Single-Phase AC Power Electronics

Student Manual
86359-00
The following safety and common symbols may be used in this manual and on the Lab-Volt equipment:

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td><img src="image" alt="DANGER" /></td>
<td><strong>DANGER</strong> indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.</td>
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<tr>
<td><img src="image" alt="WARNING" /></td>
<td><strong>WARNING</strong> indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.</td>
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<tr>
<td><img src="image" alt="CAUTION" /></td>
<td><strong>CAUTION</strong> indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.</td>
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<td><img src="image" alt="CAUTION" /></td>
<td><strong>CAUTION</strong> used without the <em>Caution, risk of danger</em> sign, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.</td>
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## Safety and Common Symbols

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<tr>
<td><img src="image" alt="Symbol" /></td>
<td>Protective conductor terminal</td>
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<td><img src="image" alt="Symbol" /></td>
<td>Frame or chassis terminal</td>
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<td><img src="image" alt="Symbol" /></td>
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<td>Off (supply)</td>
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<tr>
<td><img src="image" alt="Symbol" /></td>
<td>Equipment protected throughout by double insulation or reinforced insulation</td>
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<tr>
<td><img src="image" alt="Symbol" /></td>
<td>In position of a bi-stable push control</td>
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<tr>
<td><img src="image" alt="Symbol" /></td>
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Preface

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions. The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand. Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

To answer the increasingly diversified needs for training in the wide field of electrical energy, Lab-Volt developed the Electric Power Technology Training Program, a modular study program for technical institutes, colleges, and universities. The program is shown below as a flow chart, with each box in the flow chart representing a course.

The Lab-Volt Electric Power Technology Training Program.
The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics. The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, large-scale electricity production from wind power (doubly-fed induction generator [DFIG], synchronous generator, and asynchronous generator technologies), smart-grid technologies (SVC, STATCOM, HVDC transmission, etc.), storage of electrical energy in batteries, and drive systems for small electric vehicles and cars.
About This Manual

This course introduces the student to power electronic circuits (rectifiers and inverters) used to perform ac/dc power conversion in single-phase circuits. The course begins with the study of single-phase diode rectifiers. The student then becomes familiar with the operation of the single-phase inverter and the single-phase PWM inverter. The course concludes with the study of power flow in a single-phase PWM inverter.

Manual objectives

When you have completed this manual, you will be familiar with the main types of choppers. You will also be familiar with high-speed power switching (voltage-type and current-type circuits, free-wheeling diodes, etc.). Finally, you will know how to control ripple in choppers, and to build a battery charger using a buck chopper.

Prerequisite

As a prerequisite to this course, you should have read the manual titled DC Power Circuits, part number 86350, DC Power Electronics, part number 86356, and Single-Phase AC Power Circuits, part number 86358.

Safety considerations

Safety symbols that may be used in this manual and on the Lab-Volt equipment are listed in the Safety Symbols table at the beginning of the manual.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Systems of units

Units are expressed using the International System of Units (SI) followed by the units expressed in the U.S. customary system of units (between parentheses).
The Discussion of Fundamentals covers the following points:

- Introduction

Power electronics circuits can be found wherever there is a need to modify a form of electrical energy (i.e., change in voltage, current, or frequency). In modern systems, the conversion is performed with semiconductor switching devices such as diodes, thyristors, and transistors. By contrast with microelectronics systems concerned with transmission and processing of signals and data, substantial amounts of electrical energy are processed in power electronics.

As efficiency is at a premium in power electronics, the losses caused by a power electronic device should be as low as possible. The instantaneous power dissipated in a device is equal to the product of the voltage across the device and the current through it. From this, one can see that the losses of a power device are at a minimum when the voltage across it is zero or when no current flows through it. Therefore, a power electronic converter is built around one or more devices operating in switching mode (either on or off). With such a structure, the energy is transferred from the input of the converter to its output by bursts and with minimal power losses.

For instance, uninterruptible power supplies (UPS) use a battery (dc power) and an inverter to supply ac power when main power is not available. When main power is restored, a rectifier is used to supply dc power to recharge the battery. The following figure shows a typical uninterruptible power supply for computer equipment.

![Figure 1. Typical uninterruptible power supply for computer equipment.](image-url)
When you have completed this exercise, you will know what a diode is, and how it operates. You will be familiar with two types of circuits using diodes to convert single-phase ac voltage into dc voltage: the half-wave rectifier and the full-wave (bridge) rectifier. You will be familiar with the waveforms of the voltages and currents present in these rectifiers. You will know how to calculate the average dc voltage provided by each type of rectifier.

The Discussion of this exercise covers the following points:

- The diode
- Operating principles of a diode
- Characteristic voltage-current curve of a diode
- Single-phase half-wave rectifier
- Single-phase full-wave (bridge) rectifier

The diode

A diode is a semiconductor device that allows electrical current to flow in one direction only. Figure 2 shows a typical low-power diode. The diode has two terminals, called the anode and the cathode. A ring mark on the diode case identifies the terminal corresponding to the cathode. The other terminal corresponds to the anode.

![Figure 2. The diode.](image)

Figure 3 shows the construction and schematic symbol of a diode.

![Figure 3. Construction and schematic symbol of a diode.](image)
As the figure shows, the diode consists of two layers of semiconducting material (semiconductors):

- A **P-type** semiconductor layer containing positive charge carriers (holes). The P-type layer corresponds to the anode (A) terminal of the diode.
- An **N-type** semiconductor layer containing negative charge carriers (electrons). The N-type layer corresponds to the cathode (K) terminal of the diode.

**Operating principles of a diode**

The diode is an essential component of *rectifier* circuits, as you will see in another subsection. When used in a rectifier, the diode operates as a high-speed switch with no movable parts.

- When no voltage is present across the diode terminals, the diode is in the “off” (blocked) state. No current flows through the diode, and the diode acts like an open switch as shown in Figure 4.

![Figure 4. When no voltage is present across the diode terminals, the diode acts as an open switch. Therefore, no current flows through the diode.](image)

- When a voltage is present across the diode terminals and the voltage at the anode is lower than the voltage at the cathode, the diode acts as an open switch. Therefore, no current flows through the diode. In this condition, the diode is said to be **reverse biased** as shown in Figure 5.

