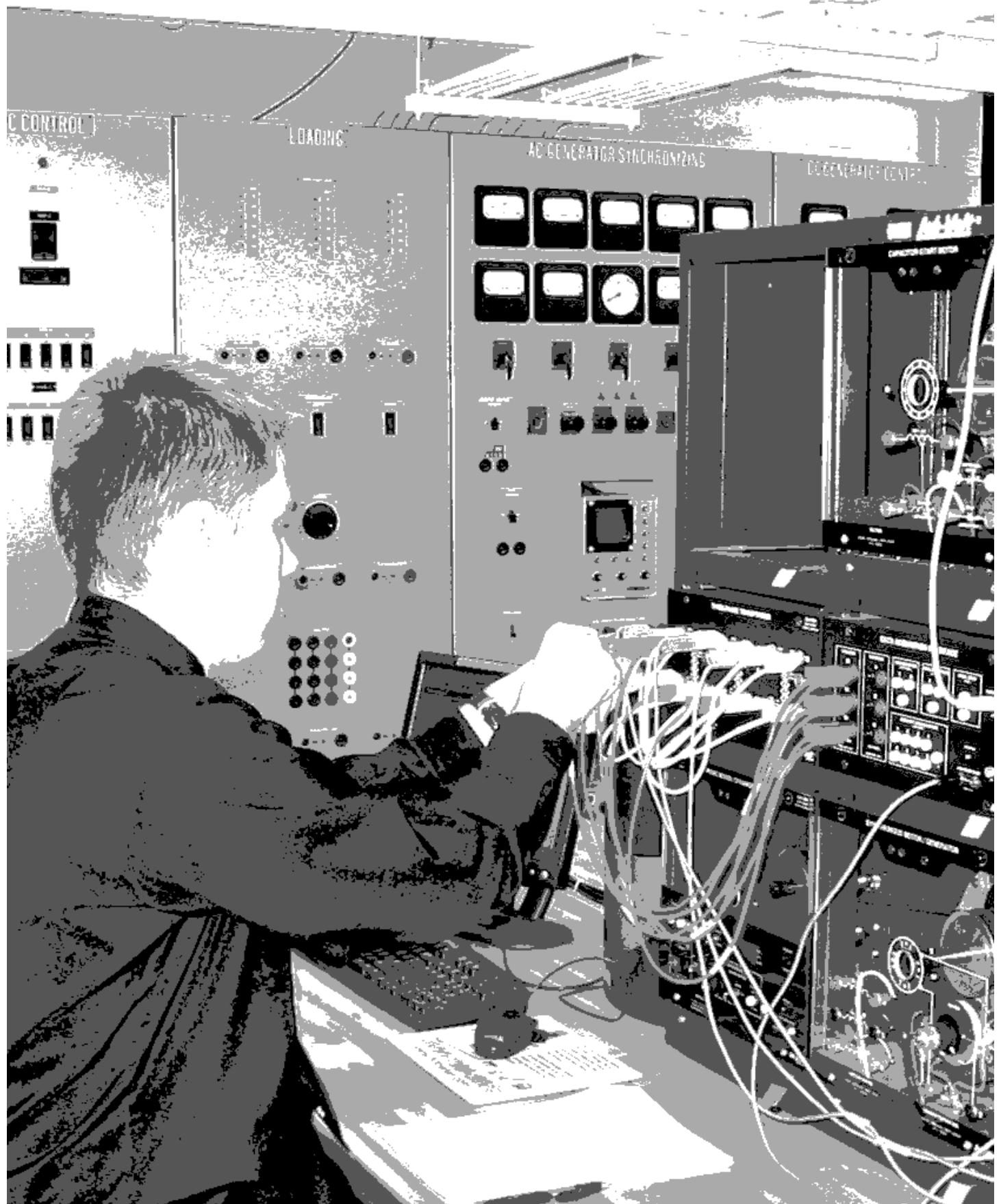


EN 3111L

Electrical Machines Lab



Massachusetts Maritime Academy

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Spring 2023

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Course Goal

The purpose of the Electrical Machine Lab is to increase your understanding of the theory, design, construction, operation, and maintenance of electrical machinery commonly found aboard ship and in industrial facilities.

You will develop practical electrical skills such as using electrical measuring equipment, reading schematic diagrams, wiring circuits, troubleshooting faulty circuits, and following safe working practices. Additionally you will verify electrical theory by making measurements of electrical machinery in operation.

The material covered in the laboratory supplements the material studied in EN-3111 Electrical Machines and it is assumed that anyone taking the laboratory has either passed this course or is taking it concurrently with the lab. Three STCW skills will be demonstrated during the lab.

Learning Objectives

At the completion of this course, the student should be able to:

- Measure voltage, amperage, and resistance with a DMM
- Measure amplitude, frequency, period and phase shifts of sine waves using an oscilloscope
- Measure wattage, vars, va, and power factor using a power meter
- Lock-out and tag out electrical circuits
- Wire a three-way lighting circuit
- Connect three phase transformers in delta and wye configurations, and describe the resulting voltage and current relationships
- Demonstrate the operating characteristics of three phase induction motors
- Demonstrate the operating characteristics of single phase motors
- Demonstrate the operation of unloaded and loaded synchronous generators
- Parallel a AC Generator with the bus or another generator
- Demonstrate the operating principles of two-wire and three-wire control circuits
- Demonstrate the operating principles jogging and breaking circuits
- Demonstrate the operating principles reduced voltage and soft starters
- Wire single- and three-phase motors to UVR and UVP motor controllers
- Describe the operation of and troubleshoot a magnetic motor controller
- Describe the purpose a thermal overload relay
- Describe what is meant by sustained overload protection and interrupting capacity
- Describe safety requirements for working with high voltage equipment

- Describe configuration and operation of 5 kV circuit breaker in the laboratory
- Demonstrate proficiency in the following STCW elements:
 - OICEW-3-1A Plan and use test equipment
 - OICEW-3-1B Troubleshoot electrical motor control system
 - OICEW-7-1E Parallel generators

Schedule

This course meets for two hours every week and consists of twelve lab exercises. Six are conducted in the upstairs laboratory and six are conducted in the downstairs lab. At each class meeting students will complete one upstairs or one downstairs lab.

The laboratory schedule is shown on page 5.

Technology

Blackboard will be used to communicate with the class and to collect homework assignments.

Grades

Your final grade will be determined using the following weights

Component	Weight	Notes
Upstairs Lab Quizzes	20%	
Downstairs Lab Quizzes	20%	
HW 1 and 2 (Troubleshooting)	20%	Grade penalties for missing deadlines.
HW 3 (Meter video)	20%	Grade penalties for missing deadlines.
Lab Final Exam	20%	
Attendance		Grade deduction for missed labs.

STCW Assessment

This lab addresses the STCW Function: Electrical, electronic and control engineering at the operational level. All students are required to satisfy the STCW assessments of the course. These assessments will be satisfied as follows:

- OICEW-3-1A Create and submit homework assignment 3, Metering Video and demonstrate competence in the upstairs lab.
- OICEW-3-1B Complete homework assignments 1 and 2 by deadline, and individually demonstrate competence by troubleshooting a motor controller in the upstairs lab.
- OICEW-7-1E Demonstrate competence in Lab 6 downstairs, or using simulator.

Students must demonstrate competence in all of these areas or they will receive an Incomplete for the course. Incompletes must be made up by the second week of the following semester or the will automatically turn to F. It is your responsibility to make up any missed assessments by contacting your instructor.

Homework

There are three mandatory homework assignments required as part of the course. Specific details about the assignments are found on Blackboard.

HW	Description	Deliverables	Deadline
1	Create troubleshooting Account	No submission required	March 24, Midnight
2	Complete 12 Basic and Advanced Faults	Submit Completion Certificate	April 7, Midnight
3	Multimeter Safety and use Video	Submit Video	April 24, Midnight

Assignments will be collected via Blackboard only. Submissions will **not** be accepted via email.

Late assignments will incur a 20% grade penalty, minimum.

Quizzes and Final

Quizzes will be given at the end of each lab. Quizzes will not be returned.

The final exam will have questions covering things that you saw or did in the twelve labs.

Attendance

Students are expected to attend all twelve labs.

It is critical that you make every effort to come to your scheduled lab since usually all sections are filled to capacity. If you must miss a lab due to unavoidable circumstances, you may attend another session of the same lab if space is available, however you are only guaranteed a space at your scheduled lab. Make-up labs may be offered at the end of the semester if time permits. If you need to attend a make-up lab, contact your instructor in advance.

You will be penalized as follows for absences:

- Miss 1 lab – Course Grade reduced by 1 Letter Grade
- Miss 2 labs – Course Grade reduced by 2 Letter Grades
- Miss 3 or more – Automatic course failure

Textbook

You will receive a lab manual during the first class meeting. This manual will be used in every lab, so always bring it with you. Review each lab before you come to the lab.

The Electrical Machines course textbook, *Operating, Testing, and Preventive Maintenance of Electrical Power Apparatus*, by Charles I. Hubert, and *Electrical Machines, Drives, and Power Systems*, by Theodore Wildi are also recommended.

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Downstairs Labs

- **Lab 1** Alternating Current
- **Lab 2** Three Phase Transformers
- **Lab 3** DC Generators
- **Lab 4** Induction Motors
- **Lab 5** AC Synchronous Generators
- **Lab 6** Generator Paralleling Satisfies: STCW 7-1E (Parallel generators)

Upstairs Labs

- **Lab 1** Residential Wiring; Lock-out/Tag-out Procedures; Use of DMM, Clamp-on Ammeter, Wiggy
- **Lab 2** Basic Principles of Motor Control.
- **Lab 3** Basic Control Circuits.
- **Lab 4** Jogging Control Circuits.
- **Lab 5** Reduced Voltage Starters.
- **Lab 6** Timing Relays. High Voltage Switchgear

IMPORTANT LAB RULES

Safety First.

No food or drink in the lab.

Spring 2023

		28 <i>Commence Classes</i>	1	2	3
March	6 H1	7 H1 <i>Last day to add</i>	8 H1	9 H1	10 H1
	13 L1	14 L1	15 L1	16 L1	17 L1
	20 H2 <i>Last day to drop</i>	21 H2	22 H2	23 H2	24 H2
	27 L2	28 L2	29 L2	30 L2	31 L2
	3 H3	4 H3	5 H3	6 H3	7 H3
April	10 L3	11 L3	12 L3	13 L3	14 <i>No Classes</i>
	17 <i>Patriots' Day</i>	18 H4 <i>Deficiencies due</i>	19 H4	20 H4	21 L3
	24 H4	25 L4	26 L4	27 L4	28 H4
	1 L4	2 H5	3 H5	4 H5	5 L4
	8 H5	9 L5 <i>Last day to withdraw</i>	10 L5	11 L5	12 H5
May	15 L5	16 H6	17 H6	18 H6	19 L5
	<i>USCG Exam Class of 2023</i>				
	22 H6	23 L6	24 L6 <i>Change of Command</i>	25 L6	26 H6
	29 <i>Memorial Day</i>	30 L6 <i>Monday Schedule</i>	31 MU	1 MU	2 L6
	5 MU	6 <i>Begin Finals</i>	7	8	9

Figure 0.1: Lab Schedule

Lab 1

Alternating Current

Introduction

Objective

In the laboratory exercise, you will verify Ohm's law by measuring circuit current for various combinations of voltage and resistance; observe sinusoidal waves on an oscilloscope and determine important circuit parameters such as frequency, period, amplitude and RMS values; and identify phase shifts between voltage and current in an LRC circuit on both the oscilloscope and the phasor analyzer.

After completing this lab, you should be able to calculate the resistance of various combinations of resistors in series and parallel; use Ohm's law; adjust, use, and interpret an oscilloscope display; determine whether and by how much one sinusoidal wave leads or lags another and represent them using a phasor diagram.

Sinusoidal waves

Alternating current (AC) is used throughout the world for powering electrical equipment. As its name suggests, alternating current is an electrical current that continuously alternates in direction and magnitude. This alternating current is caused by a similarly alternating voltage produced by a generator. The term *alternating current* is used describe many aspects of the electrical system, so for example we speak of ac generators, ac voltages, and ac meters, etc.

AC voltages and currents change in value from instant to instant in a repeating pattern which can be plotted as a function of time or viewed on an oscilloscope. The shape of this *periodic* waveform depends on the power supply generating the voltage, and it is possible to create square waves, triangular waves or other forms, but the type of wave form created by standard electrical generators is *sinusoidal*. A sine wave of voltage permits us to obtain the highest efficiency from motors, generators, and transformers, and results in the quietest operation.

One *cycle* is one complete sequence of positive and negative values that make up the repeating pattern of the periodic waveform. After completing one cycle, the waveform returns to its starting value, and begins the cycle again. The length of time it takes to

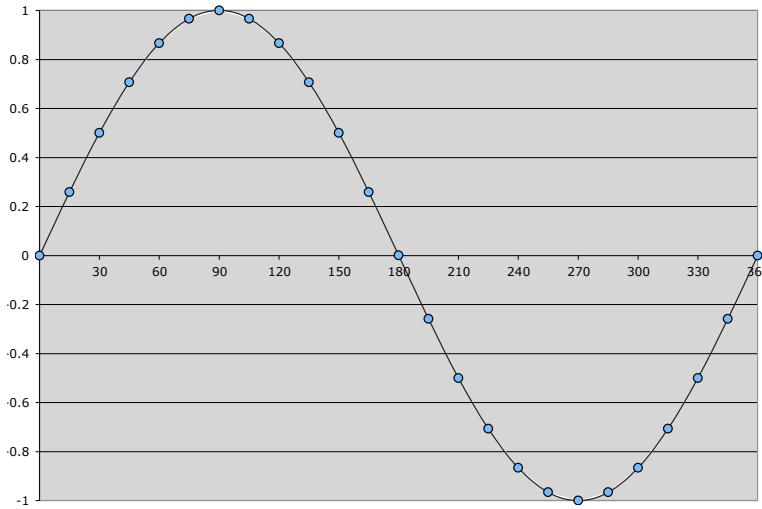


Figure 1.1: The sine wave

complete one cycle is called the *period*, and the number of times that the cycle repeats in one second is called the *frequency* of the waveform. Therefore the frequency and period are inverses of each other.

$$T = 1/f \quad f = 1/T \quad (1.1)$$

Frequency is measured in Hertz (Hz) where 1 Hz is 1 cycle/sec. The normal ac line frequency in North America is 60 Hz, while most countries in Europe, and several others, have an ac line frequency of 50 Hz. When the value reaches zero for the second time, a full revolution of 360 angular degrees has been completed. For a 60-Hz system, in one second, 60 complete cycles, or periods, of the sine wave take place. Therefore, the period of a 60-Hz sine wave is 1/60 of a second.

$$T = 1/60 \text{ sec} = 0.01667 \text{ sec} = 16.67 \text{ ms}$$

Angular velocity, ω , describes the frequency in radians per second and since there are 2π radians per revolution, the relationship between angular velocity and frequency is

$$\omega = 2\pi f$$

Phasors

Each cycle of a sine wave is equivalent to one 360° revolution of a *rotating vector*. The vector rotates with an angular velocity $\omega = 2\pi f$. The instantaneous value of voltage is the y -component of the vector, and its value changes through one cycle as the vector rotates through 360° . Time is taken to be zero when the vector is aligned with the positive x axis, and the vector is always considered to be rotating in the counterclockwise direction. A *phasor* is a similar rotating vector which uses the rms value rather than

Table 1.1: Values of the Sine Function for One Cycle

θ	$\sin \theta$	θ	$\sin \theta$
0°	0.000	180°	0.000
15°	0.259	195°	-0.259
30°	0.500	210°	-0.500
45°	0.707	225°	-0.707
60°	0.866	240°	-0.866
75°	0.966	255°	-0.966
90°	1.000	270°	-1.000
105°	0.966	285°	-0.966
120°	0.866	300°	-0.866
135°	0.707	315°	-0.707
150°	0.500	330°	-0.500
165°	0.259	345°	-0.259
180°	0.000	360°	0.000

the peak value as the length of the phasor. Using the rms values makes calculations involving rms values simpler.

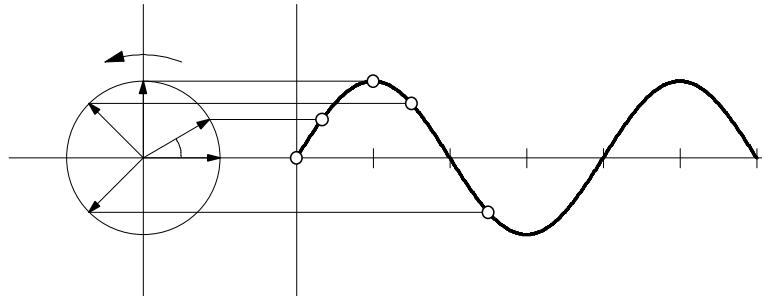


Figure 1.2: Relation between rotating vector and the sin wave.

The sinusoidal value starts at zero, increases to a maximum, then decreases until it reaches zero again, at which point the value changes sign. When an electrical quantity changes sign, we say that it has reversed its *polarity*. The quantity then continues to decrease until it reaches a negative maximum, and then returns to zero. The maximum value, which is equal to the length of the rotating vector, is called the *Amplitude*, or sometimes, the *peak value*. The *peak-to-peak* value is the difference between the maximum and minimum values, which is simply twice the peak value.

Since an ac voltage constantly changes in value, a 100 V (peak) ac voltage will not deliver the same amount of power as a steady 100 V dc voltage. To facilitate this comparison, we define the *rms (root-mean-square)* or *effective value* of an ac voltage to be the value of a dc voltage that would produce the same amount of heat in a given resistor.

For example, suppose that a sine-wave voltage with a peak value of 100 V were connected to a load resistor and the resistor's temperature was measured after it had stabilized. The effective value of the ac voltage could be found by using a variable dc supply, and adjusting the dc voltage until the temperature of the resistor stabilized at the same point as before. The resulting dc voltage would be 71 V, meaning that the rms value

of the ac voltage is 71 V. Another way to obtain a measure of the rms value would be to connect a dc voltage to one lamp and an ac voltage to another. The lamp brightness will be a fairly accurate indicator of the power being dissipated, and the dc voltage could be adjusted to obtain the same brightness as the ac voltage. Naturally, these methods would be time consuming and not very efficient for determining the rms value of an alternating voltage or current. Fortunately, they are rarely necessary because standard ac voltmeters and ammeters are calibrated to indicate the rms value directly. In equations, the rms subscript is understood, and not usually indicated unless required for clarity.

Mathematically, the rms voltage is determined by taking the square root of the average of the square of the instantaneous voltage over one cycle. When this process is carried out for a sinusoidal waveform, the rms value is always found to be equal to the peak value times $1/\sqrt{2}$.

$$V_{rms} = \frac{V_{max}}{\sqrt{2}} = 0.707 V_{max}$$

$$I_{rms} = \frac{I_{max}}{\sqrt{2}} = 0.707 I_{max}$$

Phase Angle

Phase angle is used to measure the amount of separation in time or angle between two sine waves of the same frequency. The sine waves being compared must have the same frequency, but they do not have to be the same amplitude. When making comparisons, one of the two sine waves is designated the *reference waveform*, and taken to have a *phase angle* of $\theta = 0$ at $t = 0$. The other waveform is said to *lead* or *lag* the reference.

To determine the phase shift using an oscilloscope, the waveform on one channel is designated the reference waveform, and the other channel displays the waveform for which we wish to measure the relative phase difference. The horizontal separation between two corresponding points on the waveforms is measured, and using the horizontal scale of the oscilloscope, the time difference T_d is determined. The angular phase difference can be easily found since the ratio of the time difference to the period is the same as the ratio of the phase difference to 360° .

$$\frac{T_d}{T} = \frac{\Delta\theta}{360^\circ}$$

For example, in Figure 1.3 the two sin waves are separated by one major division on the oscilloscope. If the horizontal scale is 20 ms/div, then the two waves are out of phase by 20 ms, so $T_d = 20$ ms. It takes the waves 4 major divisions to complete one cycle, so the period $T = 80$ ms. Using equation 1 to find the phase difference we have

$$\begin{aligned}\Delta\theta &= \frac{T_d}{T} \cdot 360^\circ \\ &= 20/80 \cdot 360^\circ \\ &= 90^\circ\end{aligned}$$

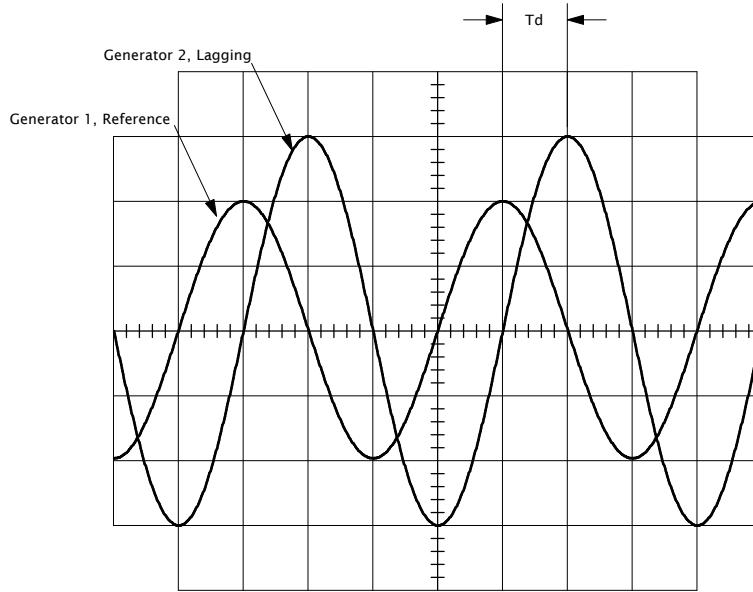


Figure 1.3: Phase shift

Lead or lag is determined by the relative positions of the two waveforms. Choosing two corresponding points that are less than or equal to 180° apart, the wave that reaches the point earliest in time is said to lead the other. A leading wave appears to the left of the reference, while a lagging wave is shifted to the right. In this case, generator 2 lags. When the phase is lagging, it is common to see a minus sign or the word *lagging* included with the number, i.e. -90° or 90° lagging. Note that when generator 2 lags the reference, the reference leads generator 2 by the same amount. When a wave lags by 90° , it also leads by 270° , but the convention when speaking of phase difference is to use the value closest to zero.

Three Phase Power

Electrical power is most commonly generated by *three-phase* generators. Three-phase generators have three identical windings 120° apart which produce three identical sine waves of voltage simultaneously. The three voltage phases, typically called A, B and C, have identical amplitudes but are evenly separated in time and thus separated from each other by 120° . Figure 1.4 shows three-phase voltage sinusoids and the corresponding phasor diagram.

Procedure

Sine Waves

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

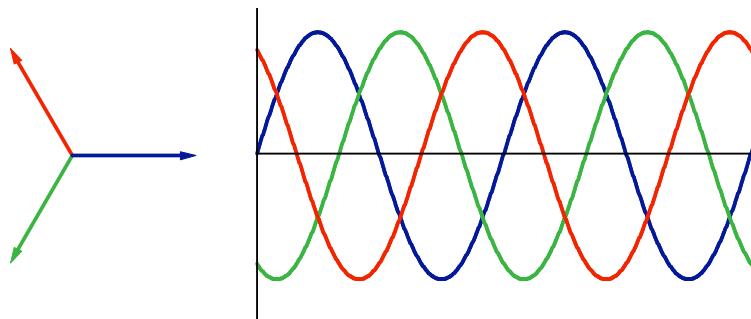


Figure 1.4: Three phase voltage

- 1. Start the computer on the lab bench and log in.
- 2. Verify that the *Power Supply, Data Acquisition and Control Interface* (DAI), and *Resistive Load Modules* are installed in the *EMS Workstation*.
- 3. Make sure the main power switch of the Power Supply is **off**, and that the output control knob is turned fully ccw. Set the voltmeter select switch on the power supply to the 4-N position.
- 4. Ensure that the 24 V power supply is connected to the DAI, and that the USB cable from the computer is connected to the DAI. Set the 24 VAC power switch to the 1 (ON) position and leave it turned on throughout the exercise. Loss of power to the DAI will cause it to lose communication with the metering software. When building circuits, start at the power supply and construct around the circuit and back to the power supply. Ignore the voltmeters until the main circuit is built, then add them last.
- 5. Open the E: drive and then open meter configuration file *Lab 1 AC*. When prompted, choose 120 V and 60 Hz. This will configure the program for this lab and set up the virtual meters as indicated in the table:

Meter	Setup
E1, E2, E3	AC Volts
I1	AC Amps
PQS1 (E3, I1) Mode P	Power
F(E3)	Frequency

Important: The display should show **READY** in the status bar at the bottom of the screen.

- 6. Set up the circuit shown in Figure 1.5. Note the symbol used to indicate a *variable ac source* in this circuit. Note that voltmeter E3 is placed across the power supply and measures the supply voltage, and that I1 is placed in series with the load, and measures the load current. When connecting the ammeter, use the 4 A connection. Set the resistances of R_1 and R_2 to **300 Ω** each.

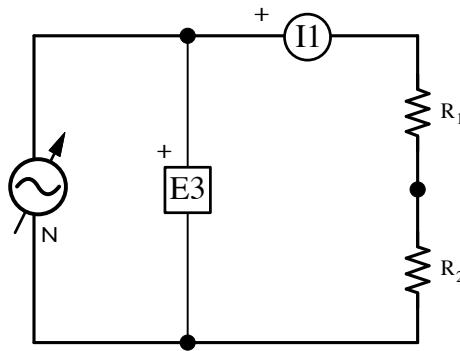


Figure 1.5: AC sine wave circuit

What is the total resistance of the circuit in this configuration? _____

- 7. Have your circuit checked by the instructor before moving on.
- 8. After your circuit has been checked, turn on the power, and set the voltage control knob to 100%.
- 9. Open the meter display, and activate it by clicking on the *continuous refresh*. Record the circuit current and voltage (rms values).

$$E_3 = \text{_____} \quad I_1 = \text{_____}$$

- 10. Click on the *Oscilloscope* button and display E3 on Channel 1 and I1 on Channel 2. Activate the display by clicking on the *continuous refresh* button. Set convenient vertical and horizontal scales for the display to show one whole cycle of the sine wave.
- 11. Read the peak amplitudes of the voltage and current waves from the display and record them.

$$V_p = \text{_____} \quad I_p = \text{_____}$$

- 12. Calculate the ratios of peak to rms values.

$$V_p/V_3 = \text{_____} \quad I_p/I_1 = \text{_____}$$

Are the ratios approximately equal to $\sqrt{2}$

Yes No

- 13. Compare the current waveform to the voltage waveform.

Are they both sine waves?

Yes No

Do they have the same frequency?

Yes No

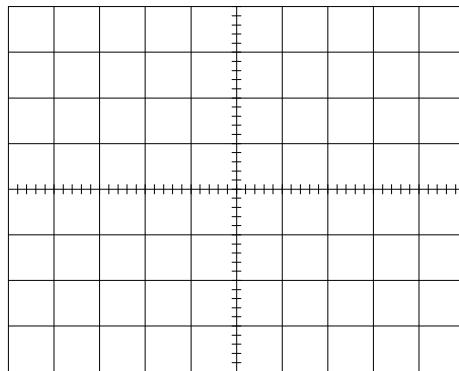
Are their amplitudes approximately equal?

Yes No

Are the two waves in phase?

Yes No

- 14. Carefully sketch and label what you see on the oscilloscope.



15. The *period*, T of a sine wave is the length of time that it takes to complete one cycle. Use the cursors to determine the period of the voltage wave.

$$T = \text{_____} \text{ ms}$$

16. The *frequency*, f of a sine wave is the inverse of the period and is usually expressed in Hz, which are cycles/sec. Calculate frequency in Hz based on your measurement of the period and compare with the measurement shown on the frequency meter.

$$f = 1/T = \text{_____} \text{ Hz}$$

Ohm's Law

17. Turn the voltage control knob to the zero position.
18. Click on the *Data Table* button to bring up the data table, then click on the *Record Data* button. Accept the default selection of values to record.
19. Use the *Record Data* button to record the voltage and current measurements in the *Data Table*, for **0, 25, 50, 75 and 100%** positions of the voltage control knob. To collect accurate data, wait 2–3 seconds after adjusting the voltage before recording.
20. Adjust the load resistor R_1 to **171 Ω**, and repeat the previous step. Use the same data table and do not delete the data from the previous step.

What is the total resistance of the circuit in this configuration? _____

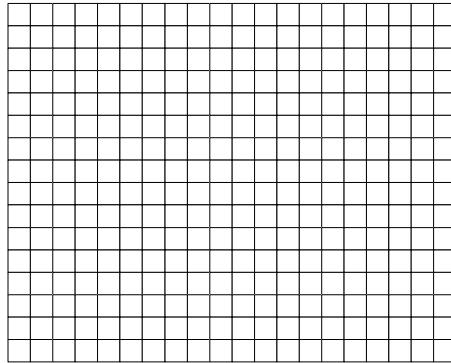
21. Click on the graph icon, and create a graph of line voltage (meter E3) as a function of line current (meter I1).

How does the graph demonstrates Ohm's Law?

Sketch the graph here.

Hint Do you remember the formula for resistors in parallel?

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \dots$$



22. Use your vast knowledge of Ohm's law to predict the voltage drops across resistors R_1 and R_2 when a 100 V supply voltage is applied to the circuit.

$$I_1 = \text{_____ A} \quad E_1 = \text{_____ V} \quad E_2 = \text{_____ V}$$

23. Add E1 and E2 to measure the voltage drop across resistors R_1 and R_2 , as shown in Figure 1.6, and adjust the source voltage to **100 V** with the voltage control knob.

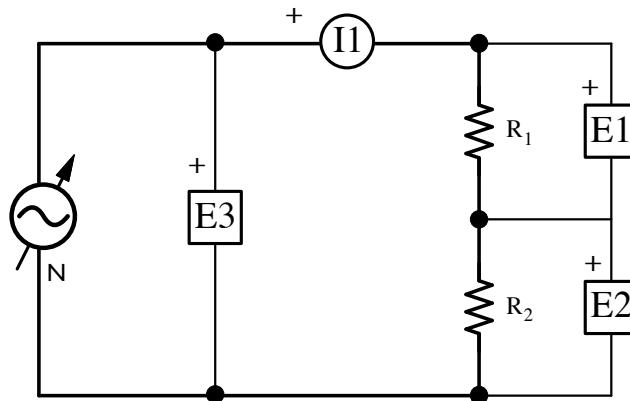


Figure 1.6: Voltage Divider Circuit

24. Record the actual, measured voltage drop across the two resistors, and the actual line current.

$$I_1 = \text{_____ A} \quad E_1 = \text{_____ V} \quad E_2 = \text{_____ V}$$

How well do the measured values agree with the predictions that you made?