![Figure 5. When the voltage at the anode is lower than the voltage at the cathode (i.e., when voltage $E_{AK}$ is negative), the diode acts as an open switch: no current flows through the diode.](image)
- When a voltage is applied across the diode terminals, and the voltage at the anode is higher than the voltage at the cathode, the diode passes from the “off” (blocked) state to the “on” (conducting) state. In this case, the diode is said to be **forward biased**: it acts as a closed switch, allowing the current to flow from the anode to the cathode as shown in Figure 6.

![Figure 6. When the voltage at the anode is higher than the voltage at the cathode (i.e., when voltage $E_{AK}$ is positive), the diode acts as a closed switch and the current flows through the diode in the direction indicated.](image)

- As long as current flows through the diode, the diode remains forward biased and acts like a closed switch. When the current stops flowing through the diode (even for a very brief period), the diode becomes like an open switch and the voltage across the diode terminals drops to 0 V as shown in Figure 7.

![Figure 7. When the current stops flowing through the diode, the diode becomes like an open switch and the voltage across the diode terminals drops to 0 V.](image)

**Characteristic voltage-current curve of a diode**

The **characteristic curve** of a diode represents the current flowing through the diode as a function of the voltage across its terminals. Figure 8 shows the characteristic curve of an ideal diode and that of a real diode.

- **Ideal diode**: when the diode is reverse biased, it acts like a perfect insulator. Therefore, no current flows through the diode. When the diode is forward biased, it acts like a perfect conductor. Therefore, current flows through the diode without a voltage drop across the diode.
- **Real diode**: when the diode is reverse biased, a small *leakage current* flows through it. When the diode is forward biased, the current flowing through it increases very rapidly as the voltage increases, until the diode becomes fully conducting. Note that the diode conducts little when the forward voltage is below a minimum value, called the *knee voltage*. The knee voltage is the voltage drop across the diode (typically 0.7 V in the case of a silicon diode) when the current starts to increase very rapidly.

![Characteristic voltage-current curves of an ideal diode and a real diode.](image)

*Figure 8. Characteristic voltage-current curves of an ideal diode and a real diode.*
**Single-phase half-wave rectifier**

A single-phase half-wave rectifier simply consists of a diode connected between an ac voltage source and a load (resistor $R$) as shown in Figure 9a.

(a) During the positive half of source voltage $E_s$, the diode is forward biased.

(b) Waveforms of the circuit voltages and current.

Figure 9. Single-phase half-wave rectifier.
The + and – signs next to voltage $E_a$ in Figure 9a indicate the convention of measurement of this voltage.

The diode operates as a high-speed switch, allowing the current to flow only during the positive half-wave of the source voltage $E_S$.

- At instant $t_0$, the source voltage is zero. Therefore, the voltage across the diode is zero and it acts as an open switch, preventing current from flowing through the circuit. The voltage across the load (rectifier output voltage), $E_0$, is therefore null.

- During the positive half of the source voltage waveform (i.e., between instants $t_0$ and $t_1$), the diode is forward biased, allowing current to flow through the circuit. Therefore, the waveforms of the rectifier output current and voltage have the same shape as the source voltage waveform. The voltage drop across the diode is very low: it is equal to the knee voltage.

- At instant $t_1$, the load current (diode current) becomes 0 and the diode stops conducting current (i.e., the diode turns off).

- During the negative half of the source voltage waveform (i.e., between instants $t_1$ and $t_2$), the diode is reverse biased, preventing current from flowing through the circuit. Therefore, the rectifier output current and voltage are null. Meanwhile, all the voltage applied by the source (negative half of the source voltage) is present across the diode. The maximum value of this voltage is called the peak inverse voltage (PIV). It corresponds to the maximum voltage the diode must withstand when it is reverse biased.

- The load voltage (rectifier output voltage) is, therefore, a pulsating voltage which is positive during half of the source voltage cycle, and null during the other half of this cycle. The rectifier output voltage is unipolar because it keeps the same polarity (positive) during the whole cycle. This occurs because the current can flow in one direction only.

Neglecting the voltage drop across the diode, the amplitude of the rectifier output voltage $E_{0, max}$, is equal to the amplitude of the source voltage $E_{S, max}$. The average value of the dc voltage at the rectifier output $E_{0, avg}$, is equal to $0.318 E_{S, max}$ or $0.45 E_{S, rms}$.

The diode used in the rectifier of Figure 9 has a conduction angle of 180°, which means that it conducts current during half of the whole cycle (the whole cycle corresponding to 360°).

Since single-phase half-wave rectifiers provide power to the load during half of the ac power source cycle only, they lack the efficiency required by most applications. Furthermore, the output current of these rectifiers has a non-null average (dc) component that flows through the ac power source, i.e., the electrical power network, which is highly undesirable. Consequently, single-phase full-wave rectifiers are used in most applications instead of single-phase half-wave rectifiers.
**Single-phase full-wave (bridge) rectifier**

A single-phase full-wave (bridge) rectifier consists of four diodes connected between an ac voltage source and a load (resistor $R$) as shown in Figure 10. A pair of diodes ($D_1$ and $D_4$) allows current to flow during the positive half of the source voltage waveform. The other pair of diodes ($D_2$ and $D_3$) allows current to flow during the negative half of the source voltage waveform.

![Diagram of single-phase full-wave rectifier]

Figure 10. Single-phase full-wave (bridge) rectifier.

Figure 11 shows the waveforms of the circuit voltages and currents.

- During the positive half of the source voltage waveform (i.e., between instants $t_0$ and $t_1$), diodes $D_1$ and $D_4$ are forward biased. Therefore, the current ($I_{D_1-D_4}$) flows through diode $D_1$, the load resistor $R$, and diode $D_4$. Meanwhile, diodes $D_2$ and $D_3$ are reverse biased, so no current flows through these diodes.

- During the negative half of the source voltage waveform (i.e., between instants $t_1$ and $t_2$), diodes $D_2$ and $D_3$ are forward biased. Therefore, the current ($I_{D_2-D_3}$) flows through diode $D_2$, the load resistor $R$, and diode $D_3$. Meanwhile, diodes $D_1$ and $D_4$ are reverse biased, so no current flows through these diodes.

- Notice that the current in the load resistor $R$ flows in the same direction during each half of the ac voltage source waveform. The load voltage (rectifier output voltage) is, therefore, a full-wave rectified voltage composed of two positive half-waves per cycle of the source voltage $E_S$. This voltage is unipolar because it keeps the same polarity (positive) during the whole cycle.

Neglecting the voltage drop across the diodes, the amplitude of the rectifier output voltage $E_{o,max}$ is equal to the amplitude of the source voltage $E_{S,max}$. The average value of the rectifier output voltage $E_{o,avg}$ is equal to $0.636E_{S,max}$, or $0.9E_{o,rms}$, that is, twice the average voltage supplied by a single-phase half-wave rectifier.
Figure 11. Waveforms of the circuit voltages and currents.
**Exercise 1 – Power Diode Single-Phase Rectifiers**

**Procedure Outline**

The Procedure is divided into the following sections:

- Setup and connections
- Characteristic curve of a diode
- Single-phase half-wave rectifier
- Single-phase full-wave (bridge) rectifier

**Procedure**

![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.

**Setup and connections**

_In this part of the exercise, you will set up and connect the equipment._

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform this exercise.

   Install the required equipment in the **Workstation**.

2. Connect the **Power Input** of the **Data Acquisition and Control Interface** to a 24 V ac power supply. Turn the 24 V ac power supply on.

3. Connect the USB port of the **Data Acquisition and Control Interface** to a USB port of the host computer.

   Connect the USB port of the **Four-Quadrant Dynamometer/Power Supply** to a USB port of the host computer.

4. Make sure that the main power switch of the **Four-Quadrant Dynamometer/Power Supply** is set to **O** (off), then connect the **Power Input** to an ac power outlet.

   Set the **Operating Mode** switch of the **Four-Quadrant Dynamometer/Power Supply** to **Power Supply**.

   Turn the **Four-Quadrant Dynamometer/Power Supply** on by setting the main power switch to **I** (on).

5. Turn the host computer on, then start the **LVDAC-EMS** software.

   In the **LVDAC-EMS Start-Up** window, make sure that the **Data Acquisition and Control Interface** is detected. Make sure that the **Computer-Based Instrumentation** function for the **Data Acquisition and Control Interface** is available. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the **OK** button to close the **LVDAC-EMS Start-Up** window.
6. Set up the circuit shown in Figure 12. In this circuit, $E_S$ is an ac power source obtained by using the Four-Quadrant Dynamometer/Power Supply. $E_1$ and $I_1$ are voltage and current inputs of the Data Acquisition and Control Interface. The diode $D$ is one of the diodes in the Rectifier and Filtering Capacitors module. Load resistor $R$ is implemented with the Resistive Load module.

![Figure 12. Circuit used to observe the characteristic curve of a diode.](image)

7. Make the necessary connections and switch settings on the Resistive Load module in order to obtain the resistance value required.

   Appendix B lists the switch settings required on the Resistive Load in order to obtain various resistance values.

**Characteristic curve of a diode**

In this part of the exercise, you will observe the voltage-versus-current curve of a diode.

8. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window and make the following settings:

   - Set the Function parameter to AC Power Source. This setting makes the internal power source operate as an ac power source (i.e., a source producing a sinusoidal voltage).
   
   - Set the No-Load Voltage parameter to 100 V. This sets the effective (rms) voltage of the ac power source to 100 V.
   
   - Set the Frequency parameter to the frequency of your local ac power network. This makes the frequency of the ac power source equal to the frequency of your local ac power network.
   
   - Start the ac power source.
9. Open the Oscilloscope.

In the Data Acquisition and Control Settings window of LVDAC-EMS, set the Range of $E_1$ to Low.

On the Oscilloscope, display the diode voltage ($E_1$) and diode current ($I_1$) on Channel 1 (X) and Channel 2 (Y), respectively. Set the sensitivity of Channel 1 (X) and Channel 2 (Y) to 2 V/div and 0.5 A/div, respectively. Select the X-Y mode of operation by setting the Display X-Y parameter to On. Also, set the Acquisition Filtering parameter to On. In the X-Y mode, the horizontal axis represents the instantaneous value of the voltage across the diode, while the vertical axis represents the instantaneous value of the current through the diode.

When doing measurements using the Metering window, Oscilloscope, or Phasor Analyzer of LVDAC-EMS, always select the continuous refresh mode. This enables updated data to be seen on the computer screen at all times.

Based on the displayed curve, does current flow through the diode in one direction only? Explain.

10. Does the diode operate as a switch? Explain.

11. In the Four-Quadrant Dynamometer/Power Supply window, stop the ac power source.

**Single-phase half-wave rectifier**

In this part of the exercise, you will study the operation of a single-phase half-wave rectifier. You will observe the waveforms of the voltages and current in the rectifier using the oscilloscope. You will determine the conduction angle of the diode. You will then measure the frequency of the rectified voltage, as well as the average values of the rectified voltage, current, and power.
12. Set up the circuit shown in Figure 13. In this circuit, $E_S$ is an ac power source obtained by using the Four-Quadrant Dynamometer/Power Supply. $E_1$, $E_2$, and $I_1$ are voltage and current inputs of the Data Acquisition and Control Interface. The diode $D$ is one of the diodes in the Rectifier and Filtering Capacitors module. Load resistor $R$ is implemented with the Resistive Load module.

![Figure 13. Single-phase half-wave rectifier.](image)

13. In the Four-Quadrant Dynamometer/Power Supply window, make sure that the No-Load Voltage parameter is set to 100 V, then start the ac power source.

14. In the Data Acquisition and Control Settings window of LVDAC-EMS, set the Range of $E_1$ to Auto.

15. On the Oscilloscope, disable the X-Y mode of operation by setting the Display X-Y parameter to Off. Display the source voltage ($E_1$), the rectifier output current (source current) [$I_1$], and the rectifier output voltage ($E_2$), on channels 1, 2, and 3, respectively. Make sure that the time base is set to display at least two cycles of the sine waves.