What is the relationship between the source voltage E_3 and voltages E_1 and E_2 ?

This circuit is often called a “voltage divider.” Why?

25. In a voltage divider circuit like this one, the ratio of the the voltage drops across the two resistors should equal the ratio of their resistances.

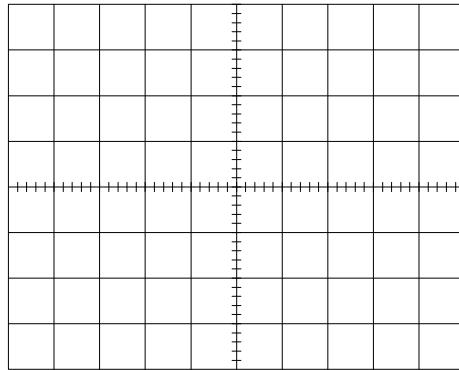
$$E_1/E_2 = \underline{\hspace{2cm}} \quad R_1/R_2 = \underline{\hspace{2cm}}$$

Are the ratios approximately equal?

Yes No

Phasors and Phase Angle

26. Continuing with the setup from the preceding section, click on the *Oscilloscope* button and display E3 and I1 on channels 1 and 2. Adjust the vertical scales and the time base to show at least one complete cycle of the sine waves.
- Is the line current still in phase with the line voltage? Yes No
27. With the power off, switch the $300\ \Omega$ resistor with a $300\ \Omega$ inductor. Turn the power back on when the circuit has been modified.
28. Observe the oscilloscope display, and sketch what you see.



29. Are the current and voltage still in phase? Yes No
30. Does the current lead or lag the voltage? Lead Lag
31. Use the cursors to determine the time delay between current and voltage in ms.

$$T_d = \underline{\hspace{2cm}} \text{ ms}$$

32. Calculate the phase shift in degrees, using the time delay and the period T you measured earlier.

$$\phi = \frac{T_d}{T} \cdot 360^\circ = \underline{\hspace{2cm}}$$

33. Turn on the *Phasor Analyzer* and set it up to display E3 and I1. Use E3 as the *reference phasor*. adjust the current and voltage scales so that the phasor arrowheads are visible within the largest circle.
34. Does the phasor analyzer show the same phase shift between current and voltage as your calculation? Yes No
35. Do the lengths of the phasors represent the Peak or rms values of the voltage and current? Peak rms

- 36. Replace the 300Ω inductor with a 300Ω capacitor, and observe the circuit behavior again.
 - 37. What does the phase shift between voltage and current tell you about the load?
-
-

- 38. **Turn off the power.** Disassemble the circuit.

Line and Phase Voltages

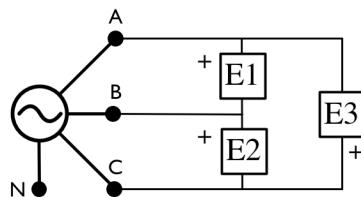


Figure 1.7: Line Voltage Measurement

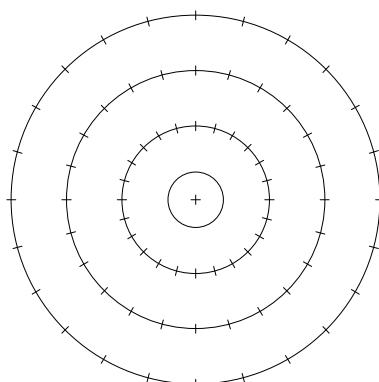
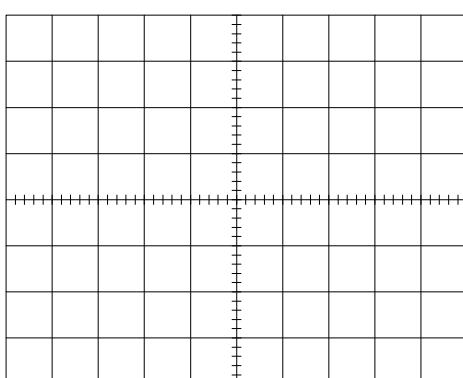
- 39. With the power off, connect voltmeters E1, E2, and E3 to simultaneously measure the LINE voltages of the fixed voltage three-phase power supply, as shown in Figure 1.7.
- 40. Turn on the power and record the measured values here.

$$E_{A-B} = \text{_____} \text{ V}$$

$$E_{B-C} = \text{_____} \text{ V}$$

$$E_{C-A} = \text{_____} \text{ V}$$

- 41. Set up the *oscilloscope* and *Phasor Analyzer* to display the three voltages, and sketch below what you see.



Hint Pay attention to the polarities of the voltmeters. Red is the positive side.

42. Turn off the power and reconnect voltmeters E1, E2, and E3 to simultaneously measure the PHASE voltages of the fixed voltage three-phase power supply, as shown in Figure 1.8.

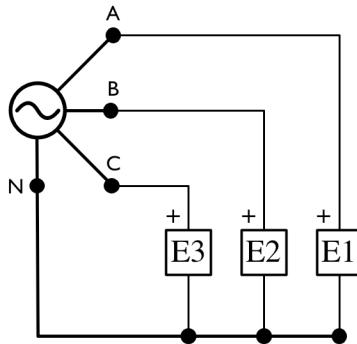


Figure 1.8: Phase Voltage Measurement

43. Observe the voltages on the *oscilloscope* and *Phasor Analyzer* and record the measured values here

$$E_{A-N} = \text{_____} \text{ V}$$

$$E_{B-N} = \text{_____} \text{ V}$$

$$E_{C-N} = \text{_____} \text{ V}$$

44. Answer these questions:

Are all three rms line voltages approximately equal? Yes No

Are all three rms phase voltages approximately equal? Yes No

Are the line voltages $\sqrt{3}$ times greater than the phase voltages? Yes No

45. What is the angular phase difference the any two voltages?

$$\phi = \text{_____}^\circ$$

46. What is the time difference between any two voltages?

$$\Delta T = \text{_____} \text{ ms}$$

47. Turn off the power, turn off the computer, and put everything away.

Lab 2

Three Phase Transformers

Introduction

Objective

After completing this exercise, you will be familiar with operating characteristics of three-phase transformers. You will be able to connect transformer windings in wye and delta configurations, and verify that windings are connected with the proper phase relationships.

You will make voltage and current measurements and investigate transformer characteristics. You will determine the primary and secondary voltage and current ratios and phase shifts caused by three-phase transformers connected in four configurations, wye-wye, delta-delta, wye-delta, and delta-wye.

Transformers

A *transformer* is an electromagnetic device which uses Faraday's principle of induction to change an ac voltage from one value to another. Transformers are also used to isolate one circuit from another.

Transformers have two coils, the *primary* and the *secondary*, magnetically linked to each other by an iron core. When an alternating voltage is applied to the primary coil, current flow creates an alternating magnetic field. This magnetic field links through the secondary winding, and the changing magnetic field there induces the secondary voltage. The output voltage is dependent on the applied voltage and the number of turns in each coil. In an ideal transformer, the input to output voltage ratio is equal to the turns ratio; if both coils have the same number of turns, a *1:1 turns ratio*, the voltage neither steps up nor steps down.

$$\frac{N_{\text{pri}}}{N_{\text{sec}}} = \frac{E_{\text{pri}}}{E_{\text{sec}}} = \frac{I_{\text{sec}}}{I_{\text{pri}}}$$

In actual transformers, the ratio is only approximate due to voltage drops occurring in the coils, and imperfect linkage of the magnetic flux through the coils.

When line voltage steps up line current steps down, and vice-versa, because their product EI is electrical power, which is conserved by a transformer.

Three phase transformers

The main features of three-phase transformer circuits that are important to understand are that transformers have two sides: *primary* and *secondary*; there are two types of connections: *wye* and *delta*; and we can measure two different voltages: *line* and *phase*. Since both the primary and secondary windings can be connected in either wye or delta there are four possible types of connections: *wye-wye*, *delta-delta*, *delta-wye*, and *wye-delta*. Three-phase transformers can physically be three single-phase units connected together or a single unit containing three transformers.

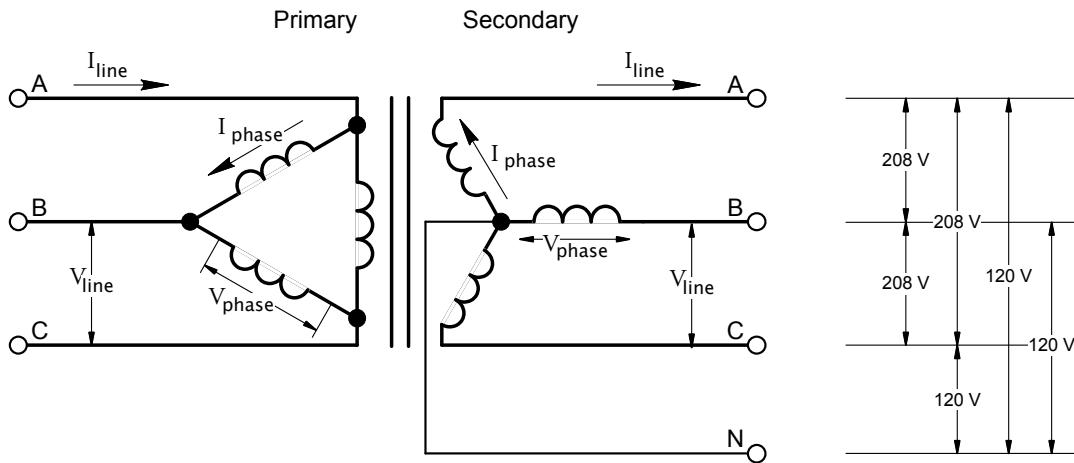


Figure 2.1: Delta Wye Three-phase Transformer

In wye-connected three-phase circuits, *line voltages* are greater than *phase voltages* by the factor $\sqrt{3}$ while the *line current* and *phase currents* are equal. A wye connected transformer can be used to provide two different voltages for different uses simultaneously. For example, in Figure 2.1 when 120 V three-phase power is supplied to the primary of a transformer 208 Volts is available between any two lines on the secondary, while 120 volts can be obtained between a line wire and the neutral wire. Therefore the wye-connected secondary provides three-phase 120/208 V power using 4 wires. The primary side of the transformer may be connected in delta as in the figure or in wye.

In delta-connected three-phase circuits, the situation is just the opposite. Line and phase voltages are equal, while line currents are greater than the phase currents by the factor $\sqrt{3}$. One advantage of using a delta configuration for the primary is that only three wires are needed to distribute the three phases. Another advantage is that two single-phase transformers (instead of three) can be operated in what is known as the *open-delta* configuration in an emergency if one of the three transformers becomes damaged or is removed from service. The open-delta transformer bank still delivers phase voltages and currents in the correct relationship, but the capacity of the bank is reduced to 57.7% ($1/\sqrt{3}$) of the total nominal capacity available with three transformers in service.

	Wye	Delta
Voltage	$V_L = \sqrt{3}V_\phi$	$V_L = V_\phi$
Current	$I_L = I_\phi$	$I_L = \sqrt{3}I_\phi$

Table 2.1: Property relations for three-phase connections

When 1:1 transformers are used, the phase voltage on the secondary equals the corresponding phase voltage on the primary. If the turns ratio is not 1:1, the the phase voltages step up or step down accordingly. The situation is more complex when comparing line voltages: in the delta-delta and wye-wye configurations, the line voltage at the secondary is equal to the line voltage at the primary times the inverse of the turns ratio; in the delta-wye configuration, the line voltage at the secondary is equal to the line voltage at the primary times the inverse of the turns ratio times $\sqrt{3}$; and, in the wye-delta configuration, the line voltage at the secondary is equal to the line voltage at the primary times the inverse of the turns ratio times $1/\sqrt{3}$.

Three phase transformers may also introduce a phase shift between the primary and the secondary line voltages. Primary and secondary line voltages in delta-delta and wye-wye connections are in phase. In delta-wye and wye-delta connections however, there will be a 30° phase difference between the primary and secondary voltages. The 30° phase shift between the primary and secondary does not create any problems for isolated groups of loads connected to the outgoing lines from the secondary. However, if the outgoing lines from the secondary of a three-phase transformer have to be connected in parallel with another source, the phase shift might make such a parallel connection impossible, even if the line voltages are the same. Recall that in order for three-phase circuits and sources to be connected in parallel, line voltages must be equal, have the same phase sequence, and be in phase when the parallel connection is made.

Figure 2.1 shows a three-phase transformer, with a turns ratio equal to 1:1, connected in the delta-wye configuration and feeding a three-phase load. The voltage across each primary winding E_{pri} equals the incoming line voltage, but the outgoing line voltage E_{sec} is $\sqrt{3}$ times that voltage because the voltage across any two secondary windings is $\sqrt{3}$ times greater than the voltage across a single secondary winding. Note that if the three-phase transformer had a turns ratio of 1:10, the line voltage at the secondary would be $10 \times \sqrt{3}$ times greater the line voltage at the primary, because the inverse of the turns ratio is multiplied by the $\sqrt{3}$ factor. The line current in the secondary is the same as the phase current, but the line current in the primary is $\sqrt{3}$ times greater than the corresponding phase current.

Phase relationship

When wiring up transformers, precautions must be taken to ensure that the secondaries are connected with the proper phase relationships. If a transformer winding is installed backwards, high voltages and short circuit currents can be produced.

In order to set up a wye connection, first connect the three components (windings) together at a common point for interconnection with the neutral wire, then connect

the other end of each component in turn to the three line wires. To set up a delta connection, connect the first component in series with the second, the second in series with the third, and the third in series with the first to close the delta loop. The three line wires are then separately connected to each of the junction nodes in the delta loop. Before closing the delta or supplying a load check the phase relationships as follows:

For a wye configuration, check that the voltage measured across any two secondary windings (line voltage) is $\sqrt{3}$ times greater than the voltage across either winding by itself (phase voltage). If not, the connections must be reversed before continuing.

For a delta configuration, the voltage measured between the ends of two series connected secondary windings must equal the voltage across either winding individually, and when one end of the third winding is connected, the voltage measured across all three series-connected windings must equal zero before connecting them together to close the delta. If not, the incorrect connection must be reversed. This is particularly important for a delta configuration, because a very high short-circuit current will flow if the voltage within the delta is not equal to zero when it is closed.

Procedure

Single Phase Transformer

- 1. Start the PC and log into your account.
- 2. Insure that the Power Supply, Three-phase Transformer module, and Data Acquisition Interface are installed in the EMS Workstation. Insure the USB cable connects the DAI to the computer.
- 3. Make sure that the **main power switch is off**, and the voltage control knob is turned fully ccw. Set the voltmeter select switch to the 4–5 position.
- 4. Use the grey cable to connect the DAI to the 24 V ac power supply, and turn it on. Leave power on the DAI for the entire exercise.
- 5. Open configuration file *Lab 2 Transformers* from the E: drive. When prompted, choose 120 V and 60 Hz. Launch the *Phasor Analyzer* and set it up to display E1, E2, and E3, with E1 as the *Reference Phasor*. The meters should display the values shown in Table 2.2.

Important: The display should show **READY** in the status bar at the bottom of the screen.

- 6. Construct the circuit shown in Figure 2.2. Note that E1 measures the input (primary side) voltage E_{1-2} , and E2 measures the corresponding output voltage E_{3-5} on the secondary side of a single-phase transformer.
- 7. **Turn on the power** and adjust the supply voltage to about **208 V**.
- 8. Observe the voltages measured by E1 and E2. Adjust the input (primary) voltage to another value and observe the output (secondary) voltage.

Meter	Display
E1, E2, E3	AC Volts
I1, I2, I3	AC Amps
Sum(E1,E2,E3)	Voltage Vector Sum
Ave(E1,E2,E3)	Voltage Scalar Average

Table 2.2: Meter Configuration

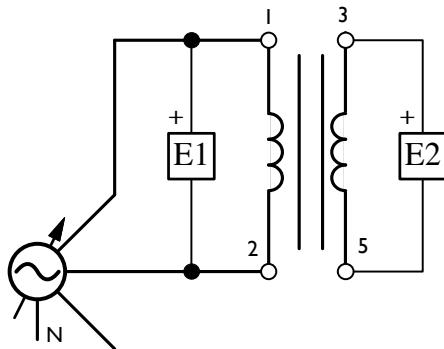


Figure 2.2: Single Phase Transformer

Do you see that a 1:1 turns-ratio, single-phase transformer does not step up or step down the voltage?

Yes No

9. Observe the *Phasor Analyzer* to compare the voltage phasor E_{1-2} on the primary side with that of E_{3-5} on the secondary side. Set the reference phasor to E1, and the voltage scale to 100 V/div.

Does the *Phasor Analyzer* display show that the voltages are equal and in phase, except for possibly a small difference due to transformer reactance? Yes No

10. Move voltmeter E2 to measure the voltage between points 4 and 5. Does the transformer now step down the primary voltage to approximately 120 V. Yes No
11. **Turn off the power**

Wye - Wye

12. With the power off, connect all three transformers together in the three-phase **Y - Y** configuration shown in Figure 2.3.

Have your circuit checked before turning on the power.

13. When your circuit has been checked, turn on the power and adjust the supply voltage to **120 V**. Use meter E1 to measure the line and phase voltages on the primary and secondary sides and record the results in Table 2.3. Check each line with *Line*, *Phase*, *Primary*, and *Secondary* as appropriate. After recording the measurements **turn off the power**.

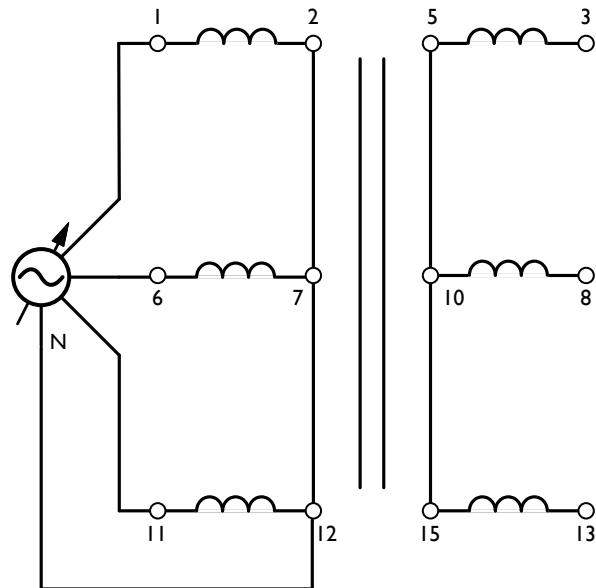


Figure 2.3: Three-Phase Transformer Connected in Wye-Wye

Line	Phase	Pri	Sec	Voltage		
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	E_{1-6}	_____	E_{6-11} _____ E_{11-1} _____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	E_{1-2}	_____	E_{6-7} _____ E_{11-12} _____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	E_{3-8}	_____	E_{8-13} _____ E_{13-3} _____
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	E_{3-5}	_____	E_{8-10} _____ E_{13-15} _____

Table 2.3: Line and Phase Voltage Comparison

Do your measurements confirm that for a wye connected transformer, the line voltages are $\sqrt{3}$ times greater than the phase (line-to-neutral) values? Yes No

14. Now connect E1, E2, and E3 to measure phase voltages E_{3-5} , E_{8-10} and E_{13-15} at the secondary, and turn the power back on. Observe the voltage phasors on the *Phasor Analyzer*.
 Does the display confirm that the secondary phase voltages are equal with a 120° phase shift between each of them? Yes No
 Is the vector sum of the three secondary phase voltages is approximately equal to zero? Yes No
15. Turn the power supply off and the voltage control knob fully ccw.

Delta - Delta

16. With the power off, connect the Three-phase Transformer module in the Δ - Δ configuration shown in Figure 2.4.

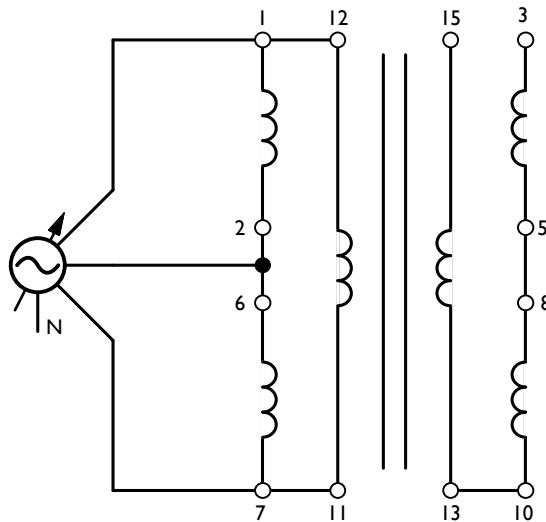


Figure 2.4: Three-Phase Transformer Connected in Delta-Delta

Note that the delta on the *secondary* is left open between points 15–3. **Do not close the delta** until the voltages have been verified to be zero in step 20 below. This is done to insure that the connections have been made properly. Incorrect wiring will produce dangerously high currents, and damage the transformer.

Have your circuit checked before continuing.

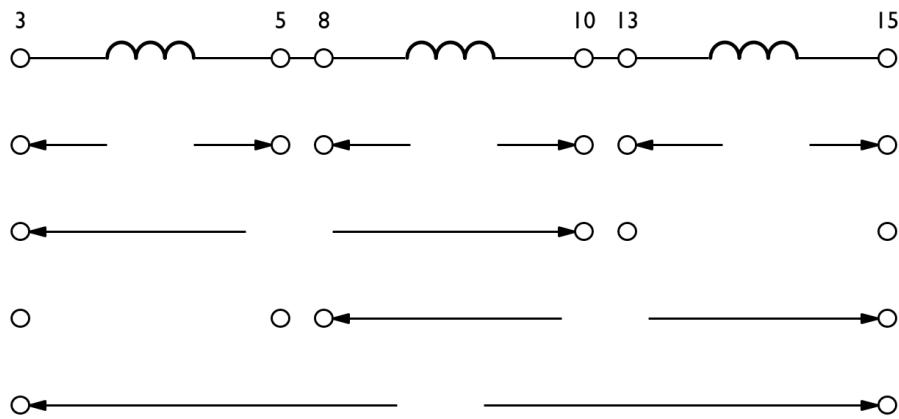
17. **Turn on the power** supply and adjust the voltage control knob to obtain 120 V supply (Line) voltage.
18. Make the following measurements with voltmeter E1 and record them on the diagram below then **turn off the power**.

Individual windings: E_{5-3} E_{10-8} E_{15-13}

Two windings in series: E_{3-10} E_{8-15}

Three windings in series: E_{3-15}

Hint Since these transformers are connected in Delta, the phase voltages measured here are also the line voltages.



19. Since these transformers have a 1:1 turns ratio the values measured on the *secondary* should be the same as the corresponding values measured on the primary. You should see that:
- the voltage across each individual coil is approximately equal to 120 V
 - the voltage across two coils in series is also approximately 120 V
 - the voltage across three coils in series is nearly zero.

Explain why this is so? (Hint: remember the phase relationships of the three phases.)

Is the voltage E_{3-15} nearly equal to zero (< 5V), confirming that the transformer is wired correctly, and that it is safe to close the delta? Yes No

20. When the winding connections are confirmed to be correct **Close the delta** on the secondary side of the transformer.
21. Connect E1, E2, and E3, to measure the line voltages at the secondary, then **turn on the power**, and adjust the voltage control knob to obtain 120 V line voltage.
22. Turn on the *Phasor Analyzer* and display the three secondary voltages.
- Does the display indicate that the secondary voltages are separated by 120° and equal in magnitude to the primary voltages? Yes No
- Is the vector sum of the three line voltages is approximately equal to zero? Yes No
23. Draw below the three voltages you see on the *Phasor Analyzer*, then arrange them in tip-to-tail fashion to show that the sum of the three voltages is zero. Next, repeat the diagrams assuming that one voltage has reversed polarity.

What would the net voltage be in that case? _____

24. Connect voltmeter E1 to measure the primary line voltage E_{1-2} , and E2 to measure the corresponding secondary voltage E_{3-5} .

Does the *Phasor Analyzer* indicate that the primary and secondary voltages are approximately equal in magnitude, and in phase with each other? Yes No

25. Turn off the power.

Wye - Delta

26. With the power off, connect the Three-phase Transformer module in the Y - Δ configuration shown in Figure 2.5. Connect E1, E2, and E3 to measure the line voltages at the primary, E_{1-6} , E_{11-1} , and E_{6-11} .

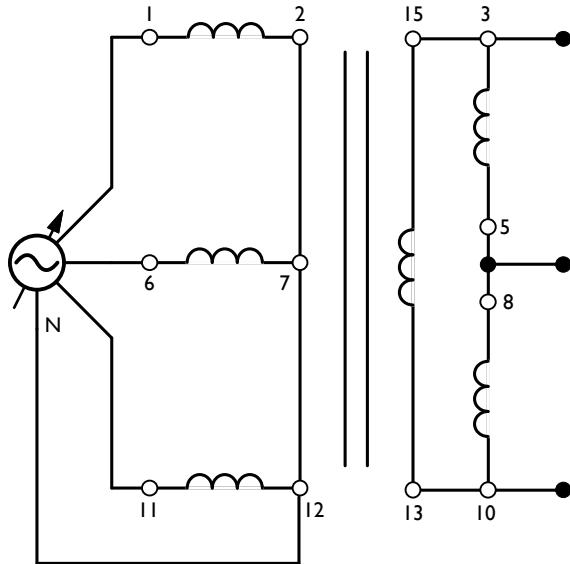


Figure 2.5: Three-Phase Transformer Connected in Wye-Delta

Have your circuit checked before turning on the power.

27. Turn on the power and adjust the voltage control knob to obtain a 120 V line-to-line voltage.
 28. Record the following values.

E_{1-6} _____ E_{11-1} _____ E_{6-11} _____

Sum _____ Average _____

29. Observe the voltage phasors on the *Phasor Analyzer*.

Does the display confirm that the primary line voltages are equal with a 120° phase shift between each of them? Yes No

Is the vector sum of the three voltages is approximately equal to zero Yes No

- 30. **Turn off the power** with out modifying the voltage control setting, and connect E1, E2, and E3 to measure the line voltages at the secondary, E_{3-5} , E_{8-10} , and E_{13-15} .
- 31. **Turn on the power**, and record the following values.

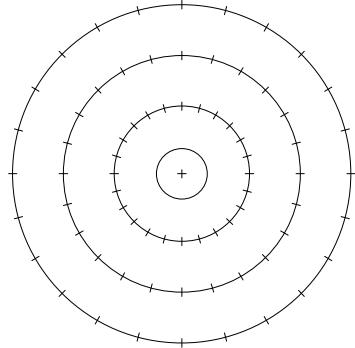
E_{3-5} _____ E_{8-10} _____ E_{13-15} _____

Sum _____ Average _____

- 32. Observe the voltage phasors on the *Phasor Analyzer*.
Does the display confirm that the secondary line voltages are equal with a 120° phase shift between each of them? Yes No
Is the vector sum of the three voltages is approximately equal to zero? Yes No
- 33. Calculate the ratio of the average secondary line voltage to the average primary line voltage.

$$\frac{E_{\text{sec}}}{E_{\text{pri}}} = \text{_____} = \text{_____}$$

- 34. With out modifying the voltage control setting, and connect E1 to measure primary line voltage E_{1-6} and E2 to measure the corresponding secondary line voltage E_{3-5} . Disconnect meter E3
- 35. Observe the *Phasor Analyzer* and sketch the voltage phasors below. Make sure that you adjust the scale so that you can see the ends of the phasors.



Do your calculations and the *Phasor Analyzer* indicate that a 1:1 turns ratio Y - Δ transformer produces a $1/\sqrt{3}$ step down in voltage, and a 30° phase shift between the primary and secondary? Yes No

- 36. **Turn off the power supply**

Delta - Wye

Important Build your circuit without the meters, then have it checked. Install the volt and amp meters after your circuit has been checked.

- 37. With the power off, connect the Three-phase Transformer module in the Δ - Y configuration shown in Figure 2.6 however do NOT include the voltmeters or ammeters until the instructor has checked your circuit. Set the load resistors to **300 Ω** each. Since all load resistors have the same resistance the load is a *three-phase balanced load*. Under these conditions the rms voltage and current values are the same in all three phases.

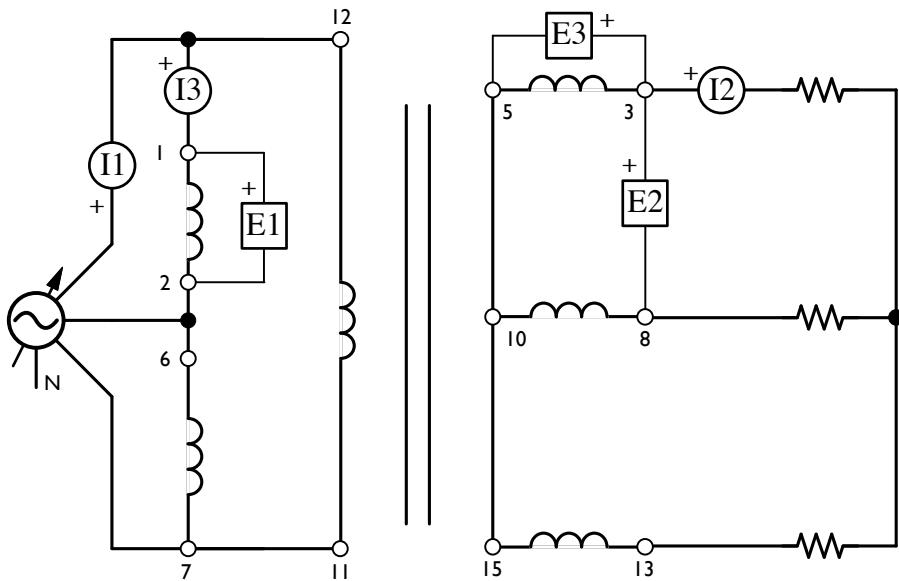


Figure 2.6: Three-Phase Transformer Connected in Delta-Wye. Note: construct circuit without meters.

- 38. In the metering window, edit the labels of the volt and ammeters to indicate what they are each measuring: line/primary, phase/secondary, etc.
- 39. **Turn on the power** and adjust the voltage control knob to obtain a **70 V** line-to-line voltage.
- 40. Determine each of following values:
- 41. Use the phasor analyzer to compare the phase voltage on the primary side to the phase voltage on the secondary side. Does the phasor analyzer confirm that the primary and secondary phase voltages are equal and in phase? Yes No
- 42. Use the phasor analyzer to compare the line voltage on the secondary side to the line voltage on the primary side.

$$\frac{E_{\text{sec}}}{E_{\text{pri}}} = \text{_____} = \text{_____}$$

	Phase Voltage	Line Voltage	Phase Current	Line Current
Primary				
Secondary				

Table 2.4: Data Table for Delta-Wye Transformer

Does your calculation confirm that this configuration produces a $\sqrt{3}$ step up in voltage? Yes No

Explain why this is so.

Does the phasor analyzer confirm that the secondary line voltage leads the primary line voltage by 30° ? Yes No

43. Use the phasor analyzer to compare the line current on the primary side to the line current on the secondary side.

$$\frac{I_{\text{sec}}}{I_{\text{pri}}} = \text{_____} = \text{_____}$$

Does your calculation confirm that this configuration produces a $1/\sqrt{3}$ reduction in current? Yes No

Does the phasor analyzer confirm that the secondary line current leads the primary line current by 30° ? Yes No

44. Use the phasor analyzer to compare the line voltage on the primary side to line current on the secondary side.

Does the phasor analyzer confirm that the primary line voltage and the secondary line current are in phase? Yes No

45. Compare the product of primary line voltage and primary line current to the product of secondary line voltage and secondary line current.

$$E_{\text{pri}} I_{\text{pri}} =$$

$$E_{\text{sec}} I_{\text{sec}} =$$

Are these products approximately equal? Yes No

Explain why.

46. Turn off the power, shut down the computer, and put everything away.

Conclusion

You connected transformer windings in three-phase wye-wye, delta-delta wye-delta, and delta-wye configurations. Before energizing, you measured winding voltages to ensure that secondary windings were connected with the proper phase relationships. You confirmed that the voltage within a delta was zero before closing the delta.

You confirmed the relations between line and phase voltage for delta and wye connections, and you saw that the delta-delta and wye-wye transformers produced no phase shift between the primary and the secondary voltages. Since 1:1 transformers were used in this exercise, no change in voltage was produced either.

In the wye-delta, and delta-wye configurations, you saw that the line voltage between primary and secondary either increased or decreased by a $\sqrt{3}$ factor. You also confirmed that the outgoing line voltages at the secondary were shifted 30° with respect to the incoming line voltages at the primary, and also that the secondary line currents were shifted 30° with respect to the incoming line currents.

Lab 3

DC Generators

Introduction

Objective

When you have completed this exercise, you will understand the factors which affect the output voltage and the main operating characteristics of separately-excited and shunt wound dc generators.

DC Generators

A dc generator is a rotating electrical machine which produces a dc voltage when it is driven by a prime mover. Typical prime movers include steam turbines, diesel engines, wind turbines, etc. The generator consists of three main parts: the *stator*, which creates a stationary magnetic field; the *rotor* or *armature*, which carries a series of windings which produces an alternating voltage as it rotates through the stationary field; and the *commutator and brushes*, which convert the ac voltage produced in the rotor windings to a dc voltage.

The stator may use permanent magnets to create the field, but more commonly, it uses an electromagnet to do the job. The stator consists of pairs field poles wrapped with many turns of a wire known as the *field windings*. The field windings are energized or *excited* with a dc power supply, which may be provided by a separate power supply, or by the output of the generator itself. A *field rheostat* (variable resistor) is usually provided in the field circuit in order to adjust the field current and hence the field strength and generator output voltage. Most generators also include an *voltage regulator* to automatically adjust the field rheostat to maintain the output voltage at the design value; however, the generator in the lab does not include a voltage regulator.

The armature is rotated by the prime mover, and in so doing the armature windings experience a changing magnetic field, which causes a voltage to be induced according to Faraday's principle of magnetic induction. This voltage rises and falls sinusoidally each time the rotor rotates past a pair of field poles, north and south; i.e. the voltage is produced by the rotor is alternating (ac). The commutator, brushes, and armature windings are arranged such that every time the alternating voltage passes through zero, the polarity of the output at the generator terminals is reversed. The result is that the

output of the generator is always in the same direction: i.e. the voltage at the generator terminals is direct current. In addition, the brushes provide the connection between the rotating armature and the stationary generator terminals.

When the generator terminals are connected to a load, the output voltage causes current to flow to the load and through the armature. The interaction between the current flowing in the rotor and the magnetic field produces a torque on the rotor which is proportional to the load current, and is in the opposite direction from the driving torque of the prime mover. This *countertorque* opposes the prime mover torque and increases as the generator supplies more electrical load. The power required to drive the generator is the product of torque and angular velocity.

$$P = T\omega$$

Field Arrangement

Several arrangement of the generator's field windings are possible, and are shown in figure 3.1. When the field is excited by an external power source, the generator is said to be *separately excited*; when the generator supplies its own field excitation, it is *self excited*. A field winding placed in series with the generator load is called a *series winding*, while a winding in parallel with the load is called a *shunt winding*. The strength of a series winding is proportional to the generator load current and not adjustable, while the strength of a shunt winding is relatively constant, but can be adjusted by means of a field rheostat placed in series with the field winding.

A generator with only a shunt winding is called a *shunt generator*, one with only a series winding is a *series generator*, and one with both is called a *compound generator*. When the windings in a compound generator are with the same polarity, the generator is said to be *cumulatively compounded*; if they oppose each other, *differentially compounded*. The relative strengths of the series and shunt windings determines whether the generator is *over-, under-, or flat- compounded*.

The *separately-excited* dc generator provides flexible use because its characteristics can be changed by changing the field current. However, a separate dc power source is required to excite the field electromagnet. Therefore, dc generators that operate without an external dc power source were designed. These are referred to as self-excited dc generators.

In a self-excited dc generator, the field electromagnet is a shunt winding connected across the generator output (shunt generator) or a combination of a shunt winding connected across the generator output and a series winding connected in series with the generator output (compound generator). The generator output voltage excites the field electromagnet. The way the field electromagnet is implemented (shunt or compound) determines many of the generator's characteristics.

Self-excitation is possible because of the residual magnetism in the stator pole iron. As the armature rotates, a small voltage is induced across its winding and a small current flows in the shunt field winding. If this small field current is flowing in the proper direction, the residual magnetism is reinforced which further increases the armature voltage. Thus, a rapid voltage build-up occurs. If the field current flows in the wrong

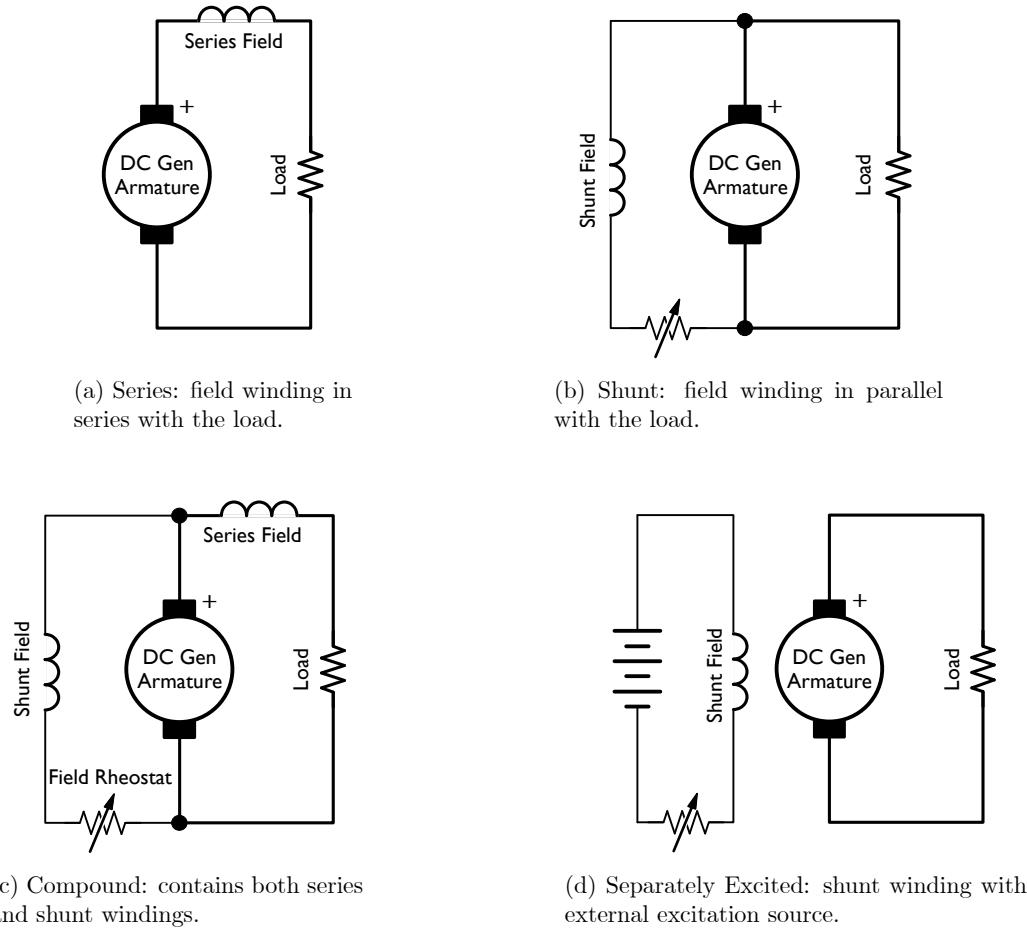


Figure 3.1: Basic DC Generator Field Arrangements

direction, the residual magnetism is reduced and voltage build-up cannot occur. In this case, reversing the connections of the shunt field winding corrects the situation.

If there is no residual magnetism, a self-excited dc generator will not be able to build up voltage. If the residual magnetism has the wrong polarity, the output voltage after build-up will be of the opposite polarity to that required. These problems can be corrected by stopping the generator and restoring the correct polarity of the residual magnetism. This process is called *flashing the field*. To flash the field, a dc source is connected to the shunt field winding to force a small current flow in the proper direction. When the current stops, residual magnetic of the field poles is established in the correct direction, and when the generator is started once again, voltage build-up at the proper polarity occurs.

The field arrangement selected by the generator designer will determine the voltage vs. load behavior of the generator as shown in Figure 3.3. In this lab we will be comparing separately and self excited shunt generators.

Generator Characteristics

DC generators and dc motors are essentially the same device operating in different modes. A motor converts voltage to speed, while a generator converts speed to voltage. Similarly, a motor converts current to torque, while a generator converts torque to current. For separately excited shunt generators, these relations are particularly simple; they are linear. The output voltage of a separately-excited shunt dc generator is equal to the prime mover speed times some constant K_1 . The torque required to drive a separately-excited dc generator equals the current supplied to the load times another constant K_2 .

Field current I_F of a separately-excited dc generator/motor can be varied to change the strength of the field electromagnet, and thereby, the relative values of constant K_1 and K_2 . When the field current is decreased, constant K_1 decreases and constant K_2 increases, as for a separately-excited dc motor. As a result, the slope of the output voltage versus speed relationship decreases, whereas the slope of the output current versus torque relationship increases. Conversely, when the field current is increased, constant K_1 increases and constant K_2 decreases, and thereby, the slope of the output voltage versus speed relationship increases whereas the slope of the output current versus torque relationship decreases. Therefore, the output voltage E_o of a generator operating at a fixed speed can be varied by varying the field current I_F . This produces the equivalent of a dc source whose output voltage can be controlled by the field current I_F .

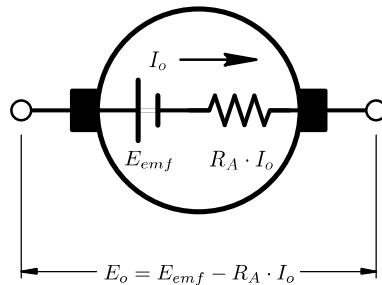


Figure 3.2: Equivalent circuit of a dc armature

The simplified equivalent electric circuit of a separately-excited dc generator is shown in Figure 3.2. It is the same as that for the dc motor, except that the direction of current flow is reversed and voltage E_{cemf} becomes E_{emf} which is the voltage induced across the armature winding as it rotates in the magnetic flux produced by the stator electromagnet. When no load is connected to the dc generator output, the output current I_o is zero and the output voltage E_o equals E_{emf} .

In this lab, we will see that when a generator turns at a fixed speed, armature resistance causes the output voltage E_o to decrease with increasing output current, I_o (electrical load). The output voltage E_o can be calculated using the following equation:

$$E_o = E_{emf} - R_A \cdot I_o$$

where E_o is the dc generator output voltage, E_{emf} is the voltage induced across the armature winding, R_A is the armature resistance, and I_o is the dc generator output

current.

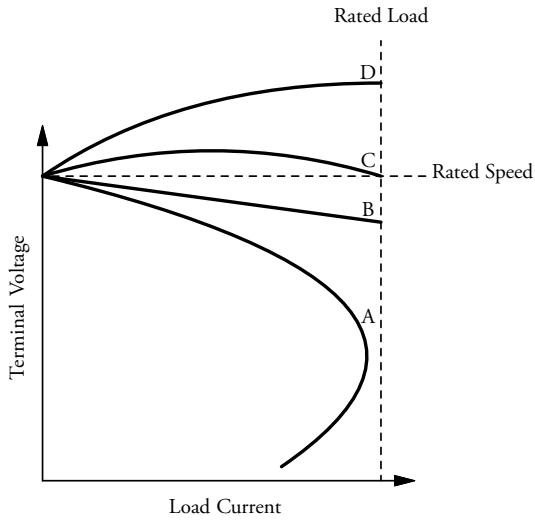


Figure 3.3: Voltage vs. load current: D overcompounded, C Flat Compounded, B, Separately Excited, A – shunt.

Figure 3.3 is a graph that shows the voltage versus current characteristics of various types of dc generators. As can be seen, the separately-excited dc generator and the shunt generator have very similar characteristics. The difference is that the output voltage of the shunt generator decreases a little more than that of the separately-excited dc generator as the output current increases. In both cases, the output voltage decreases because the voltage drop across the armature resistor increases as the output current increases. In the shunt generator, the voltage across the shunt field winding, and thereby, the field current, decreases as the output voltage decreases. This causes the output voltage to decrease a little more.

It is possible to compensate the variation in output voltage by automatically changing the magnetic flux produced by the field electromagnet as the output current varies. The shunt and series field windings of a compound generator can be connected so that the magnetic flux increases when the output current increases. Thus the output voltage remains fairly constant and changes very little as the output current increases as shown in Figure 3.3. This type of connection results in a cumulative compound generator because the magnetic fluxes created by the two field windings add together in a cumulative manner. For other applications where the output voltage must decrease rapidly when the output current increases, the shunt and series windings can be connected so the magnetic fluxes subtract from each other, resulting in a differential compound generator.

Procedure

Effect of Prime Mover Speed

- 1. Start the PC and log into your account.

- 2. Insure that the Power Supply, Prime Mover, DC Generator, Resistive Load Module, and Data Acquisition interface modules are installed in the EMS Workstation, and that the Generator is mechanically coupled to the Prime Mover with the timing belt. For this lab, we will be using a dc motor as the prime mover.
- 3. Make sure that the **main power switch is off**, and the voltage control knob is turned fully ccw. Set the voltmeter select switch to the 7-N position.
- 4. Insure that the USB cable connects the DAI to the computer. Connect the torque and speed data cables from the Dynamometer to the DAI. Connect the DAI and Dynamometer to the 24 V ac power supply with the grey cables, and turn it on. Leave power on the DAI for the entire exercise.
- 5. Launch the metering program and config file *Lab 3 DC Generators* from the E: drive. When prompted, choose 120 V and 60 Hz.

Important: The display should show **READY** in the status bar at the bottom of the screen.

This should set up the meters to display:

Meter	Display
E1	Armature Voltage, E_A , DC Volts
I1	Output Current, I_o , DC Amps
I2	Field Current, I_f , DC Amps
AI-7/T	Torque, T , N-m
AI-8/N	Speed, n , rpm

Meter T indicates the torque *produced* by the Generator. When the generator is consuming torque this value is negative.

- 6. Set the Prime Mover/Dynamometer controls as follows:
MODE = Prime Mover (P.M.), **DISPLAY** = Speed (N), and **Load Control** = Manual.
- 7. Build the circuit shown in the Figure 3.4. Notice that the prime mover is supplied from the *Variable DC* source, there is no electrical load on the generator, and that meter E1 measures the generator terminal voltage E_A .
- 8. Turn on the power and adjust the *field rheostat* to produce 300 mA field current.
- 9. Set up a *data table* to record generator output voltage, E_A , field current I_f , torque T , and speed n . You can just accept the default selection, which will record all these values and others.
- 10. Adjust the generator speed from 0 to 1800 rpm in roughly 150 rpm increments with the *voltage control knob*. For each speed setting, record the data in the *data table*.
- 11. Click on the *graph* button and make the appropriate settings to produce a graph of generator output voltage as a function of speed.

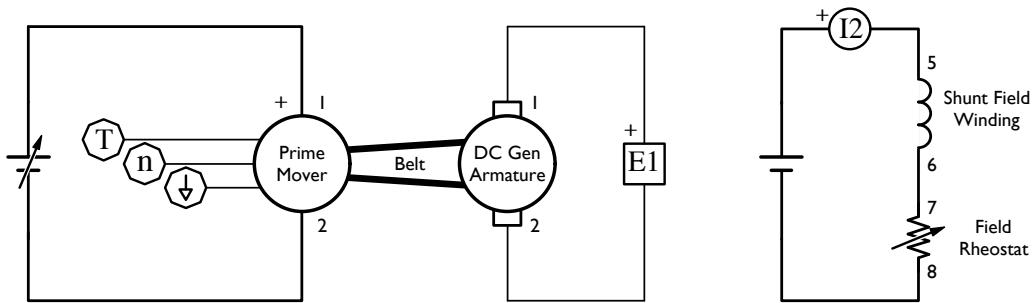
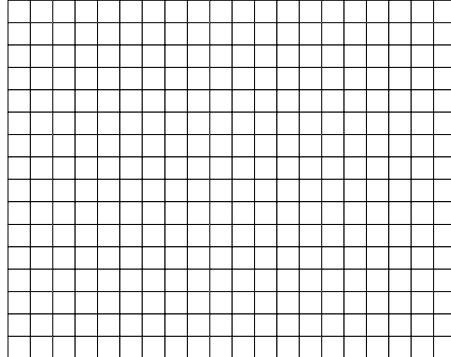


Figure 3.4: Separately Excited DC Generator

12. Describe the relation between voltage and speed mathematically.

13. Sketch the graph here.



Effect of Field Excitation

14. Adjust the voltage control knob to bring the prime mover to approximately 1800 rpm.
15. How much voltage does the generator produce at 1800 rpm?

$$E_A = \underline{\hspace{2cm}} \text{ V}$$

16. Now unplug one of the field circuit connections to bring the excitation current to zero. How much voltage does the generator produce now?

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

Does the generator produce significantly less voltage without field excitation?

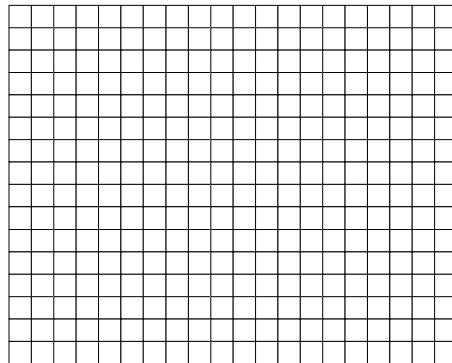
Yes No

Why?

How is the generator able to produce *any* voltage with the field circuit disconnected?

17. Reconnect the field circuit and adjust the *field rheostat* so that the field current I_f is around 300 mA, while observing the output voltage. Describe the sequence of events that causes the voltage to change when you change the position of the field rheostat.
-
-
-

18. Set up a *data table* to record generator output voltage, E_A , field current I_f , torque T , and speed n . You can just accept the default selection, which will record all these values and others.
19. Record the voltage you measured in Step 16. along with an excitation current of 0 A in the first line of your data table.
20. While operating at 1800 rpm, move the *field rheostat* from fully ccw to fully clockwise in about 8 steps while taking care not to exceed the field circuit current rating of 400 mA for more than a few seconds. For each setting, record the data in the *data table*. Note that for this part of the experiment the generator is not loaded.
21. Click on the *graph* button and make the appropriate settings to produce a graph of generator output voltage as a function of field current. Sketch the graph here.



22. Turn the voltage control knob fully CCW to stop the prime mover.

Behavior under load

23. With the power off, modify the connections to add a resistive load R_L across the generator output as shown in Figure 3.5. Use all nine resistors of the *resistive load*

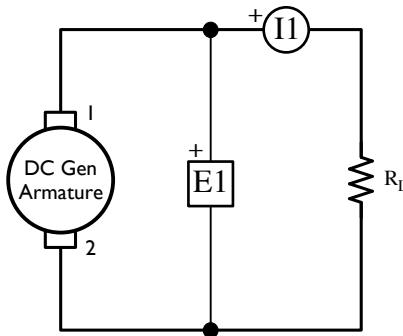


Figure 3.5: DC Generator Armature Circuit, with Load

module connected in parallel to implement resistor R_L . Meter I1 measures the load current I_o .

- 24. Turn on the Power Supply, and adjust the voltage control knob so that the generator operates at its *nominal speed*, then adjust the field current I_f using the *field rheostat* until the generator is producing its nominal voltage.
- 25. Set up a *data table* to record generator output voltage E_A , load current I_o , field current I_f , torque T , and speed n , indicated by meters E1, I1, I2, T, and N respectively. You can just accept the default selection, which will record all these values and others.
- 26. Set the switches on the *resistive load module* so that the load resistance R_L decreases in steps as indicated in the table. For each step, readjust the *voltage control knob* so that the generator speed remains equal to the nominal speed, then record the data in the data table.

Step	1	2	3	4	5	6	7	8	9
R_L	∞	1200 Ω	600 Ω	300 Ω	171 Ω	120 Ω	86 Ω	71 Ω	57 Ω

Is step 1 the full load or no load?

Full Load No Load

- 27. When all the data has been recorded, turn the voltage control fully ccw, and **turn off the power**.
- 28. In the graph window make the appropriate settings to obtain a graph of the Torque T required to drive the generator as a function of dc generator load current I_o .
- 29. Does the graph show that the absolute value of the torque increases as the load increases? Yes No
- 30. Why isn't the torque zero when the load is zero?

Hint Do you know what *nominal* means? If not, look it up!

Hint You can refer to the appendix to find out what combination of switches is needed to produce these resistance settings.

-
-
- 31. In the graph window make the appropriate settings to obtain a graph of the generator voltage E_A as a function of the separately excited generator load current I_o .

Hint Do not delete your data table. You will need it in the next part.

Self Excited Shunt Generator

32. With the power off, disconnect the field circuit from the dc power supply and plug it in to the armature terminals, while maintaining the same polarity, as shown in Figure 3.6.

You have just turned your *separately-excited* generator into a *shunt* connected *self-excited generator*. In a self-excited generator, the voltage to excite the field comes from the generator itself.

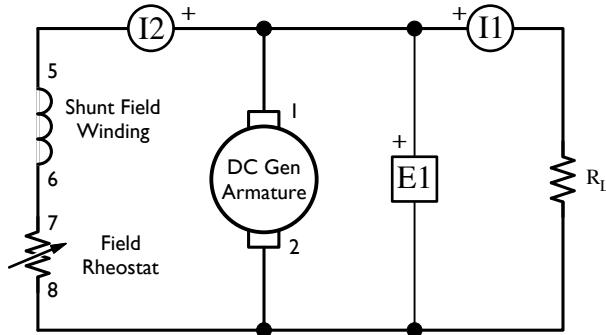


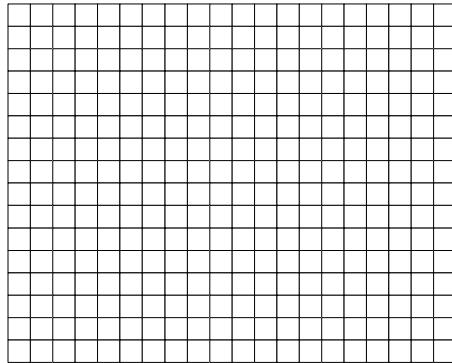
Figure 3.6: Self-excited DC Shunt Generator

33. Turn on the power supply and **adjust the generator speed and terminal voltage** to the values that are in the first line of your data table, so that the initial conditions are approximately the same as the initial conditions you used in step 26.
34. Repeat step 26 of the previous section. Continue recording your data on the same table. When you have finished, this table will contain data from both the separately-excited and the shunt generator as load is increased while maintaining constant speed.
35. Open the graph window again, and it should show the behavior of both the separately-excited and the shunt generator as load is increased while maintaining constant speed.

Compound Generator

36. A **Compound Generator** is a generator with both *Series* and *Shunt* fields. A shunt field is wired in parallel with the load, while a series field is wired in series with the load. Determine where you could add a series field to your existing shunt generator circuit, and sketch it on your circuit diagram, then show your plan to your instructor.
37. With the power off, add the series winding (terminals 3 and 4 on the DC Motor/Generator) in the position you selected.
38. Turn on the power supply and adjust the generator speed and terminal voltage to the same values as before.
39. Repeat step 26 of the previous section. Continue recording your data on the same table. When you have finished, this table will contain data from the separately excited, self-excited and compound generators.

- 40. Open the graph window again, and it should show the behavior of three different types of DC Generators as load is increased at constant speed.
- 41. Sketch and label the graph here.



- 42. Which configuration produces the best voltage regulation?
-

- 43. Turn off the power, shut down the computer, and put everything away.

Conclusion

In this exercise, you plotted graphs of the main operating characteristics of a separately-excited dc generator. You observed that the output voltage increases linearly with speed. You also observed that the output current increases linearly with the input torque. You saw that the slopes of these graphs can be adjusted by changing the field current and that this allows the generator's output voltage to be changed. You observed that the output voltage decreases as the load current increases.

You also compared the voltage versus current characteristics of a shunt generator with that of the separately-excited generator and with a compound generator. You observed that the output voltage of the shunt generator decreases more rapidly than that of the separately-excited dc generator when the output current increases, and that the compound generator has flattest voltage behavior.

Lab 4

Induction Motors

Introduction

Objective

When you have completed this exercise you will be able to demonstrate the operating characteristics of a three-phase induction motor using the Four-Pole Squirrel-Cage Induction Motor module. You will see how three-phase power is used to create a rotating magnetic field, which is used to develop a torque in an induction motor. You will next demonstrate how a capacitor can be used to develop a rotating field when used with single-phase ac supply. Finally you will observe the main operating characteristics of single-phase induction motors using the Capacitor-Start Motor module.

Three-Phase Squirrel Cage Induction Motor

According to Faraday's principle, a voltage is induced between the ends of a wire loop when the magnetic flux linking the loop varies as a function of time. If the ends of the wire loop are connected, a current flows in the loop. When current flows in a circuit, a magnetic field is created. It is the interaction of these two magnetic fields that creates the force which rotates an electric motor.

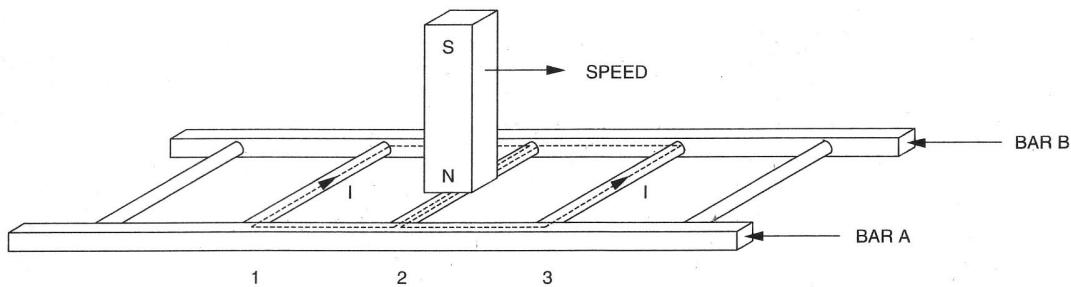


Figure 4.1: Magnet Moving above a Conducting Ladder

To begin this discussion, consider arrangement shown in Figure 4.1, where a magnet is displaced towards the right above a group of conductors shaped like a ladder. The conductors are short-circuited at their extremities by rungs A and B. Induction causes

current to flow in the loop formed by conductors 1 and 2, conductors 2 and 3, etc. These currents themselves produce magnetic fields with north and south poles as shown in Figure 4.2. The interaction between the magnetic field of the magnet and the magnetic fields produced by the currents induced in the ladder creates a force that causes the ladder to be pulled along in the direction of the moving magnet.

However, if the ladder moves at the same speed as the magnet, there is no longer a variation in the magnetic flux. Consequently, there is no induced voltage to cause current flow in the wire loops, meaning that there is no longer a magnetic force acting on the ladder. Therefore, the ladder must move at a speed which is lower than that of the moving magnet for a magnetic force to pull the ladder in the direction of the moving magnet. The greater the speed difference between the two, the greater the variation in magnetic flux, and therefore, the greater the magnetic force acting on the conducting ladder.

The rotor of an asynchronous induction motor is made by closing a ladder similar to that shown in Figure 4.1 upon itself to form a shape known as a *squirrel cage* as shown in Figure 4.3. This is where the name squirrel-cage induction motor comes from. To make it easier for the magnetic flux to circulate, the squirrel-cage is embedded inside a laminated iron rotor. The stator of the induction motor is made of three electromagnets A, B, and C, placed at 120° to one another as shown in Figure 4.4. When the stator is connected to a three-phase ac power source, so that the phase currents are shifted by 120° from each other as shown in Figure 4.5, a *rotating magnet field* is created. The rotating field causes a torque which pulls the rotor along in the same direction as the rotating field, in much the same manner as the moving magnet in Figure 4.1 pulls the ladder.

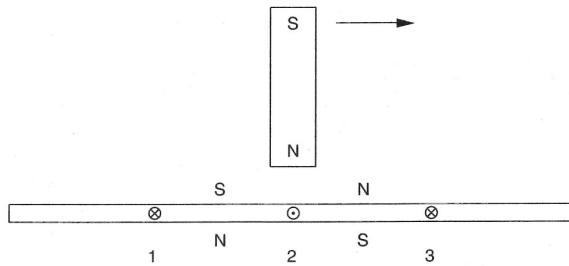


Figure 4.2: Currents in the Conductors Creates Magnetic Fields

Figure 4.6 illustrates the magnetic field created by stator electromagnets A, B, and C at instants numbered 1 to 6 in Figure 4.5. Notice that the magnetic lines of force exit at the north pole of each electromagnet and enter at the south pole. As can be seen, the magnetic field rotates clockwise. A simulation that can help you visualize the rotating magnetic field is available at http://www.ipes.ethz.ch/ipes/2002Feldlinien/feld_dreh.html.