Briefly describe the relationship between the waveforms of the rectifier output current ($I_0$), and rectifier output voltage ($E_0$), and the waveform of the source voltage ($E_S$).

16. Evaluate the conduction angle of the half-wave rectifier’s diode.

Conduction angle of the half-wave rectifier’s diode = _______°
17. Measure and record the ripple frequency (frequency of the pulses in the rectifier output voltage).

Ripple frequency = ________ Hz

18. In LVDAC-EMS, open the Metering window. Set meters E2 and I1 to measure the average (dc) values of the rectifier output voltage ($E_{o, avg}$) and rectifier output current ($I_{o, avg}$), respectively. Record these values below.

Average rectifier output voltage $E_{o, avg} = ________ V$

Average rectifier output current $I_{o, avg} = ________ A$

Calculate the rectifier output power $P_o$ from the average values of voltage $E_o$ and current $I_o$.

Rectifier output power $P_o = E_{o, avg} \times I_{o, avg} = ________ W$

19. In the Metering window, set meter E1 to measure the rms value of the source voltage $E_s$. Record this value below.

Source voltage $E_s = ________ V$

Compare the source voltage $E_s$ to the average rectifier output voltage $E_{o, avg}$, obtained in the previous step. Is $E_{o, avg} = 0.45E_s$?

☐ Yes  ☐ No

20. In the Four-Quadrant Dynamometer/Power Supply window, stop the ac power source.

**Single-phase full-wave (bridge) rectifier**

In this part of the exercise, you will study the operation of a single-phase full-wave rectifier. You will determine which pair of diodes is conducting depending on the polarity of the source voltage. You will verify that the polarity of the rectifier output current and voltage is always positive. You will then observe the waveforms of the voltages and currents in the rectifier. You will measure the frequency (ripple) of the rectified voltage, the conduction angle of the diodes, as well as the average values of the rectified voltage, current, and power. You will compare your results to those previously obtained for a half-wave rectifier.
Exercise 1 – Power Diode Single-Phase Rectifiers  

Procedure

**Circuit operation**

21. Set up the circuit shown in Figure 13. In this circuit, $E_S$ is a positive dc voltage source implemented using the Four-Quadrant Dynamometer/Power Supply. $E_1$, $E_2$, $E_3$, $E_4$, $I_1$, and $I_2$ are voltage and current inputs of the Data Acquisition and Control Interface. Diodes $D_1$, $D_2$, $D_3$, and $D_4$ are diodes in the Rectifier and Filtering Capacitors module. Resistor $R$ is implemented with the Resistive Load module.

![Figure 14. Single-phase full-wave rectifier (circuit operation).](image)

22. In the Four-Quadrant Dynamometer/Power Supply window, select the Voltage Source (+) function, then set the Voltage parameter to 100 V. Start the dc voltage source.

23. In the Metering window of LVDAC-EMS, set meters $E_1$, $E_2$, $E_3$, and $E_4$ to measure the dc voltages across diodes $D_1$, $D_2$, $D_3$, and $D_4$, respectively. Set meters $I_1$ and $I_2$ to measure the dc current at the rectifier output, $I_O$, and the dc source current $I_S$, respectively. Record your results below.

\[
E_{D1,dc} = \underline{\quad} \text{V} \quad E_{D4,dc} = \underline{\quad} \text{V}
\]
\[
E_{D2,dc} = \underline{\quad} \text{V} \quad I_{O,dc} = \underline{\quad} \text{A}
\]
\[
E_{D3,dc} = \underline{\quad} \text{V} \quad I_{S,dc} = \underline{\quad} \text{A}
\]
24. Notice that the rectifier output current $I_o$, is equal to the dc source current $I_S$. This indicates that a complete (closed) electrical path exists between the positive and negative terminals of the source, allowing current to flow through resistor $R$. Based on the dc voltages measured across the diodes, determine which diodes are in the “on” (conducting) state, and which diodes are in the “off” (blocked) state. Explain.

25. Determine the rectifier output voltage $E_o$, using the rectifier output current $I_o$, measured in step 23, and the resistance value of resistor $R$.

$$E_{o} = I_o \times R = \boxed{\text{_______ V}}$$

26. In the Four-Quadrant Dynamometer/Power Supply window, stop the dc voltage source.

Reverse the circuit connections at the yellow and white terminals of the Four-Quadrant Dynamometer/Power Supply to reverse the polarity of the source voltage. Do not make any other changes in the rest of the circuit.

In the Four-Quadrant Dynamometer/Power Supply window, start the dc voltage source.

27. Using meters $E_1$, $E_2$, $E_3$, $E_4$, $I_1$, and $I_2$, measure the dc voltages across diodes $D_1$, $D_2$, $D_3$, and $D_4$, the dc current at the rectifier output $I_o$, and the dc source current $I_S$, respectively. Record your results below.

$$E_{D_1,dc} = \boxed{\text{_______ V}}$$
$$E_{D_2,dc} = \boxed{\text{_______ V}}$$
$$E_{D_3,dc} = \boxed{\text{_______ V}}$$
$$I_{o,dc} = \boxed{\text{_______ A}}$$
$$I_{S,dc} = \boxed{\text{_______ A}}$$

28. Notice that the magnitude of the rectifier output current $I_o$, is again equal to the dc source current $I_S$. Based on the dc voltages measured across the diodes, determine which diodes are in the “on” (conducting) state, and which diodes are in the “off” (blocked) state. Explain your answers.

__________________________________________________________________________
__________________________________________________________________________
__________________________________________________________________________
29. Determine the rectifier output voltage $E_o$, using the rectifier output current $I_o$, measured in step 27, and the resistance value of resistor $R$.