The use of sine-wave currents produces a magnetic field that rotates regularly and whose strength does not vary over time. The speed of the rotating magnetic field is known as the synchronous speed (n_s) and is proportional to the frequency of the ac power source, and inversely proportional to the number of poles (P).

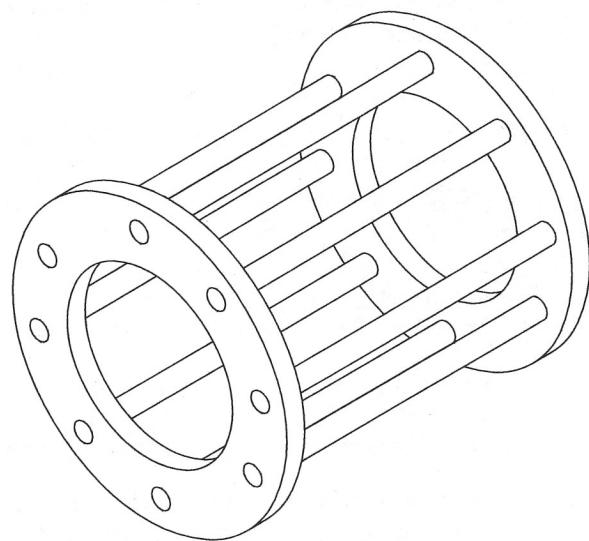


Figure 4.3: Closing the Ladder Upon Itself Forms a Squirrel Cage

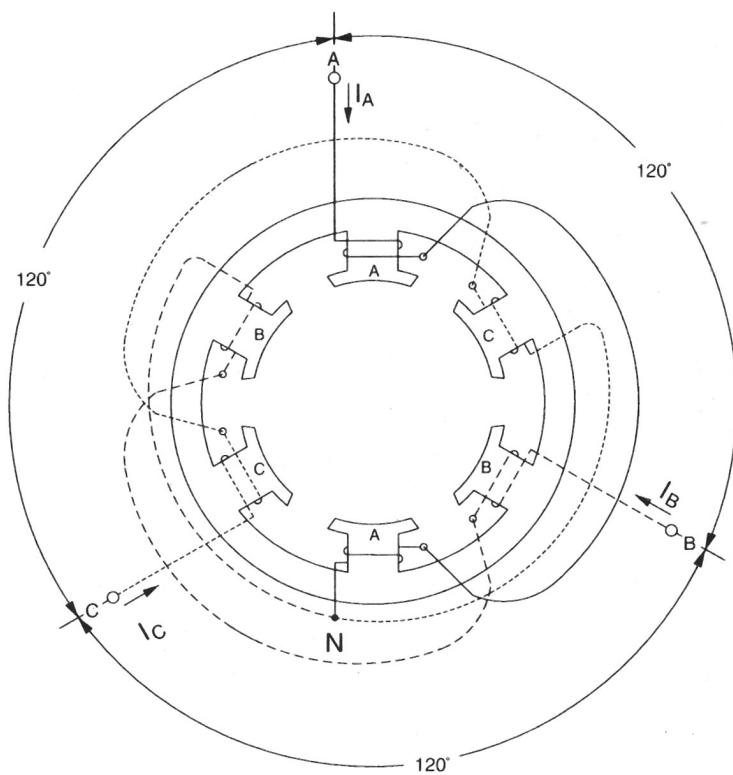


Figure 4.4: Three-phase stator windings

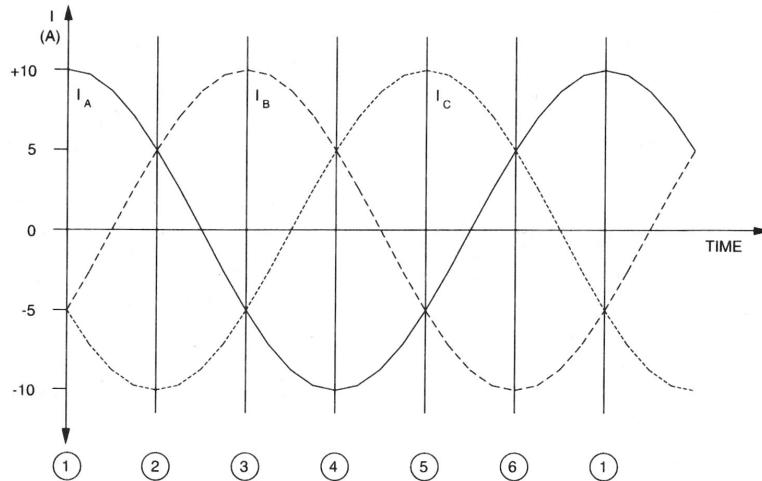


Figure 4.5: Three-phase Sine-Wave Currents Flowing in the Stator Windings

$$n_s = 120f/P$$

A rotating magnetic field can also be obtained using other combinations of sine-wave currents that are phase-shifted with respect to each other, but three-phase sine-wave currents are used more frequently.

When a squirrel-cage rotor is placed inside a rotating magnetic field, it is pulled around in the same direction as the rotating field. Interchanging the power connections to two of the stator windings (interchanging A with B for example) interchanges two of the three currents and reverses the phase sequence. This causes the rotating field to reverse direction, and as a result, the direction of rotation of the motor is also reversed.

Based on the discussion of motor action above, one can easily deduce that the torque produced by a squirrel-cage induction motor increases as the difference in speed between the rotating magnetic field and the rotor increases. The difference in speed between the two is called slip. A plot of the speed versus torque characteristic for a squirrel-cage induction motor gives a curve similar to that shown in Figure 4.7. As can be seen, the motor speed n (rotor speed) is always lower than the synchronous speed n_s because slip is necessary for the motor to develop torque. The synchronous speed for the Lab-Volt motors is 1800 r/min for 60-Hz power, and 1500 r/min for 50-Hz power.

The speed versus torque characteristic of the squirrel-cage induction motor is very similar to that of a separately-excited dc motor. However, the currents induced in the squirrel-cage rotor must change direction more and more rapidly as the slip increases. In other words, the frequency of the currents induced in the rotor increases as the slip increases. Since the rotor is made up of iron and coils of wire, it has an inductance that opposes rapid changes in current. At higher slips, the currents induced in the rotor are no longer directly proportional to the slip of the motor, and the torque begins to decrease. The torque vs. speed characteristic of the motor throughout its complete operating range are shown in Figure 4.8.

As the curve shows, the no-load speed is slightly less than the synchronous speed n_s , but as the load torque increases, the motor speed decreases. The motor's *nominal torque*

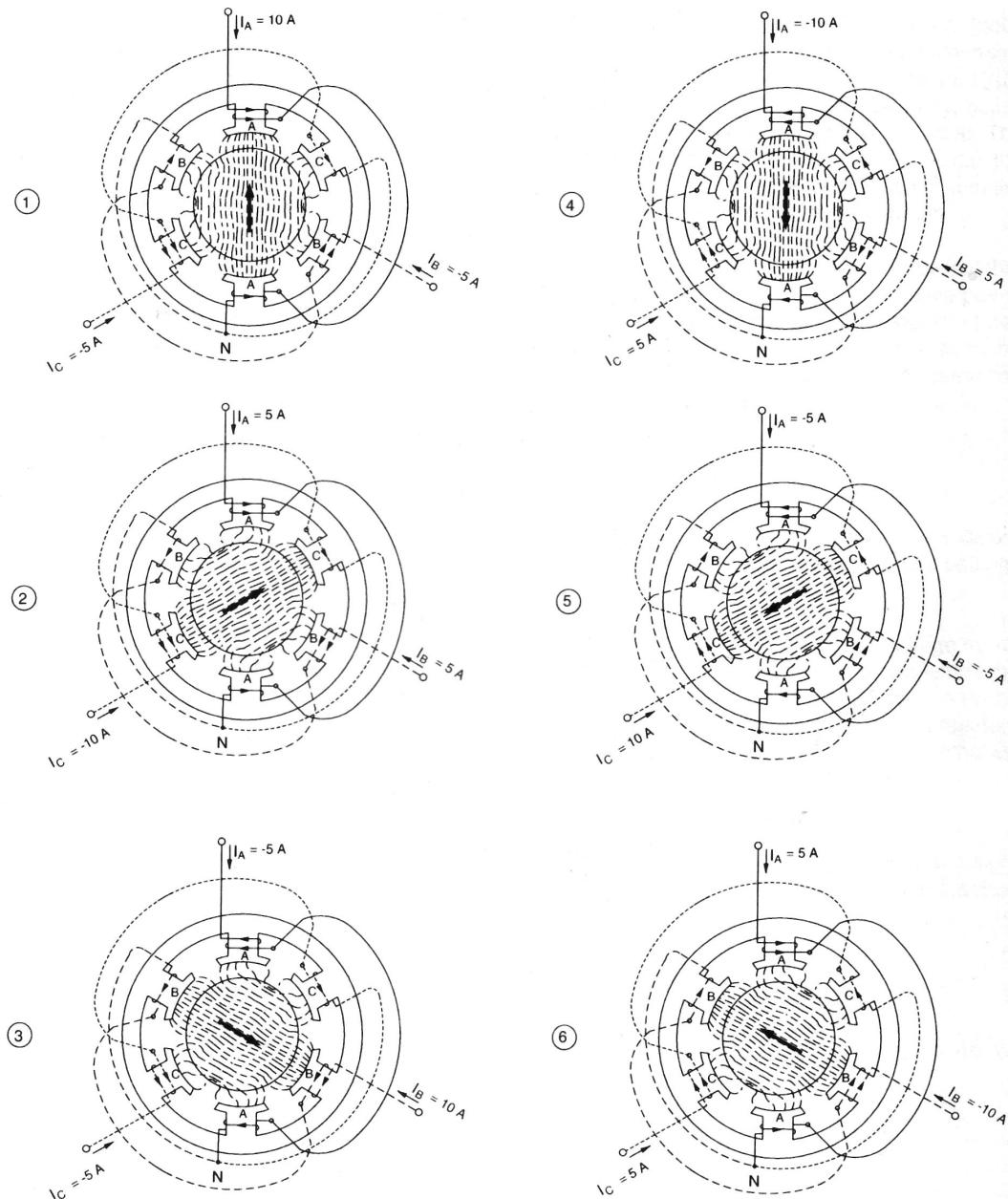


Figure 4.6: Positions of the Rotating Magnetic Field at Various Instants (From *Electrical Machines, Drives, and Power Systems* by Theodore Wildi)

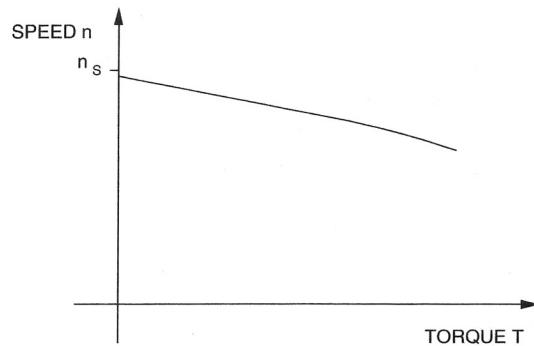


Figure 4.7: Speed vs. torque Characteristic of a Squirrel-Cage Induction Motor, in normal operating range

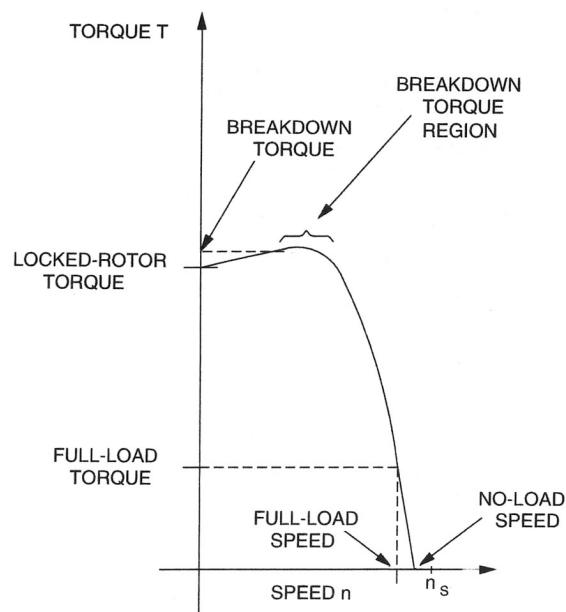


Figure 4.8: Torque vs. Speed Characteristic of a Squirrel-Cage Induction Motor

(full-load torque) is the torque produced when the motor is operating at the nominal speed. Further increases in load torque lead cause the motor to slow down slightly, and ultimately lead to a point of instability, called *breakdown torque*, after which both motor speed and output torque decrease rapidly. The torque value at zero speed, called *locked-rotor torque*, is often less than the breakdown torque. At start-up, and at low speed, motor current is very high and the amount of power that is consumed is higher than during normal operation. Motors should not be allowed to be overloaded, because this power consumption leads to high temperatures, which will damage the motor.

Another characteristic of three-phase squirrel-cage induction motors is the fact that they always draw *reactive power* from the ac power source. The reactive power even exceeds the active power when the squirrel-cage induction motor rotates without load. The reactive power is necessary to create the magnetic field in the machine in the same way that an inductor needs reactive power to create the magnetic field surrounding the inductor. Reactive power is reflected by the *power factor* of the operating motor. When a motor is lightly loaded, high reactive power combined with low active power results in a poor power factor.

Single Phase Capacitor Start Motor

It is possible to design a single-phase squirrel-cage induction motor using one electromagnet connected to a single-phase ac power source as shown in Figure 4.9, but one may wonder how this motor can turn since the single field will not be able to produce a rotating magnetic field. It can work, but the operating principle of this type of motor is more complex than that of the three-phase squirrel-cage induction motor. When the rotor of the motor of Figure 4.9 is given an initial start, a torque which acts in the direction of rotation is produced, and the motor continues to turn as long as ac power is supplied to the stator electromagnet. This torque is due to a rotating magnetic field that results from the interaction of the magnetic field produced by the stator electromagnet and the magnetic field produced by the currents induced in the rotor. A graph of speed versus torque for this type of motor, Figure 4.10, shows that the torque is very small at low speeds, and increases to a maximum value as the speed increases, and finally decreases towards zero again when the speed approaches the synchronous speed n_s .

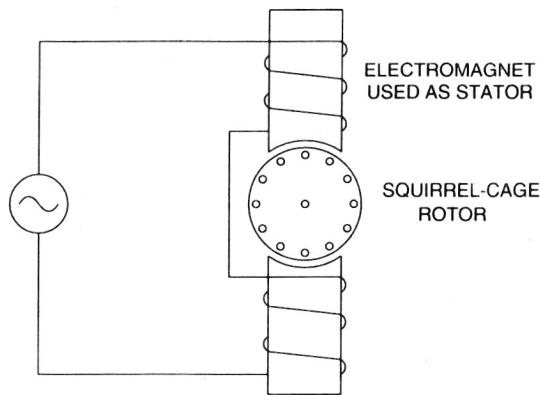


Figure 4.9: Simple Single-Phase Squirrel-Cage Induction Motor

The low torque values at low speeds are due to the fact that the currents induced in

the rotor produce magnetic fields that create forces which act on the rotor in various directions. Most of these forces cancel each other and the resulting force acting on the rotor is weak. This explains why the single-phase induction motor shown in Figure 4.9 must be started manually. To obtain starting torque, a rotating magnetic field must be produced in the stator when the motor is starting. It is possible to create a rotating magnetic field using two alternating currents, I_1 and I_2 , that are phase shifted 90° from one another, and two electromagnets placed at right angles to each other.

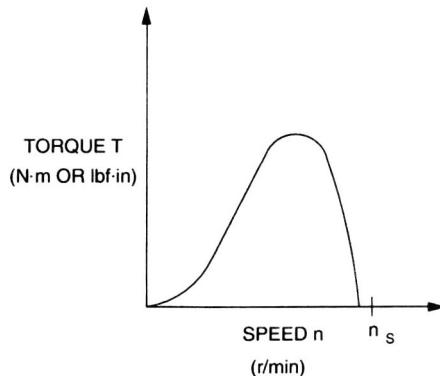


Figure 4.10: Torque vs. Speed Characteristics of a Single-Phase Induction Motor

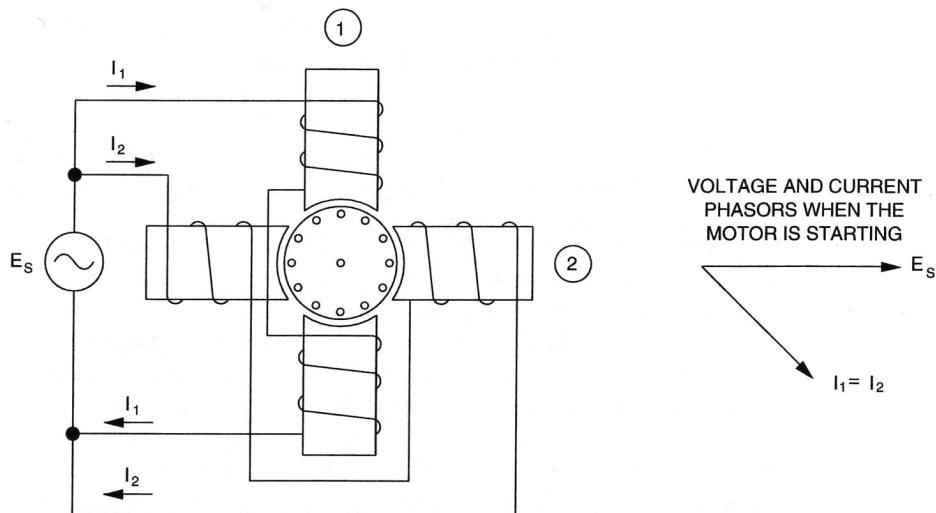


Figure 4.11: Adding a Second Electromagnet to the Simple Induction Motor of Figure 4.9

Figure 4.11 shows the simple induction motor of Figure 4.9 with the addition of a second electromagnet placed at right angle to the first electromagnet. The second electromagnet is identical to the first one and is connected to the same ac power source. The currents I_1 and I_2 in the electromagnets (winding currents) are in phase because the coils have the same impedance. However, because of the inductance of the coils of the electromagnets, there is a phase shift between the currents and the ac source voltage as illustrated in the phasor diagram of Figure 4.11.

Since currents I_1 and I_2 are in phase, there is no rotating magnetic field produced in

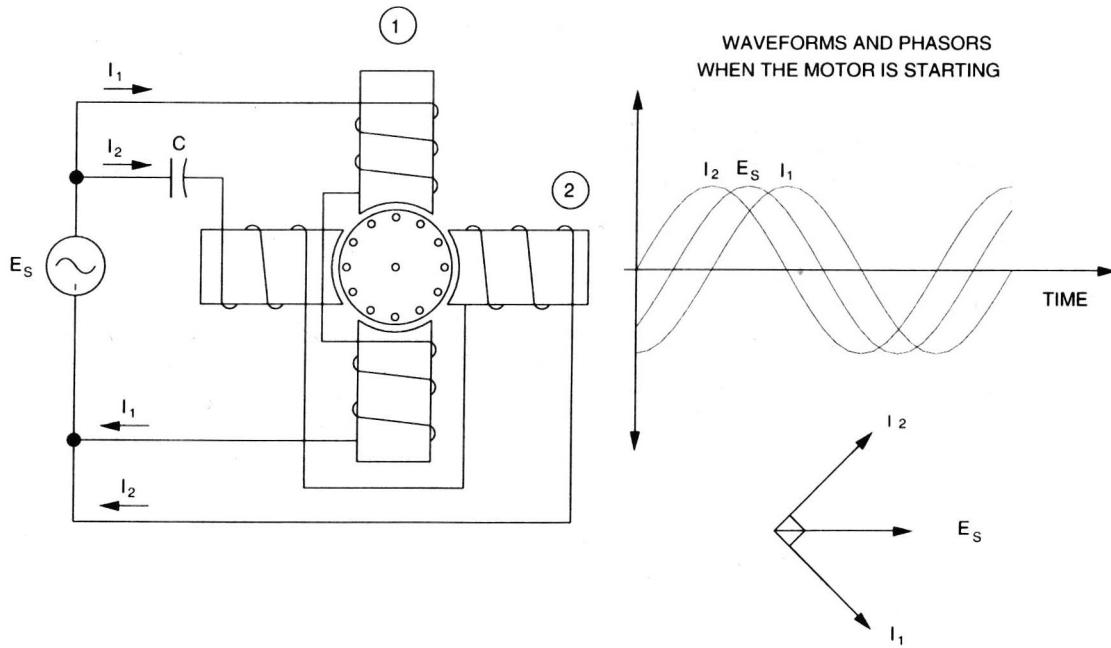


Figure 4.12: Adding a Capacitor allows the Induction Motor to Develop Starting Torque

the stator. However, it is possible to phase shift current I_2 by connecting a capacitor in series with the winding of electromagnet 2. The capacitance of the capacitor can be selected so that current I_2 leads current I_1 by 90° when the motor is starting as shown in Figure 4.12. As a result, an actual rotating magnetic field is created when the motor is starting. The capacitor creates the equivalent of a two-phase ac power source and allows the motor to develop starting torque.

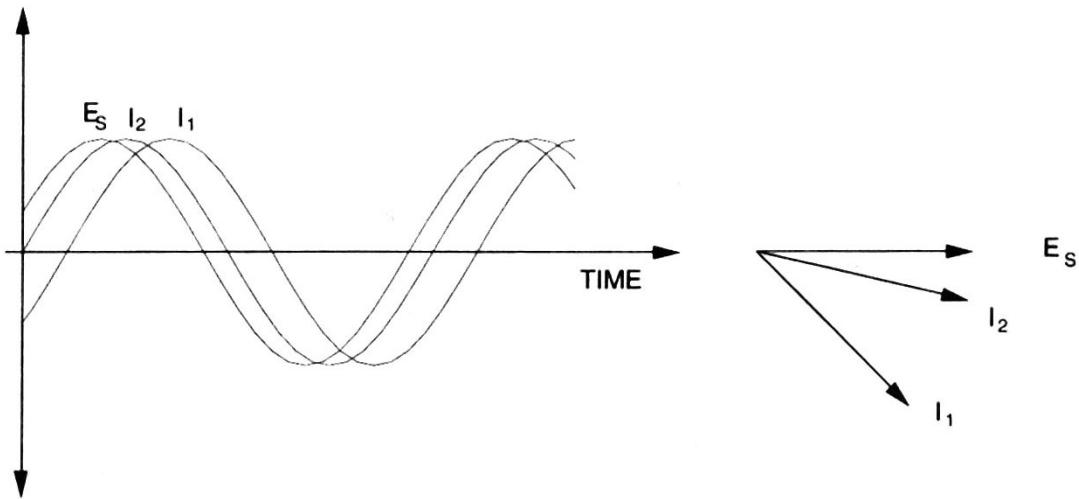


Figure 4.13: Phase Shift Between the Winding Currents when an Auxiliary Winding is Used

Another way to create a phase shift between currents I_1 and I_2 is to make a winding with fewer turns of smaller-sized wire. The resulting winding, which is called auxiliary

winding, has more resistance and less inductance, and the winding current is almost in phase with the source voltage. Although the phase shift between the two currents is less than 90° when the motor is starting, as shown in Figure 4.13, a rotating magnetic field is created. The torque produced is sufficient for the motor to start rotating in applications not requiring high values of starting torque.

However, the auxiliary winding cannot support high currents for more than a few seconds without being damaged because it is made of fine wire. It is therefore connected through a centrifugal switch which opens and disconnects the winding from the motor circuit when the motor reaches about 75% of the normal speed. After the centrifugal switch opened, the rotating magnetic field is maintained by the interaction of the magnetic fields produced by the stator and the rotor.

Procedure

Three-phase Squirrel Cage Induction Motor

- 1. Start and log in to the PC.
- 2. Ensure that the Power Supply, Prime Mover/Dynamometer, Four-pole Squirrel Cage Induction Motor, Capacitor Start Motor, and Data Acquisition Interface are installed in the EMS. Set the voltmeter switch on the power supply to 4–5.
- 3. Make sure that the main power is off and that the voltage control knob is turned fully ccw.
- 4. Connect the DAI to the computer with the USB Cable, and to the 24 V ac power source with the gray cable, and turn on the 24 V power.
- 5. Start the metering application and select meter configuration file *Lab 4 AC Motors* from the E: drive. When prompted, choose 120 V and 60 Hz.

Important: The display should show **READY** in the status bar at the bottom of the screen.

This will configure the meters to display:

Meter	Measurement	Unit
E1, E2	Line Voltage	AC Volts
I1, I2, I3	Line Current	AC Amps
AI-7/T	Torque	N-m
AI-8/n	Speed	r/min
Pm	Mechanical Power	Watt
PQS1 + PQS2 (P)	Active Power	Watt
PQS1 + PQS2 (Q)	Reactive Power	Var
PF(EI1, EI2)	Power Factor	Unitless
Pm/(P1+P2)	Efficiency	%

Hint The three stator windings must be wye-connected in order for the motor to work!

6. Connect the squirrel cage motor to the variable ac power supply as shown in Figure 4.14. Use the high current (40 A) connection for the Ammeter. Connect the motor to the dynamometer with the timing belt, and connect the data cables for torque and speed to the the DAI.

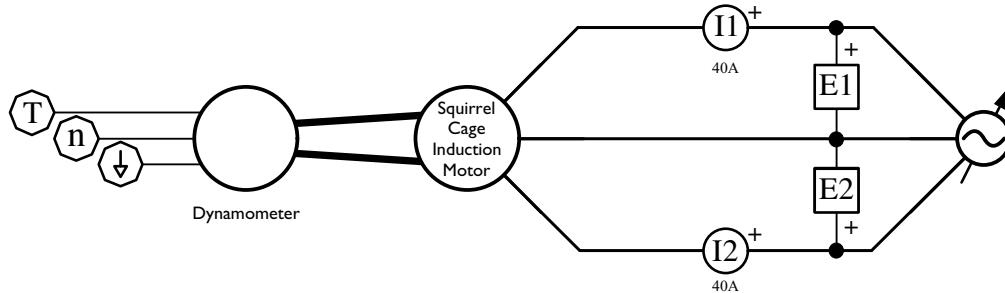


Figure 4.14: Three-Phase Squirrel Cage Induction Motor Circuit

The dynamometer measures to output torque of the squirrel-cage induction motor and displayes it on Meter T. Active and reactive electrical power are calculated by the two wattmeter method using I1, I2, E1, and E2. Mechanical Power is calculated from torque and speed. A positive power indicates the device is producing power and negative value indicates consumption.

$$P_m = T\omega = T \left(\frac{2\pi n}{60} \right)$$

7. Set the Dynamometer controls as follows:

- Mode switch to **DYN**
- Load Control Mode switch to **Manual**
- Load Control knob to **minimum**
- Display switch to **Torque**

8. **Turn on the Power** supply and set the voltage control knob so that the line voltage, E1, is equal to the motor's nominal line voltage, and adjust the load control knob fully CCW. Record the no-load speed, current, torque, and direction of the motor, then **turn off the power**.

$n_{nl} = \underline{\hspace{2cm}}$ rpm

cw ccw

$I_{nl} = \underline{\hspace{2cm}}$

$T_{nl} = \underline{\hspace{2cm}}$

9. Interchange any two of the three-phase power and **restart the motor** as before. Record the no-load speed and direction, then **turn off the power** and restore the leads to their original positions.

$n_{nl} = \underline{\hspace{2cm}}$ rpm

cw ccw

Hint You can find the nominal ratings of the motor on its name plate on the motor front panel.

Does interchanging any two leads of a three-phase motor reverse it? Yes No

10. Calculate the synchronous speed of this motor knowing that it is supplied with 60 Hz three-phase alternating current. This is the speed of the rotating magnetic field.

$$n_s = \frac{120f}{P} = \text{_____ rpm}$$

Is the no-load speed almost equal to the speed of the rotating magnetic field?

Yes No

11. Calculate the % slip when the motor is unloaded.

$$\% \text{ slip} = \frac{n_s - n}{n_s} \cdot 100\% = \text{_____}$$

12. When the motor is supplied with its *nominal voltage* and producing its *nominal power*, it will also, by definition, be running at its *nominal speed*, drawing its *nominal current* and producing its *nominal torque*.

Turn on the motor and adjust the voltage to the nominal value. Then use the load control knob of the dynamometer to set the motor load to its nominal value

13. Record the nominal speed, current, torque and power below

$$n_{nom} = \text{_____}$$

$$I_{nom} = \text{_____}$$

$$T_{nom} = \text{_____}$$

$$P_{nom} = \text{_____}$$

Do the nominal values just determined generally agree with the values on the motor nameplate? Yes No

14. Turn off the motor.

Loaded Behavior

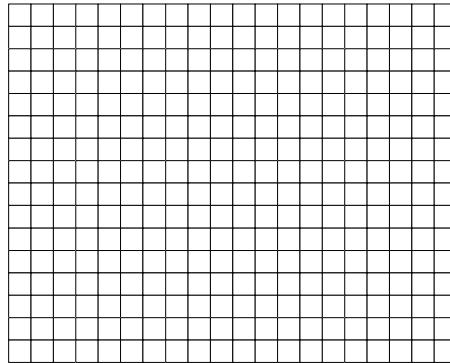
IMPORTANT Do not let the motor run in the stalled condition any longer than necessary. The motor current will be excessively high which can cause motor overheating and damage.

15. Set up a *data table* to record motor line voltage E_l , line current I_l , torque T , and speed n , active power P , reactive power Q , and Power Factor pf , indicated by meters E1, I1, T, N, A, C and D respectively. You can just accept the default selection, which will record all these values and others.
16. **Turn on the power** and adjust the voltage to the nominal value. Set the load to zero by turning the *load control knob* fully ccw, then record the data in the data table.

Increase the *load control knob* so that the torque on the motor increases by approximately 0.3 N-m increments up to about 1.8 N-m. For each setting, record the data in the data table.

At this point, continue increasing the load using smaller increments, until the motor passes the *breakdown torque* region, and slows rapidly to its minimum speed, around 300 rpm. For each additional torque setting record the data.

- 17. **Turn off the power** and return the *load control knob* to the minimum load position.
- 18. In the graph window, make a graph of motor torque T , as a function of motor speed n , and sketch the graph here:



- 19. From the graph, determine the following values:

No load Torque _____ No Load Speed _____

Nominal Torque _____ Nominal Speed _____

Breakdown Torque _____ Breakdown Speed _____

Locked Rotor Torque _____ Locked Rotor Speed _____

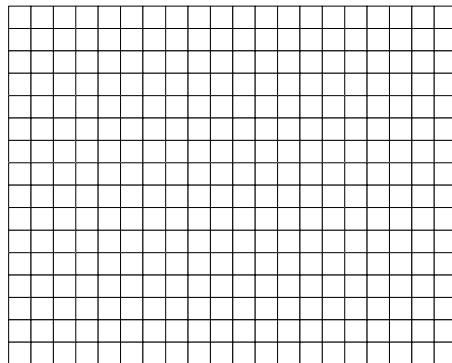
Hint Since this motor never completely stops, use the minimum speed measurements to represent the locked rotor values.

- 20. Describe how the motor speed varies as load is applied to the motor.

- 21. Calculate the ratio of the breakdown and locked rotor torques to the nominal torque.

$$\frac{T_{BD}}{T_{Nom}} = \underline{\hspace{2cm}} \quad \frac{T_{LR}}{T_{Nom}} = \underline{\hspace{2cm}}$$

22. In the graph window using this same data, make a graph of motor line current I_L as a function of speed n , and sketch the graph here:



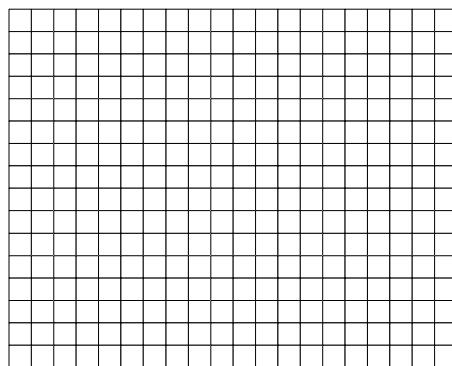
23. Describe how the motor line current varies as load is applied to the motor.

24. Calculate the ratio of the locked rotor current to the nominal line current.

$$\frac{I_{LR}}{I_{Nom}} = \underline{\hspace{2cm}}$$

In a typical induction motor the the starting current is 5–7 times greater than the normal running current. Is that true for this motor? Yes No

25. In the graph window using this same data, make a graph of motor active power P , and reactive power Q as a function of speed n , and sketch the graph here:



Does the graph indicate that the squirrel-cage induction motor always draws reactive power? Yes No

Does the graph indicate that the motor draws more electrical power as the load increases? Yes No

What does the graph reveal about the power factor of the motor when it is unloaded?

Single Phase Motors

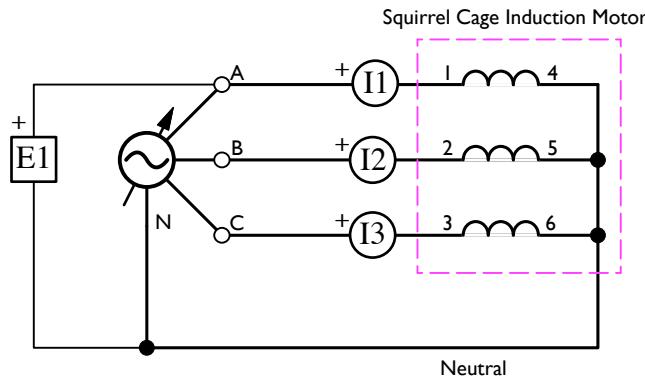


Figure 4.15: Three-Phase Motor – Three Phases

In this section you will be experimenting to determine how many phases are required to start and run an induction motor.

Important: AC motors draw excessive current when they are stalled or operating at reduced voltage, so it's best to turn the rheostat up quickly, and then turn it down quickly if the motor does not start.

- 26. Remove the belt that couples the three-phase squirrel cage induction motor to the dynamometer, and construct the circuit shown in Figure 4.15.
- 27. Set up the phasor analyzer to display I1, I2, I3, and E1 with E1 selected as the reference phasor.
- 28. Make a prediction whether you think the motor will start and run in each of the configurations in the table below. (Y = connected, N = disconnected)

A	B	C	N	start?	run?	# phases	ϕ
Y	Y	Y	Y				
Y	Y	Y	N				
Y	Y	N	Y				
Y	Y	N	N				
Y	N	N	Y				
Y	N	N	N				

- 29. Set up the power lines as indicated and test your prediction. Indicate the number of phases in operation and the phase angle between the phase currents in the ϕ column.
- 30. Turn off the Power
- 31. How accurate were your predictions? _____

32. Based on your observations, will a three phase motor start and run on two phases?
- Start** Yes No
- Run** Yes No
33. Will it start and run on one phase?
- Start** Yes No
- Run** Yes No
34. Turn off the power and disconnect the motor and meters.

Capacitor Start Motor

35. Construct the capacitor start motor circuit shown in Figure 4.16.

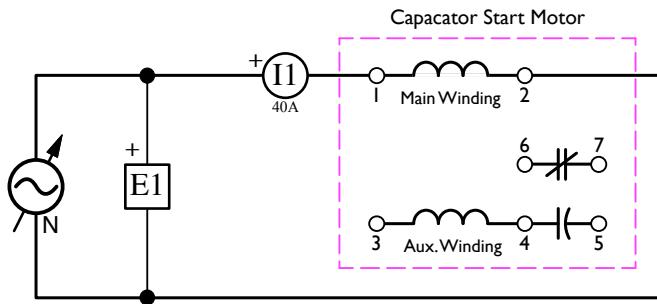


Figure 4.16: Capacitor Start Motor – Main Winding Only

36. Turn on the power and set the voltage control knob to about 10%.
37. In the *Phasor Analyzer* window, select proper sensitivities to observe voltage phasor E1 and current Phasor I1. Use E1 as the *reference phasor*. Observe that the current phasor I1 lags voltage phasor E1 due to the inductive properties of the main winding.
38. On the Power Supply, set the voltage control knob to the 50% position. Does the capacitor-start motor start to rotate? Yes No
39. **Turn off the power supply** and set the voltage control knob to zero. Connect the auxiliary winding of the Capacitor-Start Motor as shown in Figure 4.17.
40. Turn on the power and slowly set the voltage control knob to about 10%. Observe current phasors I1 and I2 in the *Phasor Analyzer* window.
- Is the phase shift of current phasor I2 (auxiliary winding) with respect to voltage E1 less than that of current phasor I1 (main winding), thus confirming that the impedance of the auxiliary winding is more resistive and less inductive than the main winding when the motor is starting? Yes No
- Is the phase shift between current phasors I1 and I2 less than 90°? Yes No
41. On the power supply, set the voltage control knob to the 50% position. Does the capacitor-start motor start to rotate? Yes No
42. **Turn off the power** and turn the voltage control knob fully counterclockwise. Modify the capacitor-start motor circuit by connecting the capacitor on the Capacitor-

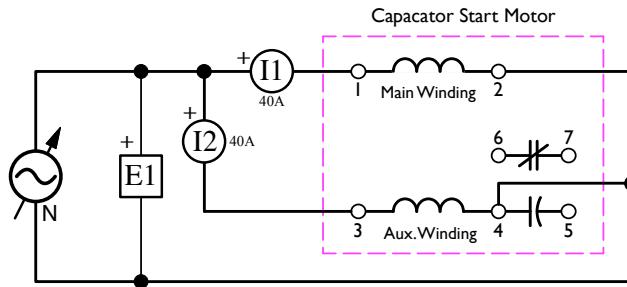


Figure 4.17: Capacitor Start Motor – Main and Auxiliary Winding

Start Motor module in series with the auxiliary winding as shown in Figure 4.18.

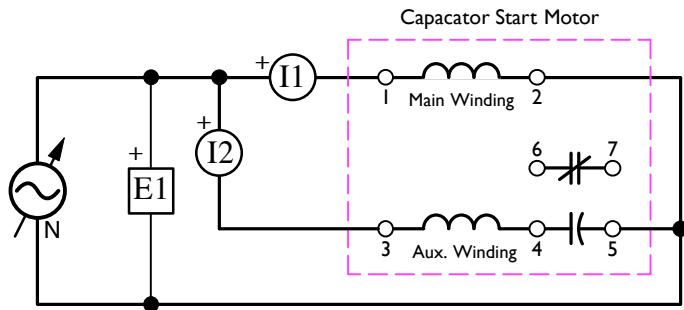


Figure 4.18: Capacitor Start Motor – Main and Auxiliary Windings, and Capacitor

- 43. Turn on the Power and slowly set the voltage control knob to about 10%. Observe current phasors I1 and I2 in the phasor analyzer window.
Does connecting a capacitor in series with the auxiliary winding create a phase shift of approximately 90° between current phasors I1 and I2? Yes No
- 44. On the power supply, set the voltage to knob to the 50% position. Does the capacitor-start motor start to rotate? Yes No
- 45. Let the motor operate for a few minutes while observing current phasors I1 and I2 in the phasor analyzer window.

$$I1 = \underline{\hspace{2cm}} \quad I2 = \underline{\hspace{2cm}}$$

What happens after a few minutes? Why?

- 46. **Turn off the power** and turn the voltage control knob fully counterclockwise. Open the front cover of the capacitor-start motor module and reset the tripped circuit breaker.

Modify the capacitor-start motor circuit by connecting the *centrifugal switch* on the Capacitor-Start motor module in series with the auxiliary winding and the capacitor as shown in Figure 4.19.

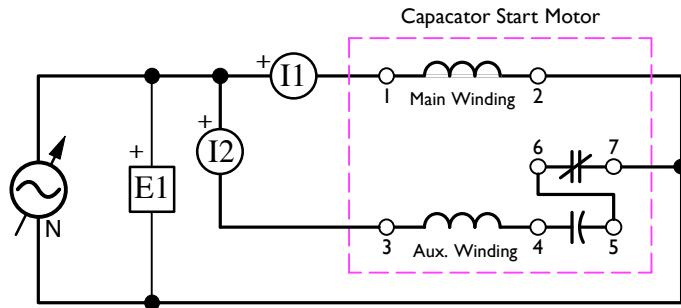


Figure 4.19: Capacitor Start Motor – Main and Auxiliary Windings, Capacitor, and Centrifugal Switch

47. Turn on the power and slowly set the voltage control knob to 100%. While doing this, observe phasors I1 and I2 in the phasor analyzer window as the voltage increases.

Does the capacitor-start motor start and run? Yes No

Briefly explain why the current phasor I2 disappears shortly after the motor has started.

48. Make the necessary wiring changes to operate the motor in the reverse direction.
49. Turn off the power and remove the Capacitor-Start Motor module from the EMS, and inspect the centrifugal switch.
50. Replace the Capacitor-Start Motor Module, reinstall the timing belt, shut down the computer and put everything away.

Conclusion

In this exercise, you observed a three-phase squirrel cage induction motor and saw that when the nominal line voltage is applied to the stator windings of an unloaded motor, the rotor turns at approximately the same speed as the rotating magnetic field (synchronous speed). You saw that interchanging any two of the three leads supplying power to the stator windings reverses the phase sequence, and thereby, causes the motor to rotate in the opposite direction. You observed that the motor line currents increase as the mechanical load increases, thus showing that the squirrel-cage induction motor requires more electric power to drive heavier loads. You plotted a graph of speed versus torque and used it to determine the nominal, breakdown, and locked-rotor torques of the squirrel-cage induction motor. You also plotted a graph of the motor reactive power versus speed and observed that the squirrel-cage induction motor draws reactive power from the ac power source to create its magnetic field. Finally, you plotted a graph of the

motor line current versus speed and observed that the starting current is many times greater than the nominal line current.

Next, you observed that a three-phase squirrel-cage induction motor starts and runs almost normally when powered by only two phases of a three-phase ac power source, because a rotating magnetic field is maintained. However, you saw that when only one phase is connected to the motor, there is no rotating magnetic field and the motor is not able to start rotating. You demonstrated that adding an auxiliary winding and a capacitor to an induction motor allows it to start and run normally when powered by a single-phase ac power source. You saw that this produces two currents (the main- and auxiliary-winding currents) that are phase shifted of approximately 90° , and that these currents produce the necessary rotating magnetic field when the motor is starting. Finally, you observed that a centrifugal switch is used to disconnect the auxiliary winding when the single-phase induction motor reaches sufficient speed to maintain the rotating magnetic field.

Lab 5

AC Synchronous Generators

Introduction

Objective

After completing this exercise, you will be able to demonstrate and explain the no-load characteristics and the voltage regulation behavior of of three-phase synchronous generator, using the Synchronous Motor/Generator and Prime Mover/Dynamometer modules.

No Load Operation

The *three-phase synchronous generator*, or *alternator*, produces most of the electricity used today. It is found in all electrical-power generating stations, whether they are of the hydroelectric, diesel, coal-fired, wind turbine, or nuclear type. The alternator also generates the electricity used in motor vehicles.

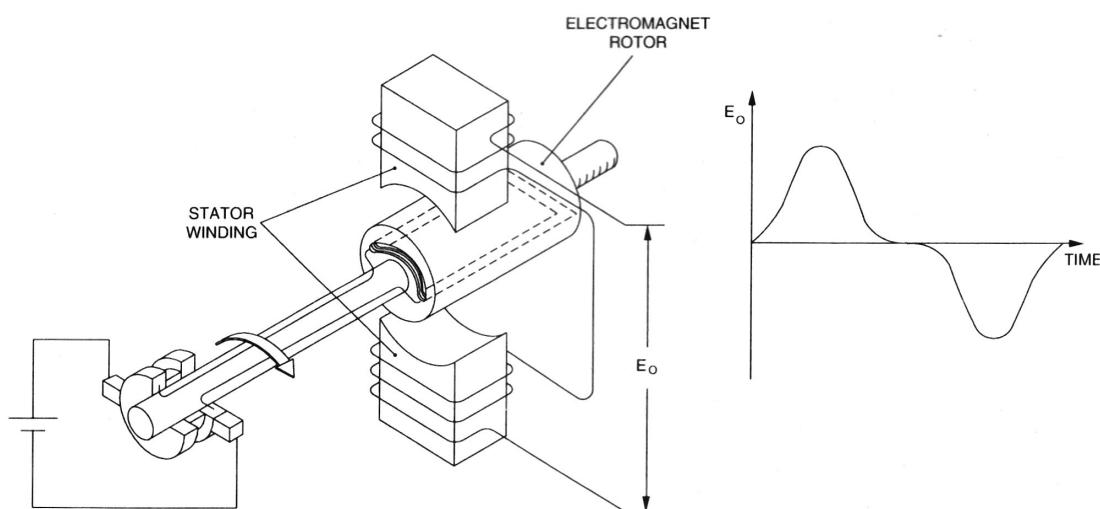


Figure 5.1: An Alternating Voltage is Produced by the Continually-Changing Magnetic Flux Linking the Stator Winding.

The basic principle of operation for alternators is quite simple and can be explained using the simplified single-phase alternator shown in Figure 5.1. An electromagnet creates a magnetic field in the rotor. The electromagnet rotor is coupled to a source of mechanical power, such as a steam turbine, to make it rotate. As a result, a continually-changing magnetic flux links the stator winding and induces an alternating voltage across the stator winding as shown in Figure 5.1.

The way the conductors are wound in the stator of a synchronous generator determines the waveform of the voltage induced across the stator winding. The stator-winding conductors in synchronous generators are usually wound in such a way that the induced voltage has a sinusoidal waveform. The stronger the rotor electromagnet, the greater the magnetic flux linking the stator windings, and the higher the alternating voltages induced across the stator windings. Furthermore, since the induced voltages are proportional to the rate of change of the magnetic flux linking the stator windings, one can easily deduce that the faster the rotor turns, the higher the amplitude of the induced voltages. In brief, the amplitude of the voltages produced by a three-phase synchronous generator is proportional to the strength of the rotor electromagnet and the rotation speed.

The stator in a three-phase synchronous generator is provided with three windings located at 120° from one another. As a result, three sine-wave voltages phase shifted by 120° with respect to each other are induced in the three stator windings. The stator of a three-phase synchronous generator is in fact very similar to the stator of a three-phase squirrel-cage induction motor shown in Figure 4.4.

There is a direct relationship between the speed of the rotor and the frequency of the voltage induced across each stator winding of a synchronous generator. When the rotor of a two-pole synchronous generator like the one shown in Figure 5.1 rotates through one revolution, it produces one voltage cycle. When it rotates at n revolutions per minute, it generates a voltage sinusoid with a frequency of n cycles per minute.

Since rotational speed is usually expressed in revolutions per minute, while frequency is usually expressed in Hz, which are cycles per second, the equation relating the speed of rotation to the frequency of the voltage produced by the synchronous generator shown in Figure 5.1 is as follows.

$$f = \frac{n \text{ [r/min]}}{60 \text{ [sec/min]}}$$

(for generators with a stator having a single pair of poles)

where f is the frequency, expressed in Hertz [Hz] and n is the speed, expressed in revolutions per minute [r/min]

However, each stator winding in large synchronous generators usually has several north and south poles instead of just a single pair as illustrated in Figure 5.1. As a result, a higher frequency is obtained for a given speed of rotation. The frequency formula can be adjusted to determine the frequency of synchronous generators, regardless of the number of pairs of north and south poles, by multiplying the speed n in the previous equation by $P/2$, where P is the number of poles per phase of the stator windings.

The equation for determining the frequency of the voltage produced by a synchronous generator is thus,

$$f = \frac{P \times n}{120}$$

(for any type of synchronous generator)

Note that the generator used in this lab has two north poles and two south poles per stator winding, thus it is known as a 4-pole generator, and P equals 4 for the Lab-Volt Synchronous Motor/Generator.

Voltage Regulation

The load on a typical generator will vary throughout the day as equipment is started and stopped. These load changes have an effect on the generator output voltage. Because many devices are sensitive to voltage changes, it is important to maintain the generator output voltage as close as possible to the correct value. The *voltage regulation* of a generator is a measure of how well the generator maintains a constant voltage under load. Voltage regulation is also known as voltage *droop*. Generator percent voltage regulation is determined by the following formula:

$$\% VR = \frac{E_{NL} - E_{FL}}{E_{NL}} \times 100\%$$

where E_{NL} is the no-load voltage and E_{FL} is the full load voltage.

The result is a percentage value which gives an indication of the generator behavior under load. The smaller the voltage regulation percentage, the less the generator output voltage varies with load. Several factors affect a generator's operation. The resistance and inductive reactance of its armature (stator) windings cause internal voltage drops that vary with the amount of current flowing to the load. If the generator is lightly loaded, current through the armature winding resistance and reactance is small, and the resulting voltage drops are also small. As the load increases, the internal voltage drops also increase.

Industrial generators include an electronic device known as a *voltage regulator* which automatically controls the generator output voltage by adjusting the field current, thus producing any desired value of voltage droop.

As seen in Lab 3 of this manual, a dc generator can be represented by the simplified equivalent circuit shown in Figure 3.2. In this circuit, the voltage E_{emf} depends on the speed at which the generator rotates and the strength of the field electromagnet. Resistor R_A represents the resistance of the armature conductors. A simplified equivalent circuit similar to that of the dc generator can be used to represent each phase of a three-phase synchronous generator. Figure 5.2 shows the simplified equivalent circuit for one phase of a three-phase synchronous generator. To represent a complete three-phase synchronous generator, three circuits like the one shown in Figure 5.2 would be used.

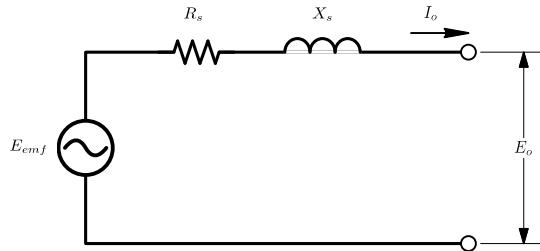


Figure 5.2: Simplified Equivalent Circuit for One Phase of a Three-Phase Synchronous Generator.

As for a dc generator, the voltage E_{emf} in the simplified circuit of the synchronous generator depends on the rotation speed as well as the strength of the electromagnet. Furthermore, there is a resistor (R_s) in the simplified circuit of the synchronous generator, as in the simplified circuit of the dc generator, that represents the resistance of the stator coil conductors. There is also an additional element in the simplified circuit of the synchronous generator, reactance X_s , which represents the inductive reactance of the stator coil conductors. Reactance X_s is known as the synchronous reactance of the synchronous generator and its value, expressed in ohms, is usually much greater than that of resistor R_s .

When the synchronous generator is operated at constant speed and with a fixed current in the rotor electromagnet (field current I_f), voltage E_{emf} is constant and the equivalent circuit for each phase is very similar to that of a single-phase transformer. Figure 5.3 shows voltage regulation characteristics (curves of the output voltage E_o versus the output current I_o) of a synchronous generator for resistive, inductive, and capacitive loads. These characteristics are very similar to those obtained with a single-phase transformer.

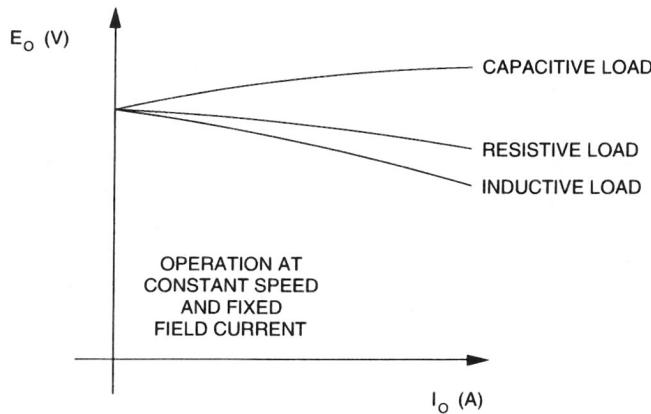


Figure 5.3: Voltage Regulation Characteristics of a Synchronous Generator.

Procedure

No Load Operation

- 1. Insure that the Power Supply, Prime Mover/Dynamometer, Synchronous Motor/Generator, Resistive Load Module and Data Acquisition Interface are installed in the EMS Workstation. Insure the USB cable connects the DAI to the computer.
- 2. Make sure that the main power switch is off, and the voltage control knob is turned fully ccw.
- 3. Connect the DAI to the 24 V ac power with the grey cable, and turn it on. Leave power on the DAI for the entire exercise.
- 4. Launch the *Metering* program, and open meter config file *Lab 5 AC Generator* to show

Meter	Measurement	Unit
E1, E2, E3	Voltage	AC Volts
I1 40 A	Line Current	AC Amps
I3 4 A	Field Current	DC Amps
AI-7/T	Torque	N-m
AI-8/n	Speed	r/min
F(E1)	Frequency	Hz

- 5. Launch the *Phasor Analyzer* and set it up to display E1, E2, and E3, with E1 as the *Reference Phasor*.
- 6. Connect the equipment as shown in Figure 5.4. Use the 4A scale for ammeter I3.
- 7. Set the Prime Mover/Dynamometer controls as follows:

Control	Position
Mode Switch	Prime Mover (P.M.)
Display Switch	Speed (N.)

- 8. Turn on the power and set the voltage control knob so that the Prime Mover rotates at the nominal speed of the Synchronous Motor/Generator.
- 9. Set the *Field rheostat* to three quarters of maximum and then close the *Exciter switch* on the Generator Module.
- 10. In the Oscilloscope window, make the appropriate settings to observe the waveforms of the phase voltages E_1 , E_2 , and E_3 induced across each of the stator windings of the synchronous generator and set the oscilloscope to *continuous refresh*.

Are the waveforms sinusoidal?

Yes No

What is the approximate phases shift ϕ between each of the voltage waveforms?

$\phi = \underline{\hspace{2cm}}^\circ$

- 11. Slowly lower and raise the speed of the prime mover with the voltage control knob. While doing this, observe the waveforms of voltages E_1 , E_2 , and E_3 in the

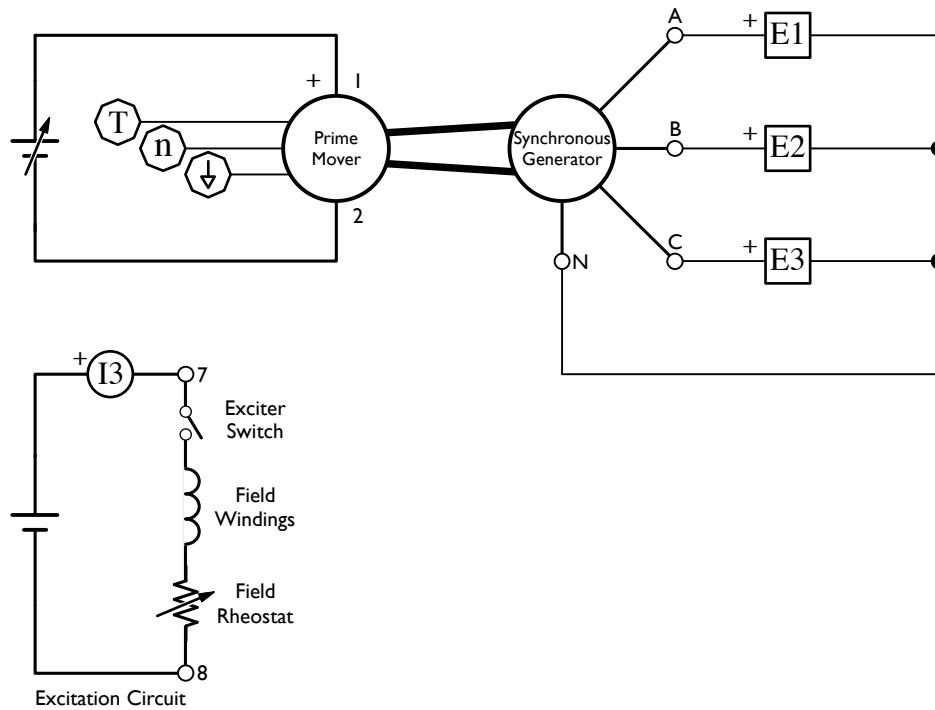


Figure 5.4: Synchronous Generator, No Load, Phase Voltages

oscilloscope window.

How do the amplitude and frequency of the voltage waveforms vary when the speed of the the synchronous generator is decreased. Briefly explain why.

The frequency produced by the Synchronous Motor/Generator follows this relationship

$$f = \frac{P \times n}{120} = \text{_____} \text{ Hz}$$

Do your observations agree with this equation? Yes No

12. Toggle the field rheostat switch open and closed and adjust the field rheostat, and while doing this, observe the waveforms of voltages E_1 , E_2 , and E_3 in the oscilloscope window.

Is the generator output voltage zero when the field current is zero? Briefly explain why.

How do the amplitude of the voltage waveforms vary when the field current I_f of the the synchronous generator is decreased. Briefly explain why.

Does varying the field current affect the frequency of the voltage waveforms, or the phase shift between them? Why?

- 13. Turn off the power and turn the voltage control knob fully counterclockwise.

Generator Characteristics

- 14. Modify the connections so that the modules are connected as shown in Figure 5.5. Note that E1 now measures the generator's line voltage E_o , not its phase voltage as before, and that resistor R_1 is inserted into the field circuit. Connect all nine of the resistors on the resistive load module in parallel to implement resistor R_1 .

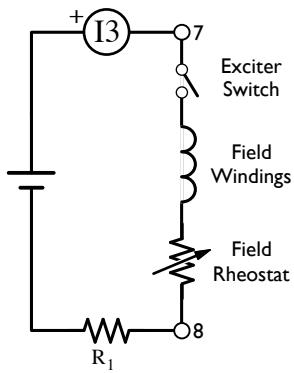
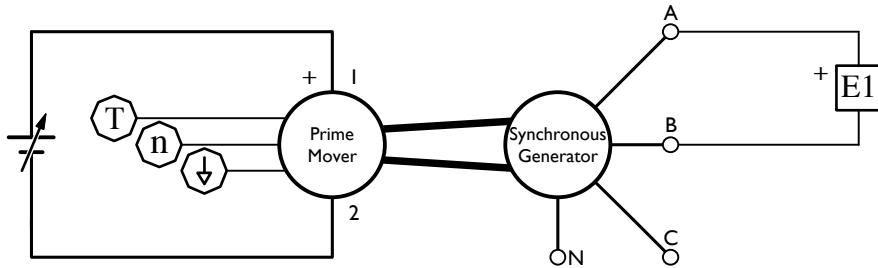
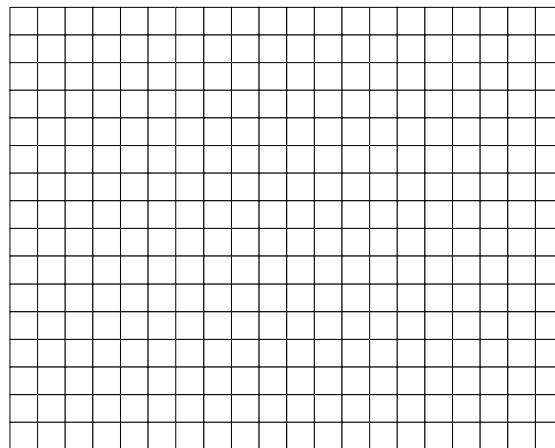


Figure 5.5: Synchronous Generator, No Load, Line Voltages

- 15. Turn on the Power and set the *field rheostat* so that the field current I_f is 500 mA.
- 16. Set up a data table to record the generator output voltage E_o , field current I_f , speed n , and frequency f , indicated by meters E1, I3, N, and B, respectively. You can just accept the default selection, which will record all these values and others.

- 17. On the power supply, adjust the voltage control knob so that the prime mover speed increases from 0 to 2400 rpm in 200 rpm increments. For each speed setting, record the data in the data table.
- 18. When all the data has been recorded, turn the voltage control knob fully counter-clockwise and **turn off the power**.
- 19. In the graph window, make the appropriate settings to obtain a graph of the generator output voltage E_o as a function of the speed n .
- 20. Sketch the graph here:



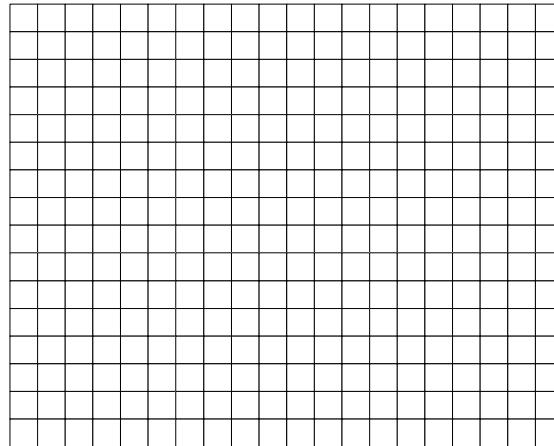
- 21. **Turn on the Power** and set the voltage control knob so that the Prime Mover rotates at the nominal speed of the Synchronous Motor/Generator.
- 22. Set up a data table to record the generator output voltage E_o , line current I_f , speed n , and frequency f , indicated by meters E1, I3, N, and B, respectively.
- 23. Change the value of resistor R_1 and vary the setting of the *Exciter knob* on the synchronous motor generator to increase the field current I_f from 0 to its maximum value in steps of about 100 mA. For each current setting, readjust the voltage control knob of the power supply so that the Prime Mover speed remains equal to the nominal speed of the motor generator. For each setting, record the data in the data table.