Rectifier output voltage $E_o = I_o \times R = \underline{\quad} \text{V}$

30. Is the rectifier output current $I_o$ always positive, no matter the polarity of the dc source voltage?
   - Yes
   - No

31. From your observations, is the rectifier output voltage $E_o$, always positive regardless of the polarity of the source voltage?
   - Yes
   - No

32. Do the diodes of the full-wave rectifier conduct in pairs, i.e., diodes $D_1$ and $D_4$ are conducting when the source voltage polarity is positive, while diodes $D_2$ and $D_3$ are conducting when the source voltage polarity is negative?
   - Yes
   - No

33. In the Four-Quadrant Dynamometer/Power Supply window, stop the dc voltage source.

*Observation of the rectifier waveforms and measurement of the parameters*

34. Set up the circuit shown in Figure 15. In this circuit, $E_s$ is an ac power source. $E_1, E_2, I_1,$ and $I_2$ are voltage and current inputs of the Data Acquisition and Control Interface. Diodes $D_1$, $D_2$, $D_3$, and $D_4$ are diodes in the Rectifier and Filtering Capacitors module. Load resistor $R$ is implemented with the Resistive Load module.
35. In the Four-Quadrant Dynamometer/ Power Supply window, select the AC Power Source function, set the No Load Voltage parameter to 100 V, and set the Frequency parameter to the frequency of the local ac power network. Start the ac power source.

36. On the Oscilloscope, display the source voltage ($E_2$), the source current ($I_2$), the rectifier output current ($I_1$), and the rectifier output voltage ($E_1$) on channels 1, 2, 3, and 4, respectively. Make sure that the time base is set to display at least two cycles of the sine waves.

Briefly describe the waveforms of the rectifier output current and voltage by comparing them to the waveforms of the source voltage and current.

37. Based on the observed waveforms, which diodes are in the conducting state during the positive half of the source voltage waveform?
Which diodes are in the conducting state during the negative half of the source voltage waveform?


38. What is the conduction angle of each diode?


39. Measure and record the ripple frequency of the single-phase full-wave rectifier.

Ripple frequency = ________ Hz

Is this frequency twice the ripple frequency of a single-phase half-wave rectifier (as recorded in step 17)?

☐ Yes  ☐ No

40. In the Metering window, make sure that meters E1 and I1 are set to measure the average (dc) values of the rectifier output voltage $E_o$, and rectifier output current $I_o$, respectively. Record these values below.

Average rectifier output voltage $E_{o,avg} = ________ V$

Average rectifier output current $I_{o,avg} = ________ A$

Calculate the rectifier output power $P_o$ from the average values of voltage $E_o$ and current $I_o$.

Rectifier output power $P_o = I_{o,avg} \times E_{o,avg} = ________ W$

41. In the Metering window, set meter E2 to measure the rms value of the source voltage, $E_s$. Record this value below.

Source voltage $E_s = ________ V$

Compare the source voltage $E_s$ to the average rectifier output voltage $E_{o,avg}$, obtained in the previous step. Is $E_{o,avg} = 0.9E_s$?

☐ Yes  ☐ No
42. Compare the average output voltage and current of the single-phase full-wave rectifier (recorded in step 40) to those previously obtained for a single-phase half-wave rectifier (recorded in step 18).

43. How does the output power of the single-phase full-wave rectifier, calculated in step 40, compare with that previously obtained for a single-phase half-wave rectifier, calculated in step 18?

44. Stop the ac power source.

Close LVDAC-EMS, turn off all equipment, and remove all leads and cables.

**CONCLUSION**

In this exercise, you studied the operation of diodes and single-phase rectifiers. You learned that diodes act like high-speed switches, allowing current to flow in one direction only. You studied the operation of two types of rectifiers: the single-phase half-wave rectifier and the single-phase full-wave (bridge) rectifier. You saw that a single-phase half-wave rectifier uses a single diode to provide a pulsating voltage which is positive during half of the source voltage cycle, and null during the other half of this cycle. This voltage has a non-null average (dc) value, which results not only in a flow of dc current through the load, but also through the ac power source (i.e., through the ac power network), which is highly undesirable. This drawback is eliminated with the use of a single-phase full-wave rectifier. This rectifier uses four diodes to provide a voltage consisting of two positive half-waves per cycle of the source voltage. The single-phase half-wave and full-wave rectifiers both provide a unipolar (positive) output voltage that never goes negative during the whole cycle. However, a full-wave rectifier provides twice the average voltage provided by a half-wave rectifier without the highly undesirable dc component in the ac power source current.

**REVIEW QUESTIONS**

1. How does a diode act when a voltage applied across the diode terminals makes the voltage at the anode higher than the voltage at the cathode? Explain.
Exercise 1 – Power Diode Single-Phase Rectifiers • Review Questions

2. What happens when the current stops flowing (even for a very brief period) through a diode?

____________________________________________________________________

____________________________________________________________________

3. In a single-phase half-wave rectifier like the one shown in Figure 9, when do the waveforms of the rectifier output current and voltage have the same shape as the source voltage waveform? When are the rectifier output current and voltage null? Explain.

____________________________________________________________________

____________________________________________________________________

____________________________________________________________________

____________________________________________________________________

4. What is a single-phase full-wave (bridge) rectifier? How does it work? Describe the waveform of the rectifier output voltage with respect to the waveform of the source voltage waveform.

____________________________________________________________________

____________________________________________________________________

____________________________________________________________________

____________________________________________________________________

5. Compare the single-phase half-wave rectifier to the single-phase full-wave rectifier (average value of the rectifier output voltage, ripple frequency, presence or absence of a dc component in the ac power source current).

____________________________________________________________________

____________________________________________________________________

____________________________________________________________________

____________________________________________________________________

____________________________________________________________________
The Single-Phase PWM Inverter

EXERCISE OBJECTIVE  
When you have completed this exercise, you will be familiar with the operation of the single-phase PWM inverter.

DISCUSSION OUTLINE  
The Discussion of this exercise covers the following points:

- Using a four-quadrant chopper as an inverter
- Relationship between the output voltage, input voltage, and modulation index in a single-phase PWM inverter

DISCUSSION  
Using a four-quadrant chopper as an inverter

Inverters are devices which convert dc power into ac power. This allows single-phase and three-phase ac power systems with variable frequency and voltage to be obtained. For instance, three-phase inverters are widely used to build ac motor drives, while single-phase inverters are often used to power household appliances from energy produced by solar panels or wind turbines and stored in a battery or a battery bank.