Turn off the power when you have finished.

- 24. In the graph window, make appropriate settings to obtain a graph of the synchronous generator's output voltage E_o as a function of field current I_f .

Sketch the graph here:

Hint The maximum field current should be approximately 850 ma. In order to reach the maximum value it will be necessary to short out resistor R_1 . Ask your instructor for help if you need it.



Briefly explain why the relationship between the synchronous generator output voltage and field current is non-linear for high values of I_f .

Resistive, Inductive and Capacitive Loads

25. Remove resistor R_1 from the field circuit, and add a three-phase y-connected resistive load and ammeter I_1 to the output of the generator as shown in Figure 5.6. Use the 40A scale for I_1 .

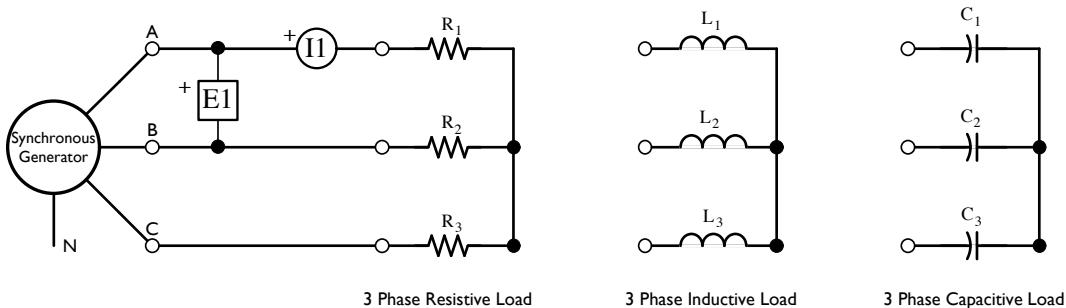


Figure 5.6: Synchronous Generator under Load

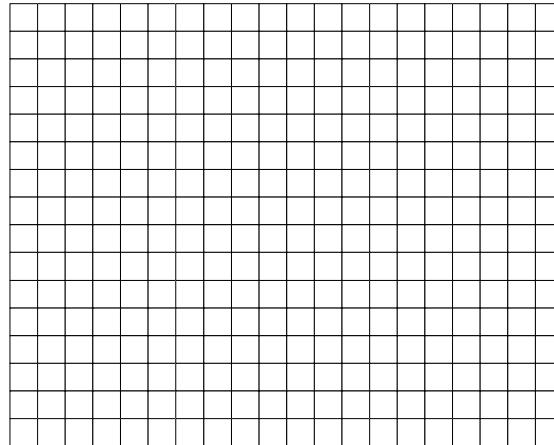
26. Turn on the power and set the voltage control knob so that the generator rotates at its nominal speed.
27. Adjust the excitation current until the generator is producing its nominal voltage.
28. Set up a data table to record the generator output voltage E_o , line current I_l , speed n , and frequency f , indicated by meters E1, I1, N, and B, respectively. You can just accept the default selection, which will record all these values and others.

Hint Use the blue cables to connect the generator to the load.

29. Modify the settings on the resistive load module so that the resistance of resistors R_1 , R_2 , and R_3 decrease in these steps: ∞ , 1200, 600, 400, 300, 240, 200, and 171 Ω .

For each setting, readjust the voltage control knob of the power supply so that the prime move speed remains equal to the nominal speed of the generator, then record the data in the data table.

30. **Turn the power off** and replace the resistive load with a three-phase y-connected *inductive* load. Then turn the power on and repeat step 29. Continue to collect your data in the same table.
31. **Turn the power off** and replace the inductive load with a three-phase y-connected *capacitive* load. Then turn the power on and repeat step 29. Continue to collect your data in the same table.
32. **Turn the power off**. In the graph window, make the appropriate settings to obtain a graph of the generator output voltage E_o as a function of the load indicated by I_l . Sketch the graph here:



Hint Refer to the appendix to find out the resistor combinations needed to produce the required resistance values.

33. Calculate *voltage regulation*, VR for each type of load using the following formula:

$$VR = \frac{V_{NL} - V_{FL}}{V_{NL}} \times 100\%$$

Load	V_{NL} No Load Voltage	V_{FL} Full Load Voltage	VR Voltage Regulation
Resistive			
Inductive			
Capacitive			

- 34. Put everything away.

Conclusion

In this exercise, you observed that a three-phase synchronous generator produces three sine-wave voltages that are phase shifted by 120° from each other. You saw that decreasing the prime mover speed decreases the amplitude and frequency of the sine-wave voltages, while decreasing the field current decreases the amplitude of the sine-wave voltages. You plotted a graph of the synchronous generator output voltage versus the field current. This graph showed that the synchronous generator starts to saturate when the field current exceeds a certain value. This graph also showed that the synchronous generator produces voltages even when the field current is zero because of the residual magnetism in the rotor. You plotted graphs of the synchronous generator output voltage and frequency versus speed. These graphs showed that the output voltage and frequency are proportional to the synchronous generator speed.

Next, you obtained the voltage regulation characteristics of a three-phase synchronous generator. You observed that the output voltage decreases as the output current increases when the synchronous generator supplies power to either a resistive or inductive load. You saw that the output voltage increases as the output current increases when the synchronous generator supplies power to a capacitive load. The voltage regulation characteristics of the synchronous generator are similar to those of a single-phase transformer because the equivalent circuit is almost the same for both.

Lab 6

Generator Paralleling

Introduction

Objective

When you have completed this exercise, you will be able to synchronize a three-phase synchronous generator with the ac power network using the Lab Volt Synchronous Motor/Generator and the Synchronizing Module. You will see the indications of an incorrect phase sequence, and observe how active and reactive power are controlled and shared. You will motorize a generator, and observe the effects on torque, speed, and power.

You will then use the DAC Paralleling Simulator to parallel two generators and balance the active and reactive loads. This final exercise is an STCW assessment.

Discussion

Most of the electricity consumed today is produced by three-phase synchronous generators. Since a huge amount of electricity is consumed every day, ac power networks are generally made up of a large number of synchronous generators all operating at the same frequency. When the power demand increases, additional generators are connected to the ac power network.

Before connecting a three-phase synchronous generator to an ac power network or another generator, the following conditions are to be observed:

- The *frequency* of the voltages produced by the generator must be equal to the frequency of the ac power network's bus.
- The *voltage* produced by the generator must be equal to the bus voltage.
- The *phase sequence* of the voltages produced by the generator must be the same as the phase sequence of the bus.
- The incoming and bus voltages must be *in phase* at the instant the connection is made.

A generator can only be synchronized when all these conditions are met. A synchronous generator must never be connected to an ac power network before verifying the condi-

tions described above. Connecting a generator to an ac power network incorrectly could cause severe damages to the generator, because of the high torque that would be applied to the generator's shaft and the huge currents that would flow in the generator windings at connection. Once a synchronous generator is connected to an ac power network, no current flows between the generator and the ac power network because they produce voltages having the same amplitude and phase. As a result, the generator supplies neither active nor reactive power to the ac power network. In this case, the generator is said to be *floating* on the ac power network. Furthermore, its frequency is determined by the bus frequency, and can no longer be changed by adjusting the torque applied to the generator's shaft. This is because the ac power network is so powerful that it imposes its own frequency. However, adjusting the torque applied to the generator's shaft allows changing the amount of active power that is exchanged between the generator and the ac power network. Increasing the torque increases the amount of active power that is delivered to the ac power network. Conversely, decreasing the torque decreases the amount of active power that is delivered to the ac power network. The generator could even receive active power from the ac power network, and thus operate as a synchronous motor, if the torque applied to the generator's shaft were decreased to zero.

As in three-phase synchronous motors, the amount of reactive power that is exchanged between a synchronous generator and the ac power network can be changed by adjusting the field current. The field current is usually adjusted so that no reactive power is exchanged between the generator and the ac power network, i.e., so that the power factor of the generator is unity. This minimizes the line currents and allows the size of the conductors connecting the generator to the ac power network to be reduced to minimum.

In the first part of the lab a simple circuit is used to synchronize and connect the Lab Volt generator to the utility grid. In this circuit, a three-phase synchronous generator is connected to a three-phase power network (three-phase power source) through three lamps and a three-pole switch set to the open position. A voltmeter and a frequency meter are connected to the generator output to measure its voltage and frequency. A synchroscope is connected to indicate the phase relationship between the generator voltage and the utility network voltage.

The speed and field current of the synchronous generator are first adjusted so that the generator frequency and voltage are approximately equal to the nominal voltage and frequency of the ac power network. The brightness of the lamps will change in synchronism when the *phase sequence* of the generator is the same as that of the ac power network. On the other hand, the lamp brightness will change out of synchronism if the phase sequence of the generator differs from that of the ac power network. In this case, the connections of two of the three line wires of the synchronous generator must be interchanged to reverse its phase sequence.

Once the phase sequence of the synchronous generator is correct, the speed of the generator is adjusted so that the lamp brightness changes very slowly, and the synchroscope turns slowly in the fast direction. This adjusts the frequency of the generator to just slightly more than that of the ac power network. The field current of the generator is then adjusted so that the lamps become completely dimmed as their brightness decreases. This adjusts the generator voltage to that of the ac power network. The switch

can then be closed at any instant the lamps are dimmed completely (the voltages are in phase at this instant only) to safely connect the synchronous generator to the ac power network.

Procedure

Equipment Setup

- 1. Insure that the Power Supply, Prime Mover/Dynamometer, Synchronous Motor/Generator, Synchronizing Module, Synchroscope Module, and Data Acquisition Interface are installed in the EMS Workstation. Insure the USB cable connects the DAI to the computer.
- 2. Make sure that the main power switch is off, and the voltage control knob is turned fully ccw.

Important! Open the *synchronizing switch* on the *Synchronizing Module*.

- 3. Connect the DAI to the 24 V ac power with the grey cable, and turn it on. Leave power on the DAI for the entire exercise.
- 4. Launch the *Metering* program, and open meter configuration file *Lab 6 Synchronizing* to show

Meter	Measurement	Unit
E1, E2	Incoming Voltage	AC Volts
E3	Bus Voltage	AC Volts
I1, I2	Line Current 40A	AC Amps
I3	Field Current 4A	DC Amps
AI-7/T	Torque	N-m
AI-8/n	Speed	r/min
F(E1)	Frequency	Hz
Pm(7/T, 8/n)	Mechanical Power	Watt
PQS1 + PQS2 (P)	Active Power	Watt
PQS1 + PQS2 (Q)	Reactive Power	Var
PF(EI1, EI2)	Power Factor	Unitless
W(E1, I1)	Energy	W-h

- 5. Set the Prime Mover/Dynamometer controls as follows:

Control	Position
Mode Switch	Prime Mover (P.M.)
Display Switch	Speed (N.)

- 6. Close the *Exciter switch* on the Generator Module, and set the *field rheostat* to the mid position.

7. Connect the equipment as shown in the Figure 6.1.

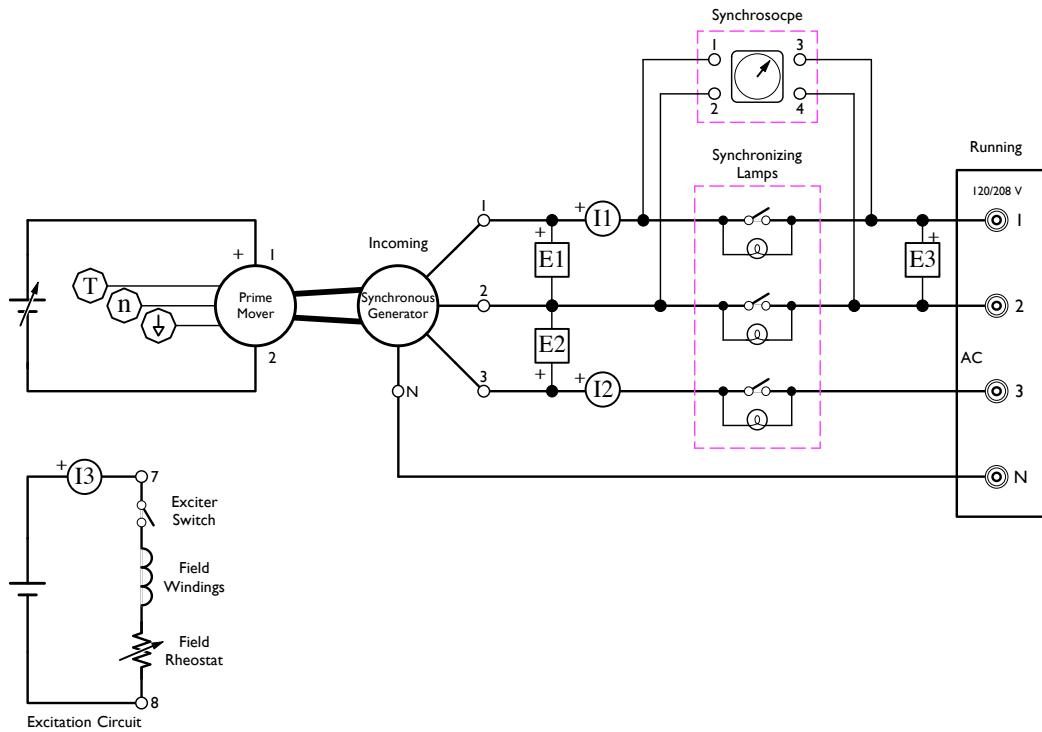


Figure 6.1: Synchronous Generator Paralleled with the AC Power Network

Phase Sequence

8. Turn on the power and adjust the voltage control knob so that the Synchronous Motor/Generator rotates at approximately 1750–1775 rpm. Observe the behavior of the *synchronizing lights* and the *Synchroscope*.

Is the synchroscope rotating slowly in the slow direction? Yes No

Are the synchronizing lights blinking together, indicating that the phase sequence of the generator matches the phase sequence of the three-phase power network?

Yes No

9. Raise the speed of the generator until it is slightly higher than the nominal speed of the generator. Describe how the behavior of the synchronizing lights and the synchroscope change.

-
-
10. **Turn off the power** and interchange the power connection leads at terminals 1 and 2 on the power supply.

11. Turn on the power and adjust the generator speed to approximately 1725 rpm. Observe the behavior of the *synchronizing lights* and the *Synchroscope*.

Warning: Never attempt to parallel generators when the synchronizing lights are “twinkling”.

Are the synchronizing lights “twinkling”? Yes No

Does the synchroscope display look unusual? Yes No

12. Turn off the power and restore power connection leads 1 and 2 to their original positions.

Synchronization

13. Turn on the power and adjust voltage control knob until the generator rotates at approximately 1700 rpm.

14. Adjust the *field rheostat* until the generator voltage indicated by meters E1 and E2 is slightly higher than the voltage of the three-phase network.

15. Adjust the speed of the generator until the synchroscope is turning *slowly in the fast direction*.

Are the synchronizing lights all dark at the moment the synchroscope is at top dead center? Yes No

16. Close the synchronizing switch on the Synchronizing module when the synchroscope is pointing *slightly before top dead center* to parallel the generator with the network.

Is the generator now paralleled with the network? Yes No

Is the generator supplying any power to the network? Yes No

How do you know?

Effect of Driving Torque

In this section you will observe how changing the input mechanical power and driving torque effects a generator paralleled with an infinite bus.

17. If it isn't already, parallel the lab generator with the bus:

- Adjust the prime mover until the incoming frequency is slightly higher than the bus frequency and the synchroscope is turning slowly in the fast direction
- Adjust excitation until incoming voltage is slightly higher than the bus voltage (2 volts or so)
- Close synchronizing switch when synchroscope is pointing at top dead center.

18. Adjust the Generator to full load by increasing the prime mover voltage until the torque supplied to the generator to approximately -1.5 N·m.

The negative sign is the result of a sign convention. A quantity like torque or power leaving the device is considered positive. Since the prime mover is supplying torque to the generator, the torque "out" of the generator is negative, and the electrical power "out" is positive. On the other hand, a motor consumes electrical power and produces mechanical power so torque "out" is positive, and electrical power "out" is negative.

19. Record the following values including units:

T Torque _____

n Speed _____

P_m Mechanical Power _____

P_e Active Power _____

Q_e Reactive Power _____

20. If the shaft speed n is 1800 rpm, what is the shaft angular velocity, ω ?

$$\omega = \frac{2\pi n}{60} = \text{_____}$$

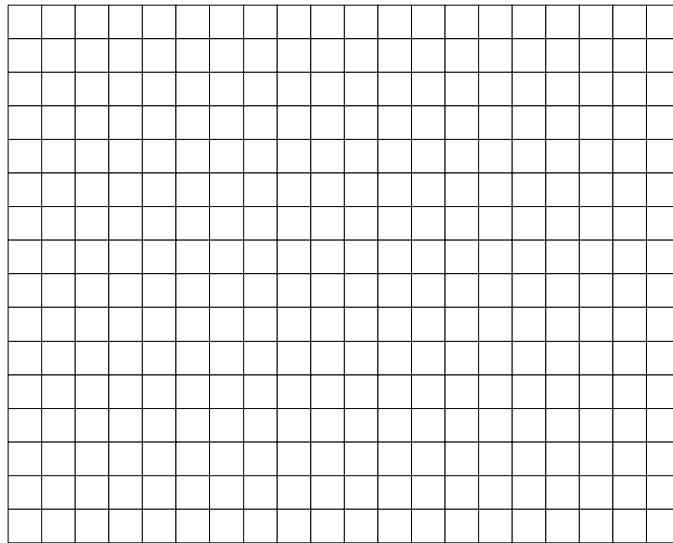
21. Mechanical Power is Torque times Angular Velocity. Calculate the input mechanical power. What are the associated units? Does this value agree with the value indicated on the computer?

$$P_m = T\omega = \text{_____}$$

22. Efficiency is the ratio of output power to input power. In this case, the input is mechanical power supplied by the prime mover, while the output is active power. Calculate the generator efficiency at full load.

$$\eta = \frac{P_e}{P_m} = \text{_____}$$

23. Set up a new, blank data table.
24. Decrease the input torque in about 15 small steps by decreasing the DC voltage to the prime mover. Record values in a data table after each step. Continue until the torque indicated stops changing. Be sure to wait about three seconds after each adjustment before recording to get good results.
25. Make of graph of active and reactive power as a function of Torque, and sketch it below. If necessary, change the colors to make the curves clearly visible.



26. Answer the following questions.

Does changing the input torque change the active power produced by the generator? Yes No

Does changing the input torque change the reactive power produced by the generator? Yes No

Which effect is predominant? _____

Does changing the torque affect the speed of the generator? Explain why or why not.

Can you adjust the torque to zero N-m? Yes No

Under these conditions, is the electrical power out positive or negative? _____

If the prime mover is supplying zero torque, where is the torque coming from to keep the generator spinning at 1800 rpm?

What is the greatest positive torque you observed? _____

Under these conditions is the generator motorized? Yes No

Did the motor direction change when it became motorized? Yes No

Did the torque change direction when the generator became motorized? Yes No

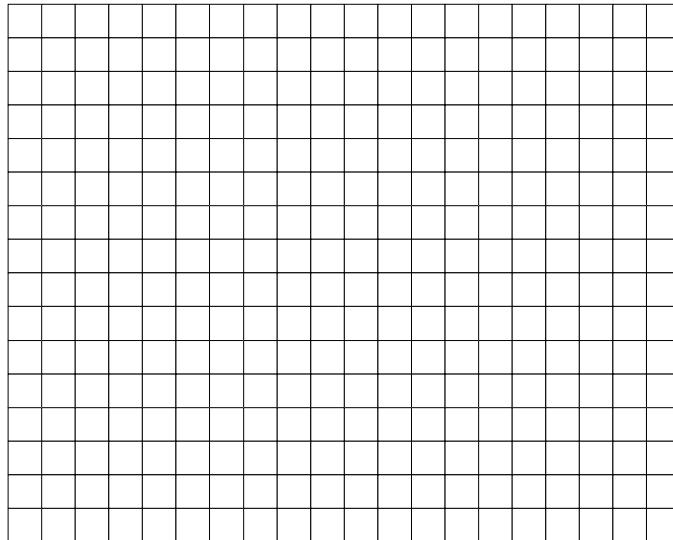
What do you think will happen if you disengage the prime mover while the generator is running?

What do you think will happen if you open the sync switch with the prime mover disengaged?

Effect of Field Excitation

In this section you will observe how changing the excitation current effects a generator paralleled with an infinite bus.

- 27. Delete your previous data table
- 28. Load the generator by increasing the prime mover voltage until the driving torque is approximately -1.5 N-m.
- 29. Turn the field rheostat fully counterclockwise while observing the generator speed and terminal voltage. Do speed or terminal voltage change? Why or why not.
- 30. Starting with the field rheostat fully counterclockwise, adjust the rheostat in small steps until it is fully clockwise, recording data after each step. Be sure to wait about three seconds after making the adjustment before recording the data to get good results.
- 31. Make a graph of Active and Reactive Power as a function of field current and sketch and label it below.



- 32. Answer the following questions.

Does adjusting the field excitation change the generator terminal voltage? Yes No

Does adjusting the field excitation change the generator rpm or frequency? Yes No

Does adjusting the field excitation change the generator active power? Yes No

Does adjusting the field excitation change the generator reactive power? Yes No

Can the generator reactive power be adjusted to zero? Yes No

Under these conditions, what is the generator power factor? _____

Turning the rheostat clockwise causes the field resistance to increase decrease
Turning the rheostat clockwise causes the excitation current to increase decrease
Turning the rheostat clockwise causes the field to get stronger weaker
Turning the rheostat clockwise causes the reactive power to increase decrease

- 33. Change the graph to show line current vs. field current. Can you explain the shape of the graph?
- 34. off the power and put everything away.

Paralleling Simulator

In accordance with the requirements of STCW Assessment OICWE-7-1E, each student will demonstrate the Paralleling Procedure using the DAC Paralleling Simulator.

- 1. Start Incoming generator
 - a) Select **Display Function D** to show incoming and running generator parameters
 - b) Raise Turbine to operating speed to bring the frequency to 60 Hz using the **speed control buttons**.
 - c) Adjust incoming generator voltage to approximately 22000 Volts using the **voltage control buttons**
- 1. Synchronize incoming generator
 - a) Use **Sync Selector** to turn on the synchroscope for the incoming generator.
 - b) Make voltage and speed adjustments as necessary in order to match incoming and running voltages while at the same time producing a slow clockwise rotation of the synchroscope.
 - c) When ready, (think..., then) close the correct **circuit breaker** when the synchroscope is at 5° before 12 o'clock.
 - d) Turn off the synchroscope using the **sync selector**.
- 1. Adjust the load on the generator
 - a) Use the **speed control buttons** to raise the load to balance the Active Power Load (MW). Use **Display Function A** to see the active-power house diagram.
 - b) Use the **voltage control buttons** to balance the Reactive Power (MVAR) Use **Display Function B** to see the reactive-power house diagram.
 - c) Readjust speed and voltage to the nominal values without unbalancing the active and reactive loads.

Conclusion

In this lab, you properly synchronized a three-phase synchronous generator with a three-phase bus first using the lab volt equipment, and then again using the DAC paralleling

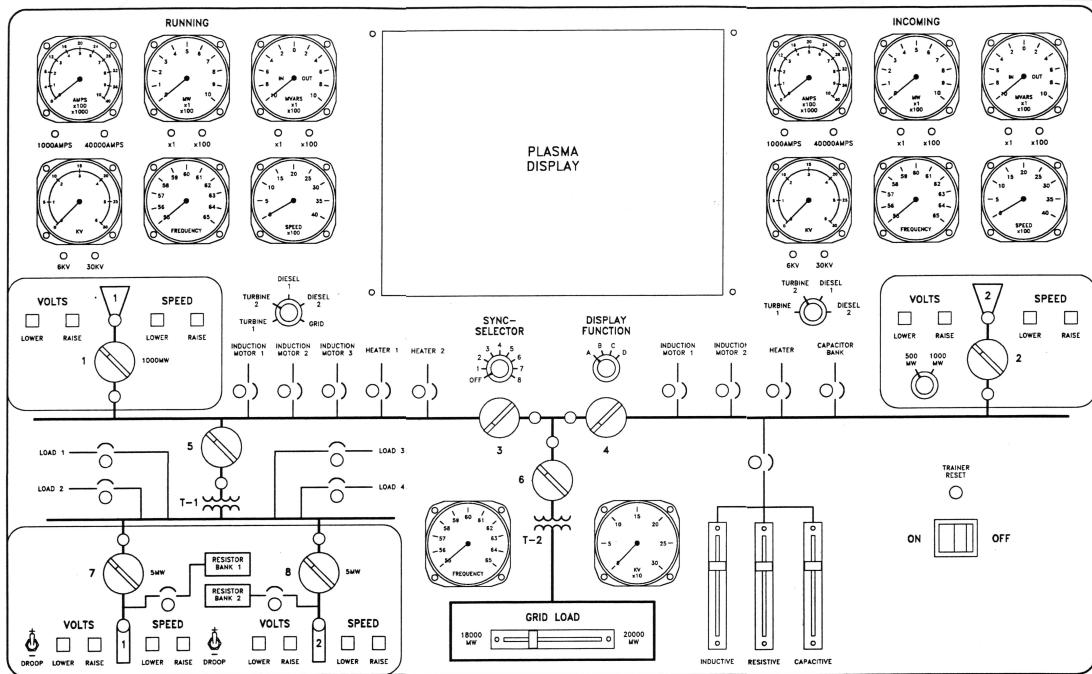


Figure 6.2: Paralleling Simulator

Table 6.1: Generator Ratings

	1000 MW TG	500 MW TG	5 MW DG
PF	0.85	0.85	0.8
MVA	1176	588	6.26
Voltage	22 KV	22 KV	4160 V ac
RPM Trips	1800	3600	900

Table 6.2: Generator Trip Limits

	1000 MW TG	500 MW TG	5 MW DG
Over speed	1980	3960	990
Over current	35 KA	17.5 KA	1000A
NL Volt Hi	24 KV	24 KV	4540 V
NL Volt Low	21 KV	21 KV	3970 V
NL RPM Hi	2000	4000	1000
NL RPM Low	1700	3400	850

simulator. When using the lab volt generator, you were paralleling with an *infinite bus*, while the simulator demonstrated paralleling two identical generators on an *isolated bus* such as found aboard ship.

You also observed the load sharing behavior of synchronized generators. You observed that varying the torque and power at the generator's shaft using the prime mover voltage in the case of the Lab Volt generator, or with the governor control on the paralleling simulator, varies the share of active load carried by each generator. You saw that varying the field current of the generator varies the amount of reactive power exchanged between the generator and the ac power network. You saw that these changes have no effect on line voltage or frequency when you are paralleled to an infinite bus, but they do when paralleled to an isolated bus.

Lab 7

Residential Wiring

Objective

To enable students in the proper methods of wiring a typical residential circuit, including wire sizing, circuit breaker selection, wire termination, and wiring techniques.

For safety purposes, the wiring system is energized at approximately 15 volts AC, however the design and methods used will be those on a residential 120 volt single phase AC system.

The Lab Setup includes four nearly identical stations. Each station will be wired by a team of 2 students. Lockout and Tagout procedures shall be strictly adhered to.

Each station is fed from a main circuit breaker panel. The student is responsible for correctly locking and tagging out the circuit breaker that feeds his/her workstation. Each station shall then be wired so that the light fixture is operable from either of two three-way switches. Additionally, a receptacle shall be wired in parallel to the light fixture, however the receptacle shall not be switched, though it shall have a common circuit breaker with the light fixture.

Procedure

- 1. The station shall be Locked Out and Tagged Out.
- 2. Circuit Breaker. The circuit breaker shall be installed in the station subpanel. The breaker shall be a 15 amp single phase breaker. Care shall be taken with the breaker so that it is installed and removed correctly and without breaking it.
- 3. The light fixture shall be installed in the 4-inch octagonal box located next to the breaker panel.
- 4. The receptacle shall be installed directly below the light fixture.
- 5. The two three-way switches that will control the light fixture and the receptacle shall be installed to the left and right of the receptacle in the “handy-box” provided.
- 6. On completion, the student will first (before energizing the circuit) check the continuity of the circuits with a multi-meter. The student shall ascertain that the

receptacle is wired correctly, that the switches work, and that the light bulb is in working order.

- 7. On completion of the continuity test, the student shall request authorization from the instructor to remove the Lockout/Tagout device and energize the circuit.
- 8. After energizing the circuit, the student shall first test the voltage at the receptacle, then at the light fixture with the multi-meter. If appropriate, the light bulb can be installed, and the switches tested.
- 9. After successful completion, the student shall return the lab station to its original condition, return all tools, and report any defects or damages found in the system. Care shall be taken to insure that the multi-meters are left in the "off" position so that the batteries do not drain.

National Electric Code Requirements: The lab is to be wired in accordance with the National Electric Code (NEC) regulations as they apply to a residential circuit. The following questions should be considered while wiring the circuit.

Reference Materials

Operating, Testing, and Preventive Maintenance of Electrical Apparatus, by Charles I. Hubert, Prentice Hall 2003. See Chapter 8 for AC circuits in general. There are "Reference Tables in Chapters" listed on page xxvii, which should be useful. Appendices A.1, A.2, A.3 show Allowable Ampacities of Insulated Conductors. This information is from the National Electric Code with permission. Appendix A.4 contains the standard color code for tubular resistors per USAS and RETMA.

Check out the web such as: <http://www.make-my-own-house.com/diagram-electrical-wiring.html> for additional info on residential wiring.

The National Electric Code has both general and specific information regarding residential wiring. Remember that there are Federal, State, County and City or Town Electric Codes which must be complied with and all wiring installed in a home by anyone should be permitted, inspected and approved by local AUTHORITY HAVING JURISDICTION (AHJ). The National Electric Code(NEC) is the MINIMUM requirements for compliance. It is possible to have requirements which exceed the NEC.

Questions

- 1. Who is responsible for installing the Lockout/Tagout?
- 2. Who can remove the Lockout/Tagout?
- 3. If the circuit breaker is in the "Tripped" position, is it de-energized?
- 4. Is this circuit acceptable for commercial as well as residential applications?
- 5. What do the numbers on the circuit breaker mean?
- 6. What are the three positions of the circuit breaker switch?
- 7. What type of wire is being used?

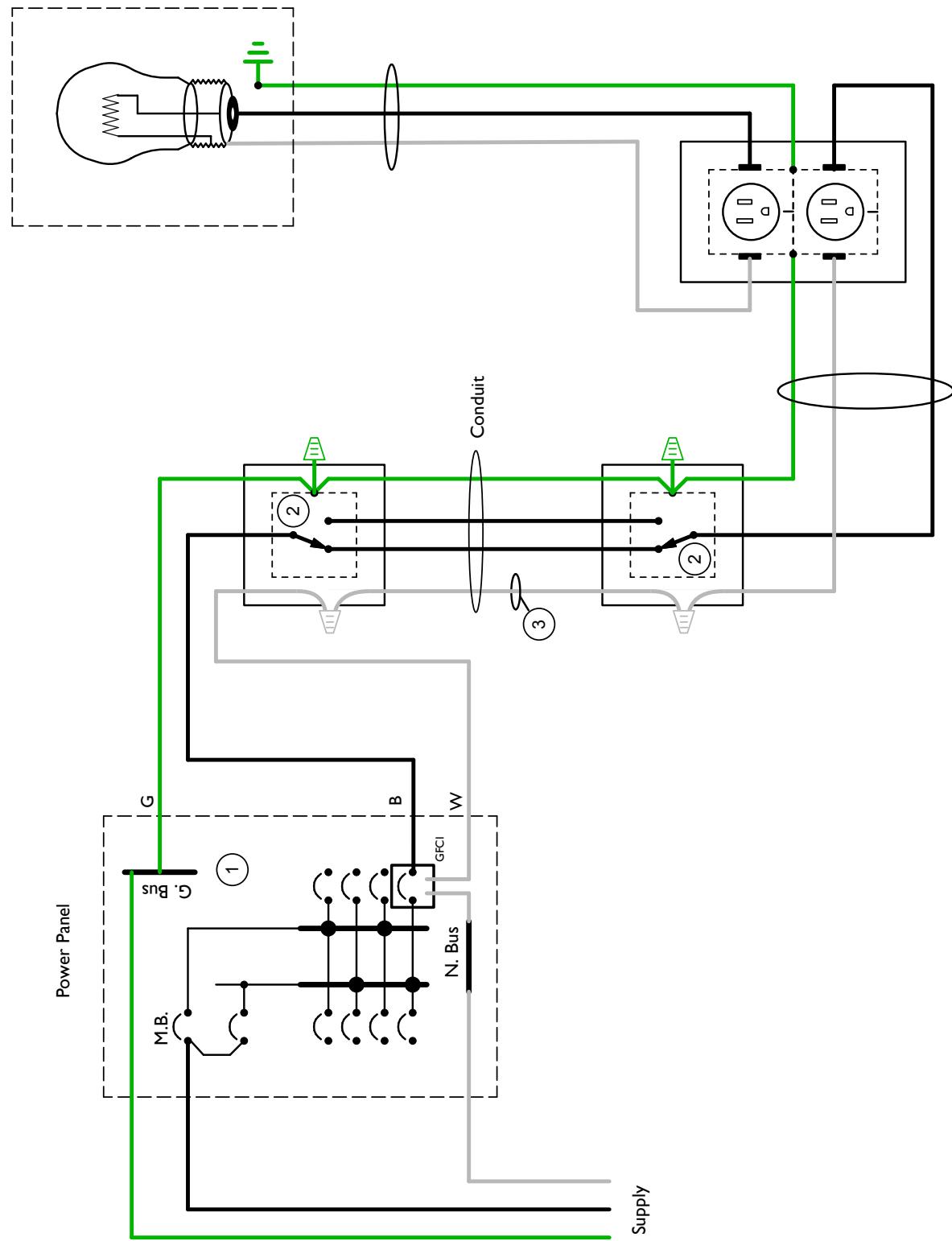


Figure 7.1: Three Way Switch Circuit

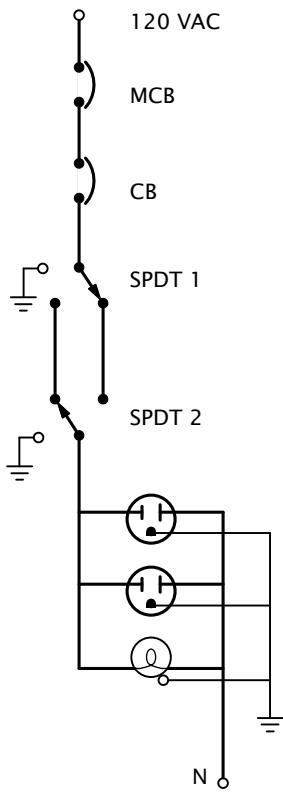


Figure 7.2: One Line Diagram

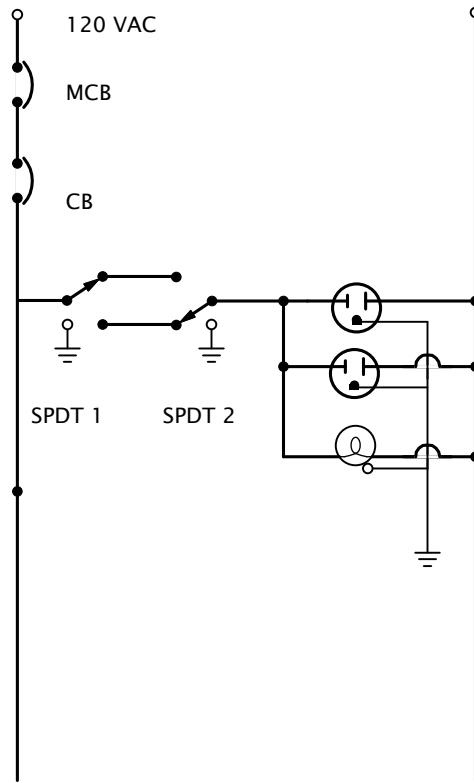


Figure 7.3: Ladder Diagram

- 8. What size wire is being used?
- 9. Can this circuit be used in a
 - a. Bedroom
 - b. Bathroom
 - c. Kitchen
 - d. Living Room
- 10. What parts of this circuit need to be grounded? Why is there a ground wire?
- 11. Why are the ground wires and neutral wires placed on different busses? They are on the same bus in my house.
- 12. The receptacle has three screws: silver, gold, and green. Which wire is attached to each?
- 13. The light fixture has two screws. Does it matter which wire goes to each screw? Why?
- 14. When wiring the switch, should I interrupt the hot (ungrounded) conductor or the neutral (grounded) conductor?
- 15. Does it matter what color wires I use?
- 16. What is a ground clip?
- 17. Can I “backstab” the wires into the devices?
- 18. Is there enough room in the electric box for all these wires? How many can I really

fit into there?

- 19. Why are the wire nuts different colors?
- 20. Does it matter which way I wind the wire around the screw?
- 21. Should I use stranded wire or solid wire? Does it matter?
- 22. Why does the conduit have a temperature rating?
- 23. Can I stuff as many wires as I want into the conduit?
- 24. When installing a switch in an AC circuit, which wire is attached to the switch?
- 25. What is the purpose of the ground wire?
- 26. What color are the three screws on a 120 volt single phase grounded receptacle, and what wire attaches to each screw?
- 27. Regarding a two wire Edison Base light fixture (as used in the lab), what wire goes to each screw?
- 28. What are the two ratings shown on a circuit breaker?
- 29. How do you determine if a circuit is de-energized?
- 30. How do you use a multi-meter to determine if a switch is operational?

Labs 8 – 11

Industrial Controls

In upstairs labs 8–11 you will be working with the Lab-Volt Industrial Controls Training System to learn about techniques of motor control and circuit wiring. You will complete the exercises in the Lab Volt manual found in ??.

Lab 12

5kV High Voltage Switchgear

In this lab you will familiarize yourself with the following high voltage switchgear

- ITE Metal-Clad Switchgear Circuit Breaker – Model 5HK 250
- 1200A Vertical Section Air Frame Training Circuit Breaker

Objective

When you have completed this lab you will be able to:

- Exercise AC high voltage switchgear
- How to safely energize (close) and de-energize (open) the main circuit breaker by using the main switch handle
- Identify all of the parts in a breaker cubicle section
- Use proper PPE; Safely rack out the breaker
- Open the cubicle; Open the charged springs
- Remove the breaker from the cubicle cell; Install the breaker remote test lead to cycle the breaker while out of the cubicle cell
- Inspect the primary and secondary contacts, Inspect the arc chutes
- Manually pump the breaker springs
- Manually close the breaker
- Inspect the inside of the cubicle cell
- Check linkages
- Ensure the breaker terminations and bolted connections are tight
- Know how to properly install and remove the circuit breaker from the cell

Safety

Safety Prior to any disassembly or inspection of the circuit breaker, the closing springs should be discharged and the breaker should be open.

Use of PPE When working on any high voltage equipment it is extremely important to ensure that the breaker is de-energized. There are several ways to ensure the breaker is safe to work on.

Remember All circuit breakers connect the line side (hot) to the load side by the movement of spring loaded moveable contacts. There is an enormous amount of energy that is transferred during the contact closing and contact opening process. Many personal injuries and equipment casualties have occurred while performing maintenance of circuit breakers. It is imperative to utilize all PPE and practice all recommended procedures when engaging in this work.

- Use all the required PPE for the task at hand: Insulated safety gloves, insulating matt, helmet and face shield, fire retardant suit and safety shoes.
- Make sure all of the electrical testing equipment is up to date and is rated for the respective load.
- Ensure all of the electrical testing equipment is in working condition. In this lab we will be using a tick tracer and a hot stick.
- Make sure the breaker you plan on working on is the correct breaker to be serviced.
- Try to reduce all load on the affected breaker. The more current flowing through the circuit when the breaker is opened, the bigger the arc.
- Make sure the breaker is in the open position. View the labeled flag on the breaker through the shutter before opening the cell access door.

Procedure

- 31. Review the circuit breaker information in the equipment manual.
- 32. **Cell Identification:** Look at the handout and identify all of the parts listed.
- 33. **Existing Conditions:** Now we will proceed with de-energizing the circuit breaker. You should find the circuit breaker in operation and online with the breaker selector switch in the “closed” position with the “red” indicating light on. Open the shutter on the bottom of the cell access panel and you should see the flag “closed” which denotes the breaker is online.

Again, the engineer should try to reduce all load on the feeder circuit BEFORE he opens the breaker to de-energize the circuit.

- Move breaker handle to the open position. You should hear the breaker cycle and the light change from red to green.
- Open the shutter in the bottom of the cell and you should see the breaker flag also state the breaker is in the “open” position.
- Once the breaker is de-energized, open the cell access doors. Use the breaker crank out handle and insert it into the rack-out connection. While your left hand is depressing and moving the lock lever to the left, simultaneously rotate the crank handle clockwise to initiate the worm gear thereby allowing the circuit breaker to begin the rack out process. Note the position of the breaker and the labels located on the right base frame of the breaker.
- You will observe three positions for the breaker. Connected, Test, Disconnected. (Please read the OEM handout).
- Once fully retracted, the breaker can then be removed for observation and discussion.

- 34. **Discussion:** Class will now discuss components and operation.

35. **Remote Test Station:**

- Insert remote test station jack. **MAKE SURE SPRINGS CHARGE SWITCH IS OFF**
- Once jack is inserted, cycle breaker manually.
- Insert manual hand pump lever to recharge springs and crank until ratchet slips free.
- Cycle breaker by hand and observe primary and secondary contacts.
- Remove jack from remote test station

 36. **Reinstall Circuit Breaker Into Cell:**

- Simply perform the same rack-in procedure as was done during the rack-out procedure.
- Test the breaker for proper operation.

Appendices

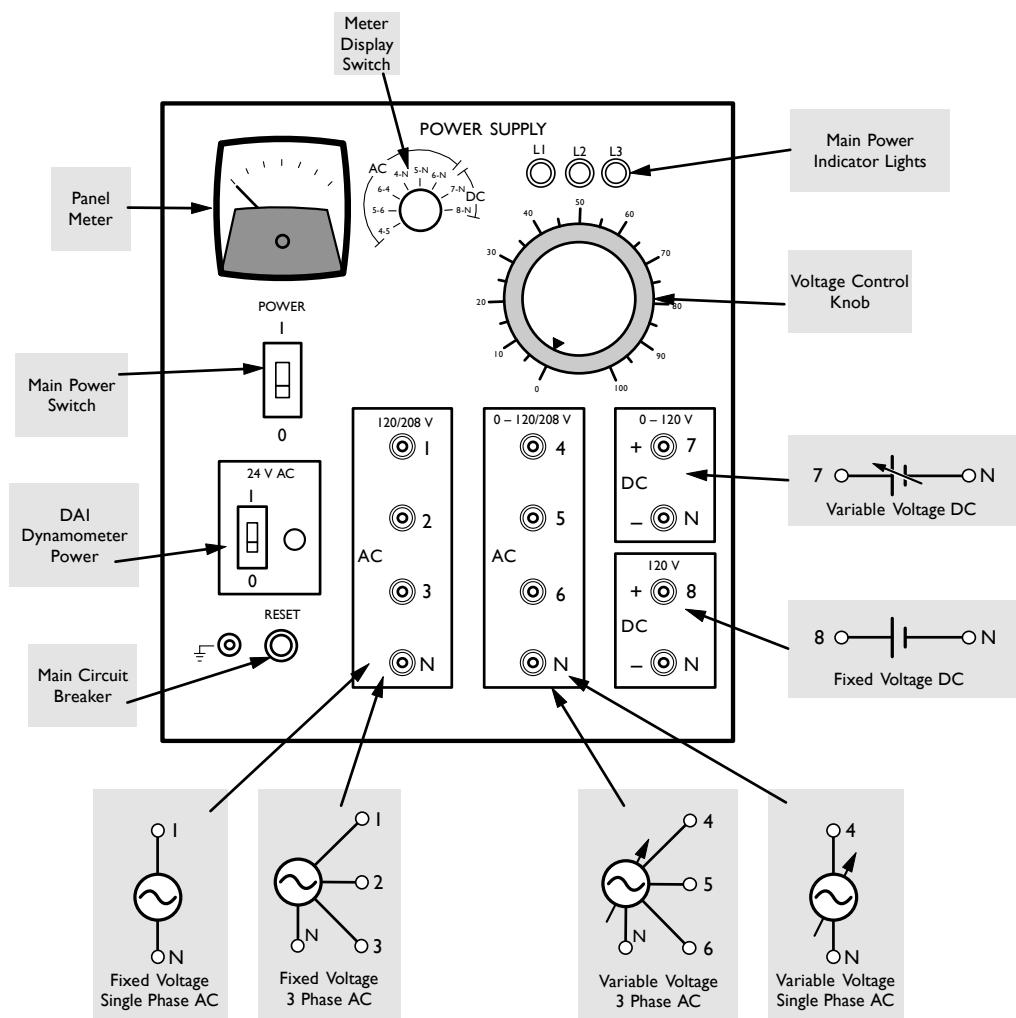


Figure A-1: Lab-Volt Power Supply

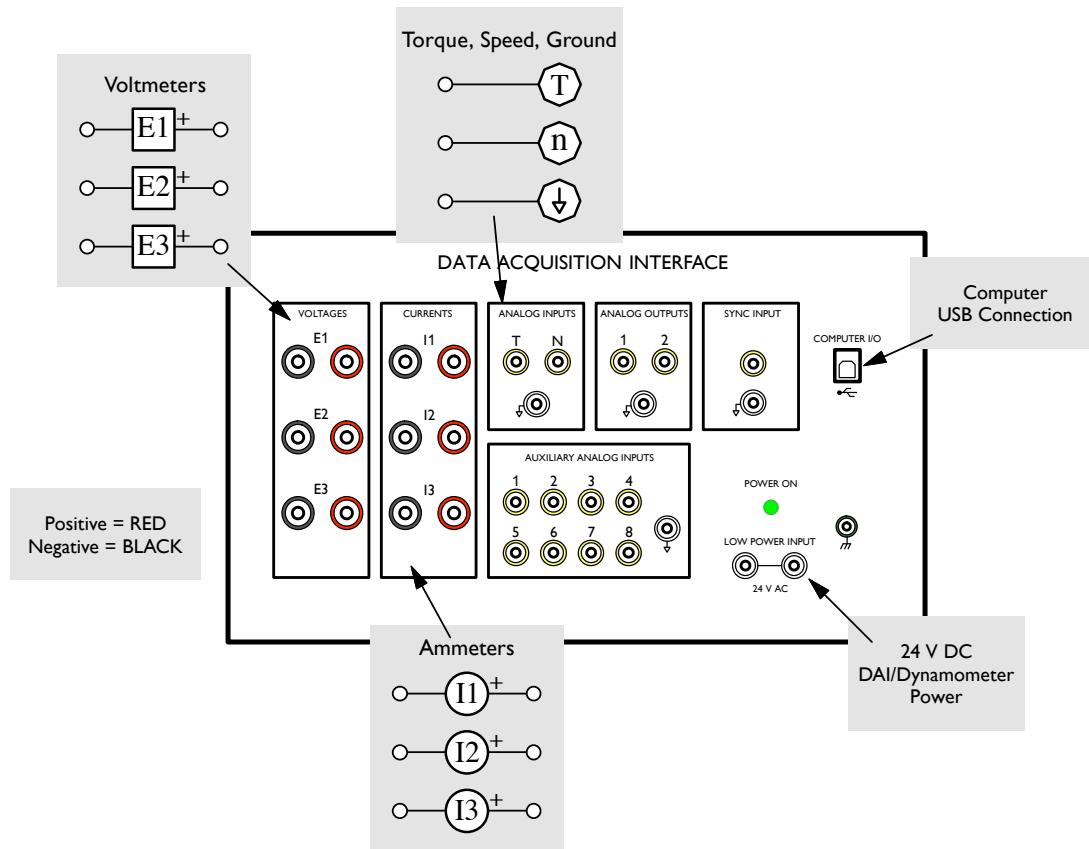


Figure A-2: Data Acquisition Interface

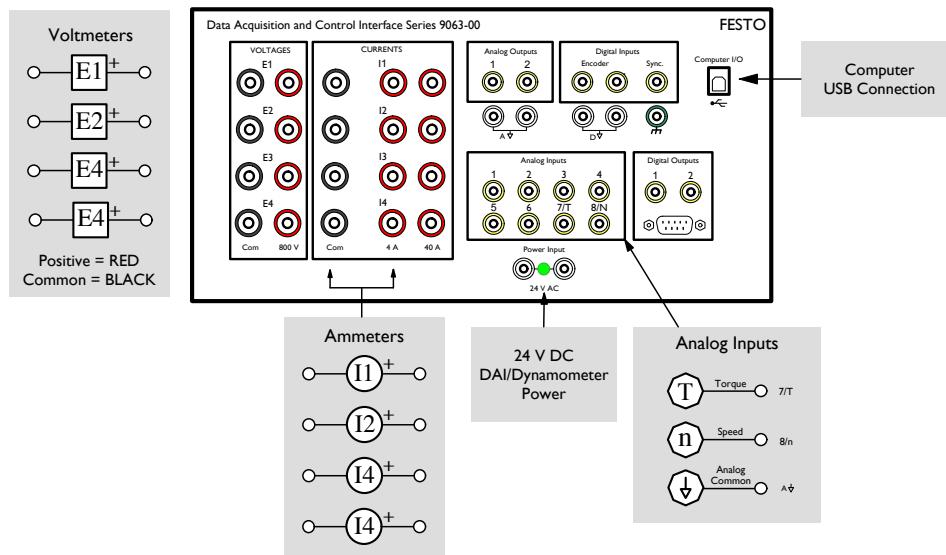


Figure A-3: Data Acquisition and Control Interface

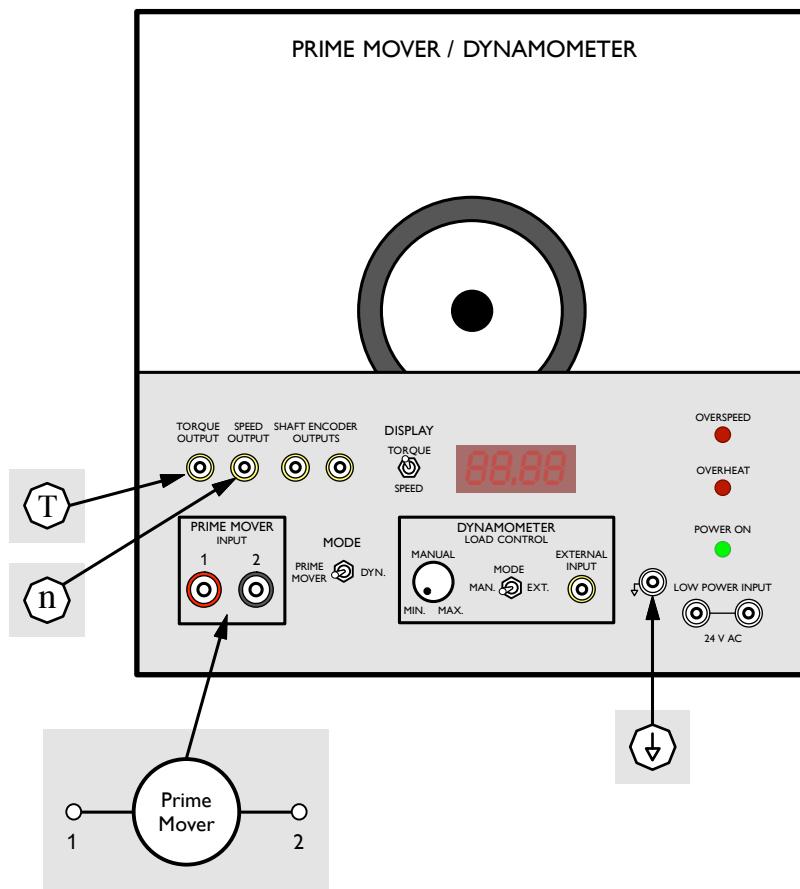


Figure A-4: Prime Mover/Dynomometer

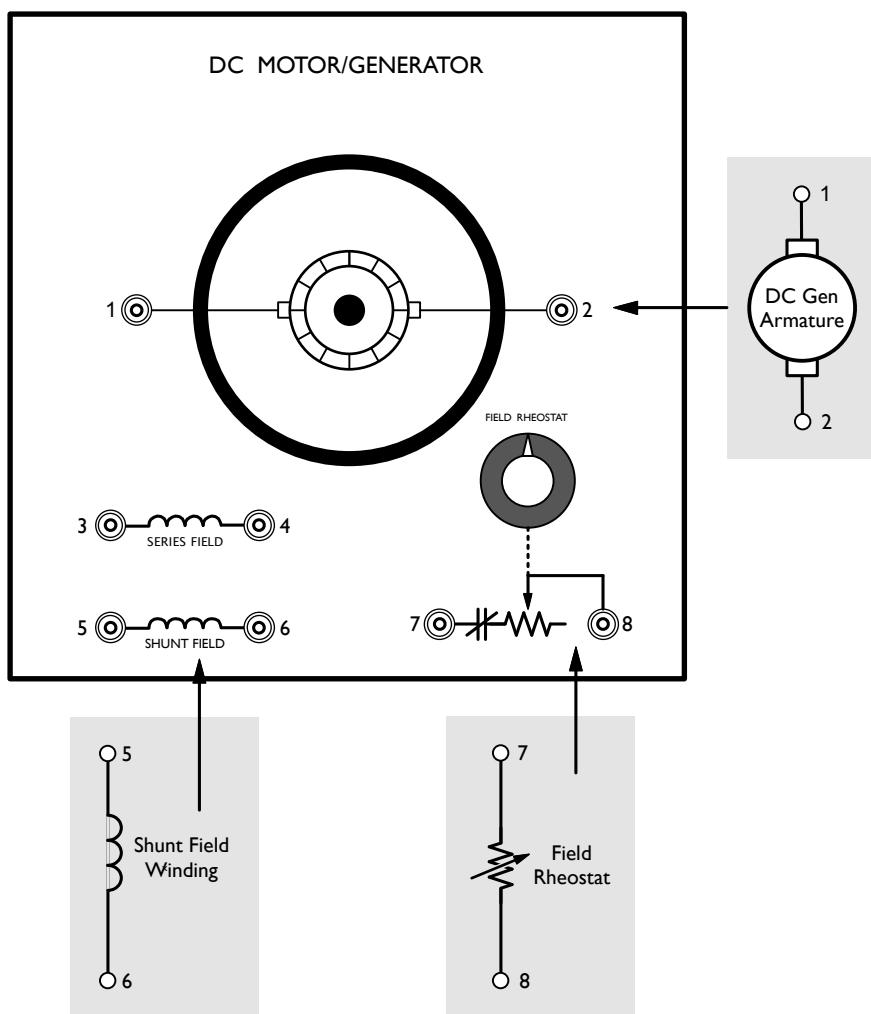


Figure A-5: DC Motor Generator

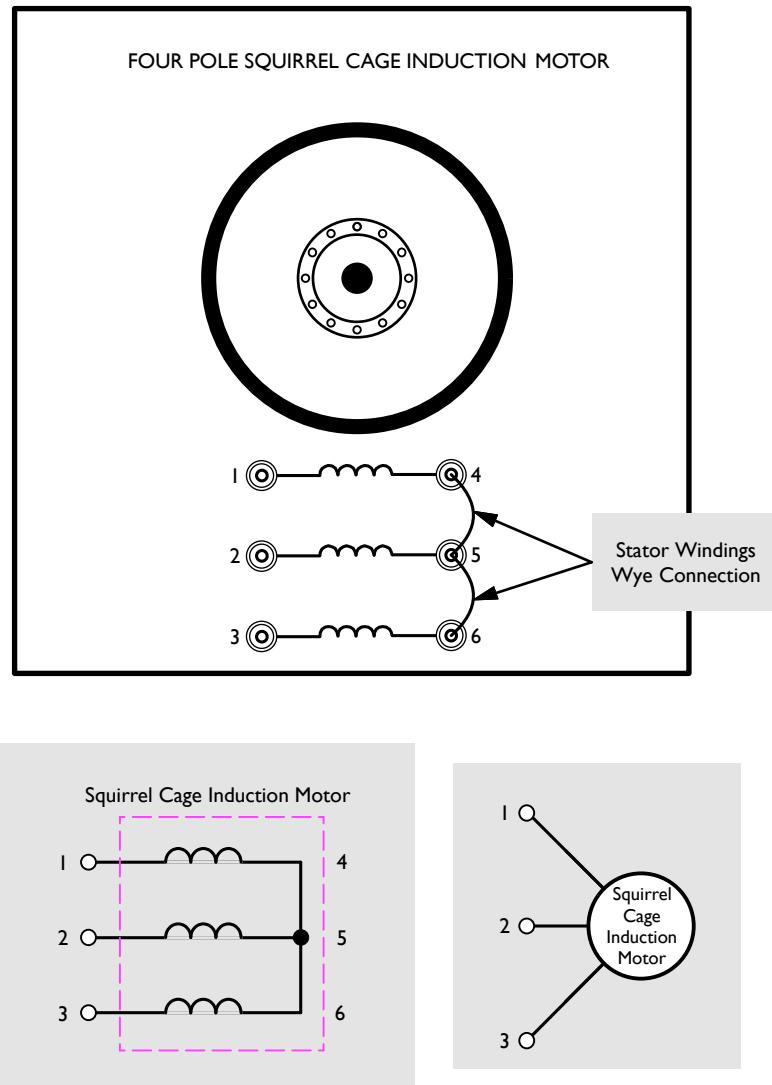


Figure A-6: Three-phase Induction Motor

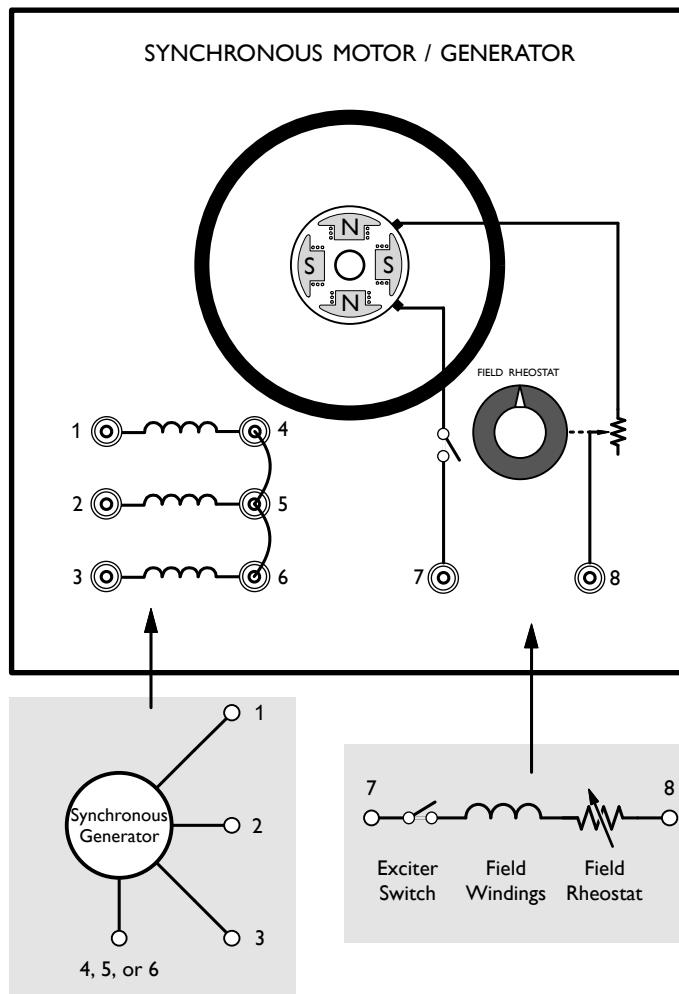


Figure A-7: Synchronous Motor/Generator

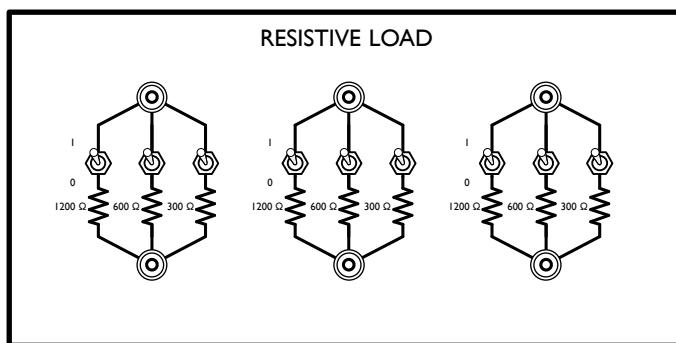


Figure A-8: Resistive Load Module

R_t	Switch Positions								
	1 1200 Ω	2 600 Ω	3 300 Ω	4 1200 Ω	5 600 Ω	6 300 Ω	7 1200 Ω	8 600 Ω	9 300 Ω
1200 Ω	1								
600 Ω		1							
400 Ω	1	1							
300 Ω			1						
240 Ω	1		1						
200 Ω		1	1						
171 Ω	1	1	1						
150 Ω	1			1	1	1			
133 Ω		1		1	1	1			
120 Ω			1		1	1			
109 Ω			1	1	1	1			
100 Ω	1		1	1	1	1			
92 Ω		1	1	1	1	1			
86 Ω	1	1	1	1	1	1			
80 Ω	1			1	1	1	1	1	1
75 Ω		1		1	1	1	1	1	1
71 Ω			1		1	1	1	1	1
67 Ω			1	1	1	1	1	1	1
63 Ω	1		1	1	1	1	1	1	1
60 Ω		1	1	1	1	1	1	1	1
57 Ω	1	1	1	1	1	1	1	1	1

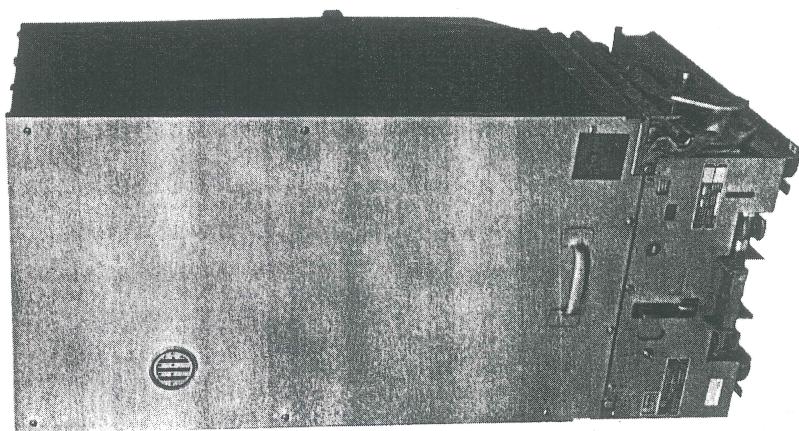
Table A-1: Resistive Load Module Resistance Combinations

5 OF 5

IB-8.2.7-2
CIRCUIT BREAKERS
ISSUE F
I-T-E METAL-CLAD SWITCHGEAR

INSTRUCTIONS

5 KV POWER CIRCUIT BREAKERS
TYPE 5HK75, 5HK150, 5HK250 AND 5HK350



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INSTRUCTIONS FOR 5 KV POWER CIRCUIT BREAKERS TYPE 5HK75, 5HK150, 5HK250 AND 5HK350

INTRODUCTION

These instructions for installation, operation and maintenance of HK circuit breakers should be read carefully and used as a guide during installation and initial operation.