A single-phase inverter can be implemented using a four-quadrant chopper. In this situation, the duty cycle of the switching control signals is made to vary so that the voltage at the chopper output alternates at a given rate between positive and negative values. Figure 16 shows a four-quadrant chopper connected to a resistive load. Figure 17 shows the waveform of the signal applied at the duty-cycle control input of the four-quadrant chopper, and the waveforms of the voltage (before and after filtering) and current at the four-quadrant chopper output.
A sine-wave signal modulates the duty cycles ($\alpha_{Q_1Q_5}$ and $\alpha_{Q_2Q_4}$) of the switching control signals. As a result, the voltage waveform at the four-quadrant chopper output is a train of bipolar pulses whose width varies in accordance with the instantaneous voltage of the sine-wave signal. The dashed line drawn over the train of bipolar pulses in Figure 17 shows the average voltage over each cycle of the bipolar pulse train at the four-quadrant chopper output. This voltage is an ac voltage having the same form (sinusoidal) as the signal applied to the duty-cycle control input of the four-quadrant chopper.

The range over which the width of the bipolar pulses at the four-quadrant chopper output varies depends on the sine-wave signal (duty-cycle control signal) amplitude. Increasing the sine-wave signal amplitude increases the range of variation of the pulse width, and therefore, the amplitude of the ac voltage at the four-quadrant chopper output. The rate at which the pulse width varies at the four-quadrant chopper output depends on the frequency of the sine-wave signal. Increasing the sine-wave signal frequency increases the rate at which the pulse width varies, and therefore, the frequency of the ac voltage at the four-quadrant chopper output.

In many applications, a voltage whose waveform is a train of bipolar pulses (instead of a sine wave) can affect the operation of a device. For this reason, a filter made of two inductors and a capacitor is usually added at the output of the single-phase-inverter (four-quadrant chopper) to smooth the current and voltage waveforms. This results in a sinusoidal voltage waveform (see Figure 17). The current waveform is similar to the voltage waveform since the load is purely resistive as shown in Figure 17.
Relationship between the output voltage, input voltage, and modulation index in a single-phase PWM inverter

The electronic switches in a four-quadrant chopper are switched in pairs, that is, $Q_1$ with $Q_5$ and $Q_2$ with $Q_4$. When one pair of electronic switches is on, the other pair is off. Therefore, the input voltage $E_I$ is alternately applied to the output of the four-quadrant chopper through either one of the two pairs of electronic switches. The instantaneous polarity of the output voltage $E_O$ depends on which pair of electronic switches is on. It is positive when electronic switches $Q_1$ and $Q_5$ are on, and negative when electronic switches $Q_2$ and $Q_4$ are on. The average (dc) output voltage $E_O$ of the four-quadrant chopper depends on the time each pair of electronic switches is on during each cycle. This, in turn, depends on the duty cycle of the switching control signals.
The equation relating voltages $E_O$ and $E_I$ is written below.

$$E_O = E_I \times (2\alpha_{Q_1,Q_5} - 1) \tag{1}$$

where $E_O$ is the dc voltage at the four-quadrant chopper output.
$E_I$ is the dc voltage at the four-quadrant chopper input.
$\alpha_{Q_1,Q_5}$ is the duty cycle of electronic switches $Q_1$ and $Q_5$, expressed as a decimal.

Since the duty cycle can vary from approximately 0 to 1, the voltage $E_O$ can vary from approximately $-E_I$ to $+E_I$.

When a sine-wave signal is used to make the duty cycle $\alpha_{Q_1,Q_5}$ of a four-quadrant chopper vary between 0% and 100% (also making the duty cycle $\alpha_{Q_2,Q_4}$ vary in a complementary way), the resulting output voltage (after filtering) is a sine-wave having an amplitude $E_{O,\text{max}}$ equal to $E_I$ ($E_{O,\text{max}} = E_I$), as shown in Figure 18.

![Figure 18. When a sine-wave signal is used to make the duty cycle $\alpha_{Q_1,Q_5}$ vary between 0% and 100%, the resulting output voltage (after filtering) is a sine-wave having an amplitude $E_{O,\text{max}}$ equal to $E_I$.](image)

The modulation index $m$ of a four-quadrant chopper used as a single-phase PWM inverter is the ratio of the range over which the duty cycle varies over the maximum range of variation of the duty cycle (i.e., 100% or 1). The modulation index $m$ is calculated using Equation (2) when the duty cycle $\alpha$ is expressed as a percentage, or using Equation (3) when the duty cycle $\alpha$ is expressed as a decimal.
where \( m \) is the modulation index (pure number).
\[ m = \frac{\alpha_{\text{max}} - \alpha_{\text{min}}}{100\%} \]  \hfill (2)

\( \alpha_{\text{max}} \) is the maximum value of the duty cycle, expressed as a percentage.
\( \alpha_{\text{min}} \) is the minimum value of the duty cycle, expressed as a percentage.

where \( m \) is the modulation index (pure number).
\[ m = \alpha_{\text{max}} - \alpha_{\text{min}} \]  \hfill (3)

\( \alpha_{\text{max}} \) is the maximum value of the duty cycle, expressed as a decimal.
\( \alpha_{\text{min}} \) is the minimum value of the duty cycle, expressed as a decimal.

Figure 19 illustrates duty cycles having various modulation indexes. In Figure 19a, the duty cycle varies between 0% and 100%, the range of variation is 100%, and thus, the modulation index \( m \) is 1 \((100\% - 0\% / 100\%)\). In Figure 19b, the duty cycle varies between 15% and 85%, the range of variation is 70% and the modulation index \( m \) is 0.7. In Figure 19c, the duty cycle varies between 30% and 70%, the range of variation is 40% and the modulation index \( m \) is 0.4.
When a four-quadrant chopper is used as a single-phase PWM inverter, the amplitude $E_{0,max}$ of the voltage sine wave at the inverter output depends on both the input voltage $E_i$ and the modulation index $m$. The amplitude $E_{0,max}$ of the voltage sine wave at the single-phase PWM inverter output can be calculated using the following equation:

$$E_{0,max} = E_i \times m$$  \hspace{1cm} (4)

where $E_{0,max}$ is the amplitude of the voltage sine wave at the single-phase PWM inverter output (four-quadrant chopper output), expressed in V.  