The specific ratings of each model circuit breaker are listed on the individual nameplates.

File these instructions in a readily accessible place together with drawings and descriptive data of the switchgear. These instructions will be a guide to proper maintenance of the equipment and prolong its life and usefulness.

properly due to circumstances, it must be thoroughly checked before going into service to insure it has not absorbed moisture, rusted or become generally contaminated in any way.

CIRCUIT BREAKER INSTALLATION

GENERAL

Prior to the initial installation of the circuit breaker into switchboard, certain preliminary inspections should be made to insure proper operation. The inspection procedures for this are given in this section.

FOR SAFETY: Prior to any disassembly or inspection of the circuit breaker, the closing springs should be discharged, and the breaker should be open.

If it is necessary to raise or move the breaker, attach a lifting yoke at points 4 (Fig. 1) or a fifth wheel at point 5 (Fig. 2) to transport the breaker as required.

INSTALLATION INSPECTION

Inspect condition of circuit breaker arc chutes, contacts and electrical connections prior to installing the circuit breaker into the switchboard. Even though each circuit breaker is completely adjusted and tested at the factory, shipping and handling conditions could cause defects.

REMOVING INTERPHASE BARRIER

For 5HK75, 150 and 250, remove two lower front sheet screws, lift straight up above arc chutes by grasping front handle and top sheet at rear, then draw barrier forward and away from circuit breaker.

For 5HK350, remove two lower front sheet screws, and lift front sheet up and away from the breaker. Remove arc chute tie bar at upper front of arc chutes. Pivot rear brace at rear of each barrier upward and slide the separate barriers forward and away from the circuit breaker.

CAUTION: The 5HK350 barriers will not stand unsupported and must be braced.

These instructions do not purport to cover all details or variations in equipment nor to provide for every possible contingency to be met in connection with installation, operation, or maintenance. Should further information be desired or should particular problems arise which are not covered sufficiently for the purchaser's purposes, the matter should be referred to Gould Inc.

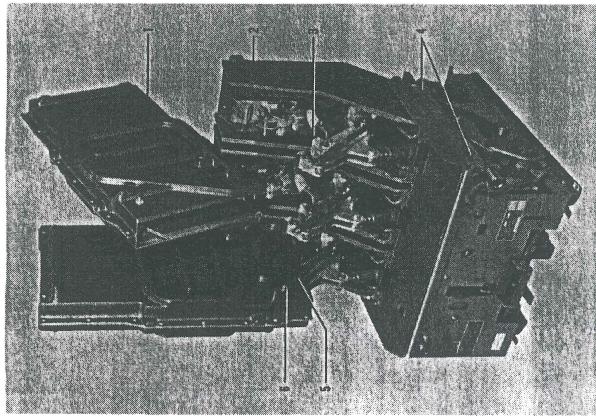


Fig. 1 — View Showing Arc Chute and Contact Structure

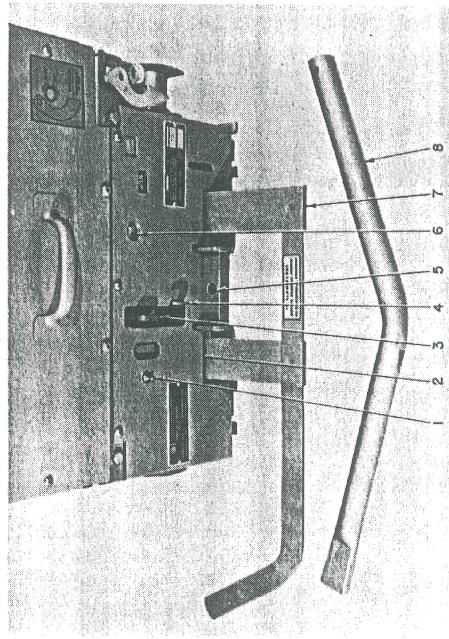


Fig. 2 — Front View of Control Panel

REMOVING ARC CHUTES (See Fig. 1)

For 5HK75, 150 and 250, remove nut (6) and gently disconnect return connection (5). Grasp the arc chute (1) at the front and top and gently tilt on its pivot towards the rear until it rests on the lead support molding (2). If other than visual inspection is to be done, the arc chute, in the tilted position, should be lifted straight out of the pivot guide slots and fingers and removed from the circuit breaker.

For 5HK350, remove nut (6) and gently disconnect return connection (5). Remove bolt connecting the front leg of the arc chute to the block on the base sheet of the circuit breaker. Attach the accessory lifting bracket to the tie bar bushing at the top front of the arc chute and slowly raise the arc chute as required by means of a hoist. It will pivot at its terminal connection and then should be guided straight out of the pivot guide slot and fingers and removed away from the circuit breaker. If only a visual examination is to be made, each arc chute may be tilted back gently, hand held and then slowly lowered.

CAUTION: Be sure return connection is clear and does not catch on the arc chute. Also block wheels to prevent breaker from rolling.

ARC CHUTE EXAMINATION

Examine arc chutes carefully before placing into service. Look for any breakage to liner plates and arc chute plates. Check for presence of any foreign particles such as chips of ceramic and metal. Inspect exterior for any damage or deformation. The polyester glass moldings occasionally have some small cracks develop in resin rich areas but these cracks do not indicate defective material and should not cause concern.

INSULATION STRUCTURE

All insulated parts should be checked for damage. Any dust or dirt should be removed by air or wiped with a clean lintless cloth saturated with an oil-free solvent. This is important because the soot or dirt can accumulate and, with moisture, can place the circuit breaker in jeopardy, dielectrically. The lead support moldings are polyester glass and occasionally have some resin rich cracks or crazing develop but these do not indicate defective material and should not cause concern.

MANUAL SLOW CLOSE TO CHECK CONTACT PRESSURE (See Fig. 2)

NOTE: Insure that accessories that affect electrical/mechanical operation are set in their operating position; i.e., undervoltage devices should be energized or mechanically closed; mechanical interlocks, key or other, should be properly set; etc.

Turn racking screw clockwise approximately two to three turns until the racking-unlocking lever snaps into the first position corresponding to the "DISCONNECT" position.

Engage manual charge handle (8) with charging lever (3). Pump charging lever until breaker closing springs snap into charge position, then remove handle.

INSTALLING ARC CHUTES (See Fig. 1)

Insert BOTH tangs of spring retainer bracket (7) into holes of closing spring guides (2).

Pull manual close lever (4) to discharge closing springs onto tangs of spring retainer bracket (7). At this time the contacts will partially close.

Re-engage manual charge handle (8) with charging lever (3), then slowly pump to slow close breaker contacts. Check contact pressure as listed in Adjustment Section, using the manual trip button (6) to open the breaker.

To remove spring retainer bracket (7) from circuit breaker, continue pumping until closing springs are again heard to snap into charged position. Spring retainer bracket can now be removed.

Discharge closing springs by pulling manual close lever (4) and pushing manual trip button (6) at the same time to effect a trip free operation. (Or the breaker can be closed first and then tripped.)

INSTALLING ARC CHUTES (See Fig. 1)

Position arc chute (1) in tilted position, squarely down into its rear pivot guide slots and fingers (avoid bumping and chipping of all moldings), then lower slowly into position.

CAUTION: Be sure return connection is clear and does not catch on the arc chute.

Securely fasten return connection (5) by its nut (6). Also, on 5HK350 breakers the front arc chute support leg must be secured to its hold down block.

INSTALLING INTERPHASE BARRIER

For 5HK75, 150 and 250, lift barrier and slide it approximately halfway on the breaker. Then, after aligning the vertical sheets of the barrier properly between the lead support moldings and inside the clips on the outside moldings, slide the barrier as far to the rear as possible. Lift the barrier slightly by its handle at the lower front (Fig. 2) to permit the rear brace of the barrier to drop down behind the arc chutes. Then, push firmly down and back on the barrier handle to properly position the interphase barrier in place. Secure the barrier in place with the two lower front sheet screws.

For the 5HK350, slide the right and left interphase barriers, as marked, in place between the lead support moldings and inside of the clips on the outside moldings, and pivot the rear brace downward behind the arc chutes. Install the arc chute tie bar at the upper front on the arc chutes. Then, left front sheet in place so that it hooks over the arc chute tie bar. Secure the barrier front sheet in place with the two lower front sheet screws.

CAUTION: On 5HK350, for older unmarked barriers, ensure that the flux shunt pad is installed between poles.

INSTALLING CIRCUIT BREAKER INTO COMPARTMENT

(See Figs. 2 & 3)

NOTE: CLOCKWISE ROTATION of racking crank for inserting breaker. COUNTERCLOCKWISE rotation of racking crank for removal of breaker.

Turn motor disconnect switch (if supplied) (1, Fig. 2) to "OFF" position.

5HK75, 5HK150 and 5HK250 circuit breakers be inspected after 1000 operations and that the 5HK350 circuit breakers be inspected after 500 operations because of the switching severity.

If however, after the first inspection period, there is no indication of any problems, actual operating experience can then dictate the inspection cycle.

Regarding maintenance recommendations following fault duty, reference is made to ANSI Standard C37.04 to which the circuit breakers have been tested. In accordance with this standard, a total of 400% asymmetrical fault duty can be accumulated. This is to be ten or less close-open operations at less than 85% of full fault duty, but it can be an accumulation over a long time period of lower currents. The condition of the breaker should be such that after this duty it is capable of one more close-open operation at full fault current. Inspection is to be made at this time to insure this and then the final operation can be made if everything is satisfactory. At this time, maintenance should be performed and reconditioning done and replacements made as indicated.

Further, in accordance with the same standard, it is recommended that after a major fault duty cycle (CO-15 SEC. -CO) which is known to be between 85 and 100% of the circuit breaker rated asymmetrical short circuit current that the circuit breaker be inspected regardless of any time period or number of operations. Also, when the circuit breaker is applied on reclosing duty, it should be inspected immediately after the series of fault operations in the same range of currents. The condition of the circuit breaker after interruption depends on the circuit conditions regarding such things as power factor, X/R ratio and relay delay times. Experience with specific circuits will indicate the future amount of maintenance that will be required for the various breakers and then modification in procedure can follow.

Of course, where unusual service conditions, as covered by ANSI Standard C37.04, exist, it must be assumed that these conditions were considered at the time of order; that the equipment supplied was designed for the special application; and that an appropriate supplemental maintenance program has been developed. These maintenance instructions only cover circuit breakers used under the standard usual service conditions.

After normal service without major fault interruption, the following tests and adjustments should be made:

NOTE: The following tabulated tests and adjustments are all that are normally necessary for proper maintenance and operation of the HK circuit breaker. The remaining portions of the breaker — close coil assembly, shunt trip device, control relay, auxiliary switch and motor — require no maintenance during the standard life of the circuit breaker regardless of the operating duty.

MILLIVOLT DROP TEST

During normal maintenance periods, the condition of the circuit breaker can easily be determined by per-

forming a millivolt drop test. This test should be performed regardless of whether the circuit breaker had interrupted low or high currents or has minimum operations.

The following table lists the millivolt drop and resistance values for the circuit breakers covered by this instruction book, from terminal to terminal, exclusive of the primary disconnects.

CIRCUIT BREAKER	MAXIMUM MV DROP*	MAXIMUM MICRO-OMMS
5HK75, 5HK150, 5HK250	5	45
5HK350 1200 Amperes	9	45
5HK150, 5HK250, 5HK350 2000 Amperes	7	35
5HK350 3000 Amperes	4	20

* Millivolt drop with 200 amperes flowing.

If the millivolt drop does not exceed 150% of the above values, on breakers with normal loading, no maintenance is necessary. If the millivolt drop does exceed 150% of the above values, the main and arcing contacts should be dressed with a fine file, cleaned and be adjusted for proper contact pressure and then rechecked. If the values are still in excess of the 150% value, the bridge pivot pressure should be readjusted as outlined elsewhere.

However, for optimum performance of the circuit breakers during periods of increased loading, it is recommended that the listed values be met.

After all above steps have been taken and the millivolt drop is still excessive, contact Gould for recommendations.

CONTACT AND INSULATION CLEANING

Any dirt, soot or grease should be removed from the circuit breaker contacts and surface of entire current carrying structure, as well as all insulation surfaces, with a cloth saturated with an oil-free solvent. Cleaning of the insulation is important because the soot and dirt can accumulate and, with moisture, can place the circuit breaker in jeopardy, dielectrically.

A degree of burning and pitting on the circuit breaker arcing contacts is to be expected from normal operation; also, on highly inductive or capacitive circuits and after major interruptions, some pitting may occur on the main contacts. A moderate amount of pitting will not interfere with the operation of the contacts. When necessary to dress the contacts, cover the puffer nozzle (3 - Fig. 1) with a cloth, then follow the contour of the contacts with a fine file. Do not attempt to eliminate pitting entirely. After this maintenance, the contact pressure and millivolt drop should be checked.

NOTE: Replacement of contacts need only be considered when: after repeated dressing of any contacts, less than 50% of the original contact material thickness is left; the tips of the stationary arcing contacts have been eroded away; any contact has been broken or cracked.

CONTACT PRESSURE (See Fig. 4)

A. With the circuit breaker withdrawn from the switchboard, the following step-by-step procedure should be followed for properly checking and/or adjusting the contact pressure on an "HK" type circuit breaker.

1. Remove interphase barrier assembly and remove arc chutes as described previously.
2. Turn racking screw clockwise approximately two to three turns until the racking-unlocking lever snaps into the first position corresponding to the "DISCONNECT" position.
3. Manually slow-close the circuit breaker as described on page 5, but only to the point that the arc contacts just touch. All arcing contacts should touch within $1/32''$.

4. Continue the slow-close operation to fully close the breaker. Each pole should have between $7/64''$ minimum and $3/16''$ maximum main contact compression measured at "A" between the EDGE of the metal stop plate and the main contact stop. (This dimension measured on either side is sufficient.) A rod or drill of these sizes can be used for measuring.

At this point, if the adjustments are correct, complete steps B6, B7, B8 and B9 following.

B. If any adjustment is incorrect, use the following procedure to readjust contact pressure or to initially adjust when changes are made:

1. Completely slow-close the circuit breaker and set each pole for $7/64''$ main contact compression at "A". (A $7/64''$ rod or drill should fit tightly between the EDGE of the metal stop plate and the main contact stop.)
2. Open the circuit breaker, manually recharge the closing springs, and partially slow-close the circuit breaker until the arcing contacts of any pole or poles just touch.

3. Advance the adjustment of the lagging pole or poles so that the three arcing contacts touch simultaneously within $1/32''$. This adjustment is made by loosening locking bolt or set screw (depending on model) (2) and rotating adjusting stud (3).

4. Complete slow-close operation to fully closed position and check that the main contact compression of the pole or poles that were advanced does not exceed $3/16''$. Also, the arcing contact springs on these poles should not be fully compressed. If the $3/16''$ dimension is exceeded, the entire procedure should be repeated to obtain the correct gap at "A".

NOTE: Occasionally, the center pole contact pressure may slightly exceed $3/16''$. However, if the outer contact springs of the center pole are not fully compressed no readjustment need be made. When this condition exists, the center pole parts before the outer poles on opening.

5. Open the circuit breaker, recharge the closing springs, remove the slow-close bracket, fast-close the breaker, recheck adjustments and trip open.

NOTE: Fast-closing the circuit breaker results in a slight increase in contact pressure over slow-closing.

6. Tighten the locking bolt (2) on each adjusting stud (3) to lock the contact pressure adjustment stud in place.

7. The arc chutes can now be replaced, and the interphase barrier assembly can now be reinstalled.

8. Return the racking screw to its original position by turning it counterclockwise approximately two to three turns until it stops.

9. The circuit breaker can now be replaced in its compartment and returned to service.

PUFFERS (3, Fig. 1)

The performance of the puffers can be readily checked during a maintenance interval. Each puffer should provide a moderate blast of air at the breaker contacts, on opening of the circuit breaker. This can be detected by holding the hands or arm over the top of the contacts and opening the circuit breaker. All three poles must have puffing action or else the circuit breaker must not be placed in service.

FOR SAFETY: Keep clear of all moving parts.

CLOSING AND OPENING TIMES

After the operation intervals noted previously or a change in bridge pivot adjustment, the closing and opening times are recommended to be checked by use of a cycle counter, time-travel analyzer, oscillograph etc. to monitor the time from energizing to arcing contact touch or part.

*Analyzer mounting support and instructions available on special order.

The circuit breaker closing and opening times should be within the following time ranges for normal operation.

CIRCUIT BREAKER	CLOSING TIME RANGE - MS *	OPENING TIME RANGE - MS *
5HK75, 5HK150, 5HK250 1200 Amperes	50 - 90	23 - 35
5HK150 & 5HK250 2000 Amperes	60 - 95	23 - 35
5HK350 1200 & 2000 Amperes 3000 Amperes	50 - 90 85 - 95	23 - 35

* At 125Vdc. Other voltages may vary slightly. Times at other voltages will increase (but NOTE: 5HK250, 800A high momentary same as 5HK350, 1200 & 2000 Amperes, in table above).

NOTES:

1. Below 0° C., the closing times will increase (but with no reduction in closing force); and opening times will be within the limits.

2. Adjustments to correct times, if found to be outside limits, are critical and Gould Inc. should be contacted for recommendations.

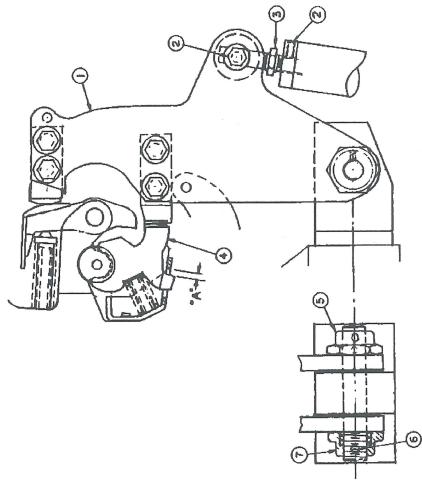


Fig. 4 — Contact Pressure and Bridge Pivot Pressure

ARC CHUTES

The arc chutes should be inspected internally to insure that no breakage occurred to the liner plates or arc plates. Further, there may be a crust formed on the liner plates if the load current interruptions were close to the continuous current rating of the breaker or moderate faults were interrupted. This crust should be removed by carefully using a carbondum stone or scraper. Then the arc chute should be blown out with air to remove the resultant dust and particles.

After 400% accumulated current or major interruptions occur, the circuit breaker should be inspected immediately afterwards, as stated previously. All maintenance checks or tests noted above should be looked out plus the arc chutes should be looked at closely. Arc plate and liner plate breakage should be carefully looked for, along with excessive erosion of the arc plates. The arc plates are made of ceramic material and perform the function of extracting heat from the arc as it is being forced into and elongated by them. The leading edges become coated with glass that comes to the surface from the extreme heat. The direct measure of use is the amount of glass beads evident.

When the entire leading edge and portions of the flat arc plate are noted to be heavily encrusted with glass beads, the arc chute should be replaced. It should be noted that this condition will vary between arc chutes on the same breaker because of single-phase fault and asymmetrical current incidences. If there are any questions, contact Gould Inc. for recommendations.

BRIDGE PIVOT PRESSURE (See Fig. 4)

Bridge pivot pressure should be adjusted only when the millivolt drop test indicates a problem.

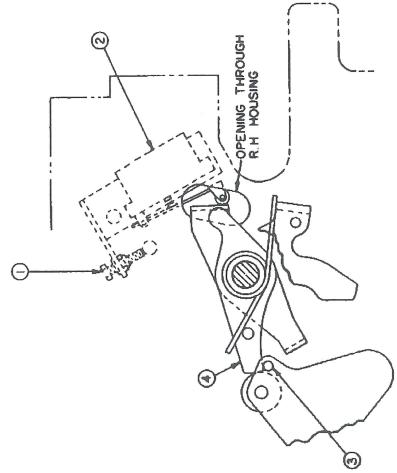


Fig. 5 — Latch Check Switch Adjustment

When this adjustment is necessary, the following steps should be done.

1. Locking bolt (2) should be loosened on solid pushrod models. Spring-loaded pushrod models do not require disconnecting.

2. Bridge (1) should be disconnected from adjusting stud (3) on solid pushrod models.

3. Loosen one set screw (6) in one pivot nut — either side.

4. Tighten bridge pivot nut (5 or 7) securely (approximately 75 ft. lbs.). Then gradually back up pivot nut (approximately $\frac{1}{2}$ - $\frac{1}{2}$ flats) until bridge motion is just free when bridge is moved by hand. On spring-loaded pushrod models, lift bridge against spring and then slowly release, insuring that it resets freely.

5. Tighten set screw (6) in nut that was loosened, reconnect adjusting stud, if disconnected, and readjust contact pressure as described elsewhere.

OPERATING MECHANISM (See Fig. 5)

The operating mechanism is adjusted at the factory for proper operation and should not be disturbed unless the circuit breaker does not close electrically on reclosing duty.

This condition is caused when the latch check switch (when used) is not actuated. Circuit breaker should not close before trip latch (4) has reset.

Adjustments should be made with latch (4) against reset stop pin (3). Turn in adjusting screw (1) until contacts of switch (2) "break" (as indicated by an audible click or check with bell ringer). Retract adjusting screw until switch contacts "make", then rotate adjusting screw one turn more. (Adjusting screw is self-locking.)

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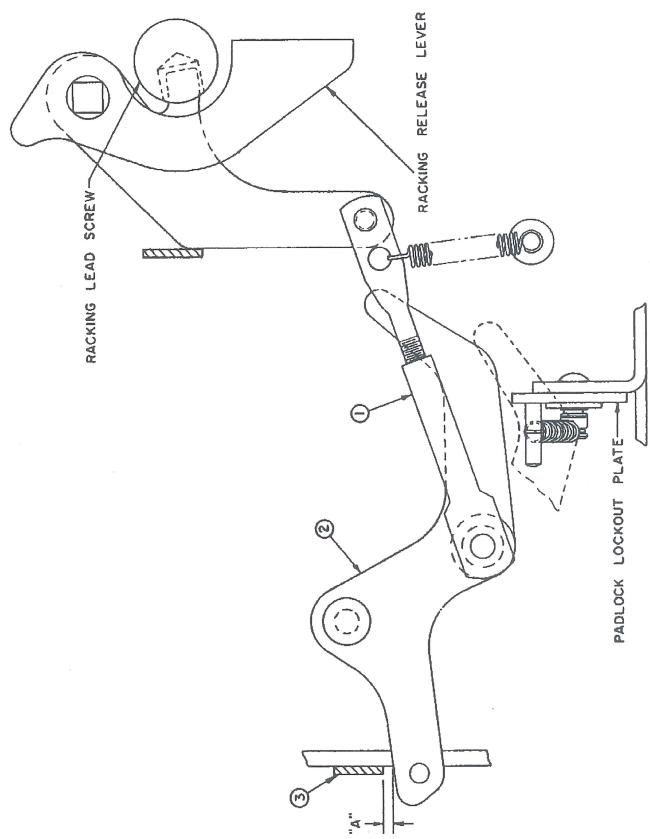


Fig. 6 — Racking Mechanism

TABLE 1 - OPERATING VOLTAGE RANGE

NOMINAL CONTROL VOLTAGE	SPRING CHARGING MOTOR	CLOSE COIL	TRIP COIL	UNDERVOLTAGE	
				PICK-UP MAXIMUM	DROP-OUT
24 V dc	-	18-28	14-30	21	7-14
48 V dc	35-50	25-50	28-60	41	15-38
125 V dc	80-130	90-130	70-140	106	38-75
250 V dc	160-260	180-260	140-260	212	75-50
115 V ac	95-125	93-125	95-125	97	34-58
230 V ac	180-250	190-250	190-250	185	69-138

TABLE 2 - AVERAGE CURRENT VALUES

NOMINAL CONTROL VOLTAGE	SPRING CHARGING MOTOR	CLOSE COIL	TRIP COIL	LOCKOUT COIL	UNDER-VOLTAGE	
					N.E.C. FUSE	
24 V dc	-	22.0	22.0	0.30	0.9	30
48 V dc	25.0	10.7	10.7	0.15	0.5	30
125 V dc	10.0	5.0	5.0	0.06	0.2	30
250 V dc	5.0	2.2	2.2	0.13	0.1	30
115 V ac	10.0	4.5	4.5	0.40	0.2	30
230 V ac	5.0	2.3	2.3	0.20	0.1	30

RACKING MECHANISM (See Fig. 6)

The circuit breaker racking mechanism is adjusted for proper operation and should not be disturbed unless it becomes possible to close the breaker during a racking operation.

It may be possible that interlocked blocking members are not positioned properly, which should be corrected as follows:

Remove the lower front mechanism coverplate and with the circuit breaker closed, make adjustments by regulating the length of connecting rod (1) for 1/8 inch minimum to 3/16 inch maximum clearance at "A" between trip link (3) and blocking lever (2).

LUBRICATION

The HK circuit breakers are lubricated during factory assembly as follows:

1. All mating surfaces of moving current-carrying joints have been lubricated with NO-OX-ID special grade "A" grease manufactured by Dearborn Chemical Company.
2. All other mechanism parts, bearings, pins, etc. have been lubricated with ANDEROL L757 manufactured by Tenneco Chemical, Inc., Intermediate Division.

The circuit breaker requires no lubrication during its normal service life. However, if the grease should become contaminated or if parts are replaced, any relubrication should be done with NO-OX-ID or ANDEROL grease as applicable.

NOTES:

1. Do not use NO-OX-ID grease on any main and arcing contact surfaces.
2. It is recommended that the primary disconnects be maintained by renewing the NO-OX-ID grease during maintenance periods.
3. Do not use light oil to lubricate any mechanism parts.
4. The charging motor is sealed and no lubrication is required.

DIELECTRIC TESTS

If it is desired to make dielectric tests during maintenance periods, the following test values should be used and are to be applied for a one minute period.

CIRCUIT	80HZ	DC
PRIMARY	11.5kV	16kV
*SECONDARY (CONTROL)	1100V	1500V

* It is necessary that the charging motor be disconnected for this test by turning the motor disconnect switch to the "OFF" position. If a test is desired on the motor, then the motor disconnect switch should be turned to the "ON" position and the circuit re-tested at 54.0V, 60Hz or 760V DC.

ELECTRICAL CHARACTERISTICS OF CONTROL DEVICES

For operating voltage ranges for various nominal control voltages refer to Table 1.

For average current values at various nominal control voltages, refer to Table 2. The current values given in this table are average, steady state values and momentary inrush currents for all charging motors and AC coils are approximately six to eight times these values.

ELECTRICAL OPERATING SEQUENCE

Please refer to the specific schematic diagrams and other operational information furnished with your order.

Fig. 7 is provided as a typical schematic for general information on electrical operation.

The operation of accessories, when installed as ordered, can affect the electrical/mechanical operations of the circuit breaker. When the circuit breaker is being tested electrically or mechanically, undervoltage devices should be energized or otherwise mechanically closed and mechanical interlocks, key or other, should be set in the operate position.

GROUND AND TEST DEVICES

These devices are supplied when ordered and are basically three design types, with certain component variations such as test ports and interlocks.

— Simple, three terminal, non-automatic.

— Simple, three terminal, electrically operated.

— Complex, six terminal, electrically operated with manual selector switch.

These devices are basically maintenance free for their normal operating life. Racking procedure is the same as for the basic circuit breaker as outlined previously, and all detailed operational instructions are attached to the individual devices and need not be repeated here.

RENEWAL PARTS

We recommend only those renewal parts be stocked that will be required to insure proper and timely maintenance for normal operation of the HK circuit breakers. Copies of the applicable Renewal Parts Bulletin for specific circuit breakers will be furnished on request to our nearest sales office.

The minimum quantity of assemblies and items recommended in these bulletins are predicated on infrequent replacement of parts based on accumulated tests and operating experience. Total assemblies are recommended for fast replacement, when necessary, to return the breaker to service as quickly as possible. Then certain replaced assemblies, such as the stationary upper terminals, can be returned to the factory for nominal reconditioning. The bulletins contain specific part ordering instructions; and if desired, specific instructions regarding replacement of those part assemblies recommended, that are not obvious, are also available if ordered.