$E_i$ is the average (dc) voltage at the single-phase PWM inverter input (four-quadrant chopper input), expressed in V.  

$m$ is the modulation index (pure number).

Equation (5) shows how the above equation can be modified to calculate the rms value of the voltage sine wave at the single-phase PWM inverter output.

$$E_{0,rms} = \frac{E_i \times m}{\sqrt{2}}$$  \hspace{1cm} (5)

As an example, Table 1 shows the amplitude ($E_{0,max}$) and the rms value ($E_{0,rms}$) of the voltage sine-wave at the output of a PWM inverter powered by a 48 V battery for modulation indexes $m$ of 1.0, 0.8 and 0.3. The duty cycle and inverter output voltage variations for each modulation index are shown in Figure 20.

**Table 1. Voltage at the output of a PWM inverter powered by a 48 V battery for modulation indexes $m$ of 1.0, 0.8, and 0.3.**

<table>
<thead>
<tr>
<th>DC voltage at the PWM inverter input (V)</th>
<th>Modulation index</th>
<th>Voltage at the PWM inverter output</th>
<th>Amplitude $E_{0,max}$ (V)</th>
<th>rms value $E_{0,rms}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48 V</td>
<td>$m = 1.0$</td>
<td>48.0</td>
<td>48.0</td>
<td>34.0</td>
</tr>
<tr>
<td>48 V</td>
<td>$m = 0.8$</td>
<td>38.4</td>
<td>38.4</td>
<td>27.2</td>
</tr>
<tr>
<td>48 V</td>
<td>$m = 0.3$</td>
<td>14.4</td>
<td>14.4</td>
<td>10.2</td>
</tr>
</tbody>
</table>

$^{(1)}$ Calculated using the equation $E_{0,max} = E_i \times m$

$^{(2)}$ Calculated using the equation $E_{0,rms} = (E_i \times m) / \sqrt{2}$
Exercise 2 – The Single-Phase PWM Inverter

**Procedure Outline**

The Procedure is divided into the following sections:

- Setup and connections
- Implementing a single-phase PWM inverter using a four-quadrant chopper – Part I
- Implementing a single-phase PWM inverter using a four-quadrant chopper – Part II
- Relationship between output voltage, input voltage, and modulation index
- Single-phase PWM inverter versus four-quadrant chopper

**Procedure**

**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.

Setup and connections

*In this part of the exercise, you will set up and connect the equipment.*

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform this exercise.

   Install the required equipment in the Workstation.
2. Connect the **Power Input** of the Data Acquisition and Control Interface to a 24 V ac power supply.

   Connect the **Low Power Input** of the IGBT Chopper/Inverter to the **Power Input** of the Data Acquisition and Control Interface. Turn the 24 V ac power supply on.

3. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

   Connect the USB port of the Four-Quadrant Dynamometer/Power Supply to a USB port of the host computer.

4. Make sure that the main power switch of the Four-Quadrant Dynamometer/Power Supply is set to **O** (off), then connect the **Power Input** to an ac power outlet.

   Set the **Operating Mode** switch of the Four-Quadrant Dynamometer/Power Supply to **Power Supply**.

   Turn the Four-Quadrant Dynamometer/Power Supply on by setting the main power switch to I (on).

5. Turn the host computer on, then start the LVDAC-EMS software.

   In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface is detected. Make sure that the Computer-Based Instrumentation and Chopper/Inverter Control functions for the Data Acquisition and Control Interface are available. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the **OK** button to close the LVDAC-EMS Start-Up window.

6. Set up the circuit shown in Figure 21. Use the two 2 mH inductors and the 5 μF capacitor of the Filtering Inductors/Capacitors module to implement $L_1$, $L_2$, and $C_1$. Make the necessary connections and switch settings on the Resistive Load in order to obtain the resistance value required.
7. Connect the **Digital Outputs** of the Data Acquisition and Control Interface (DACI) to the **Switching Control Inputs** of the IGBT Chopper/Inverter using a DB9 connector cable.

On the Data Acquisition and Control Interface, connect Analog Output 1 to Analog Input 1 using miniature banana plug leads. This connection allows control of the duty cycle of the electronic switches in the IGBT Chopper/Inverter by applying the voltage supplied by Analog Output 1 to Analog Input 1.

Connect Switching Control Inputs 1 and 2 of the IGBT Chopper/Inverter to Analog Inputs 2 and 3 of the Data Acquisition and Control Interface using miniature banana plug leads. These connections allow the observation of the switching control signals of the electronic switches in the IGBT Chopper/Inverter.

Connect the common (white) terminal of the Switching Control Inputs on the IGBT Chopper/Inverter to one of the two analog common (white) terminals on the Data Acquisition and Control Interface using a miniature banana plug lead.

**Implementing a single-phase PWM inverter using a four-quadrant chopper – Part I**

*In this part of the exercise, you will control the duty cycle of the electronic switches of a four-quadrant chopper using a dc voltage, while observing the voltage at the chopper output.*
8. In LVDAC-EMS, open the **Four-Quadrant Dynamometer/Power Supply** window and make the following settings:

- Select the *Voltage Source (+)* function.
- Set the *Voltage* parameter to 100 V.
- Start the voltage source.

9. In LVDAC-EMS, open the **Chopper/Inverter Control** window and make the following settings:

- Select the *Four-Quadrant Chopper* function.
- Set the *Switching Frequency* parameter to 2000 Hz.
- Set the *Duty Cycle Control* parameter to *AI-1* (-10 to 10 V). This setting allows control of the duty cycle of the electronic switches in the four-quadrant chopper using a dc voltage applied to *Analog Input 1*.
- Make sure that the acceleration time is set to 0.0 s.
- Make sure that the deceleration time is set to 0.0 s.
- Make sure that the \( Q_1, Q_2, Q_4, \) and \( Q_5 \) parameters are set to *PWM*.
- Start the four-quadrant chopper.

10. In LVDAC-EMS, open the **Oscilloscope** window and use channels 1 to 7 to display the duty-cycle control voltage (*AI-1*), the switching control signals of electronic switches \( Q_1, Q_5 \) (*AI-2*) and \( Q_2, Q_4 \) (*AI-3*), the dc voltage \( E_1 \) at the input of the inverter (*E1*), the voltage \( E_2 \) at the inverter output before filtering (*E2*) and after filtering (*E3*), and the current \( I_1 \) flowing through the load (*I1*), respectively.

Select the *Continuous Refresh* mode, set the time base to 0.2 ms/div, and set the trigger controls so that the Oscilloscope triggers when the rising edge of the switching control signal (*AI-2*) of electronic switches \( Q_1, Q_5 \) reaches 2 V.

Select convenient vertical scale and position settings to facilitate observation of the waveforms.

11. In LVDAC-EMS, open the **Analog Output 1** window. The analog outputs in LVDAC-EMS can be used to control various parameters such as voltage, current, speed, torque, frequency, ratio (duty cycle), and firing angle by producing a voltage that can varied between -10 V and +10 V. The correspondence between the controlled parameter and the voltage output is defined in the *Analog Output* windows.
In the Analog Output 1 window, make the following settings:

- Set the **Function** parameter to **Command Button**. This setting allows the voltage at Analog Output 1 to be set between -10 V and +10 V, using a control knob, arrow buttons, or by entering the desired value directly in the Analog Output Settings.

- Set the **Command Name** parameter to **Voltage**. This sets the type of command that you are controlling. In the present case, the command you are controlling is the voltage used to control the duty cycle of the four-quadrant chopper.

- Set the **Max Command** parameter to 10. This sets the maximum value for the command you are controlling. In the present case, the maximum voltage command that can be reached is 10 V.

- Set the **Voltage Corresponding to Max Command** parameter to 10. This sets the voltage at the analog output corresponding to the **Max Command** parameter value that you set. In the present case, a voltage equal to 10 V at Analog Output 1 corresponds to a voltage command of 10 V.

- Set the **Min Command (V)** parameter to -10. This sets the minimum value for the command you are controlling. In the present case, the minimum voltage command that can be reached is -10 V.

- Make sure that the **Voltage Corresponding to Min Command (V)** is set to -10. This sets the voltage at the analog output corresponding to the **Min Command** parameter value you have set. In the present case, a voltage equal to -10 V at Analog Output 1 corresponds to a voltage command of -10 V.

- Set the **Command Step** parameter to 1. This sets the increment corresponding to one click on the arrow buttons located under the control knob. In the present case, the voltage (command) increases by 1 V each time the up-arrow button is clicked, or decreases by 1 V each time the down-arrow button is clicked.

- Set the **Voltage** parameter to -10. This sets the voltage at Analog Output 1 to -10 V.

The value of the **Voltage** parameter and the voltage at Analog Output 1 are identical in the present case because the command type is voltage and because the values of the parameters "Voltage Corresponding to Min Command" and "Min Command" are equal. Note that if the command type were a speed command as an example, the Voltage parameter would become the Speed parameter and would set the number of revolutions per minute corresponding to the voltage at Analog Output 1.

These settings will allow you to produce a voltage variable between -10 V and +10 V at Analog Output 1 (currently set to -10 V). This voltage is used to control the duty-cycle of the electronic switches in the four-quadrant chopper.
12. In the Analog Output 1 window, rotate the control knob so that the duty-cycle control voltage varies cyclically from -10 V to +10 V and from +10 V to -10 V. While doing this, observe the voltage (before and after filtering) and current at the four-quadrant chopper output, as well as the waveforms of the switching control signals on the Oscilloscope display.

Do the voltage and current at the four-quadrant chopper output correspond to an ac waveform, i.e., varying from a polarity to the other?

☐ Yes  ☐ No

13. Successively set the duty-cycle control voltage to each of the values shown in Table 2. For each value, measure the duty cycle $\alpha_{q_1,q_5}$ and the average voltage after filtering ($E_3$) at the four-quadrant chopper output.

<table>
<thead>
<tr>
<th>Duty-cycle control voltage (V)</th>
<th>Duty cycle $\alpha_{q_1,q_5}$</th>
<th>Average output voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

14. Describe the relationship between the duty cycle $\alpha_{q_1,q_5}$ (AI-2) and the duty-cycle control voltage.

15. Describe the relationship between the average voltage at the four-quadrant chopper output and the duty-cycle control voltage.
16. From your observations, is it possible to convert dc power into ac power using a four-quadrant chopper? If so, explain how.

17. Stop the voltage source and the four-quadrant chopper.

Implementing a single-phase PWM inverter using a four-quadrant chopper – Part II

In this part of the exercise, you will control the duty cycle of the electronic switches of a four-quadrant chopper using a sinusoidal duty-cycle control voltage while observing the voltage at the chopper output.

18. In the Analog Output 1 window, make the following settings:
   
   - Set the Function parameter to Function Generator. This setting makes the output signal of a function generator available at Analog Output 1. The function generator can produce various voltage waveforms such as sine, square, triangle, and sawtooth.
   
   - Set the Waveform parameter to Sine. This sets the function generator to produce a sine wave.
   
   - Set the Frequency parameter to 1 Hz. This sets the frequency of the sine wave to 1 Hz.
   
   - Set the Amplitude parameter to 10 V. This sets the amplitude of the sine wave to 10 V.
   
   - Start the function generator.

   These settings will produce a sinusoidal voltage varying slowly between -10 V and +10 V at Analog Output 1. This voltage will be used to control the duty cycle of the electronic switches in the four-quadrant chopper.

19. Describe how the duty cycle $\alpha_{q_1,q_2}$ will be affected by the duty-cycle control voltage produced by the function generator.

20. In the main window of LVDAC-EMS, set the range of $E_3$ to High.
21. Start the voltage source and the four-quadrant chopper.

In the Oscilloscope window, set the time base to 0.2 s/div.

Does the duty cycle vary as predicted in the previous step?

☐ Yes  ☐ No

22. Observe the voltage (after filtering) at the four-quadrant output on the Oscilloscope display. Describe what happens.

23. In the Analog Output 1 window, gradually increase the frequency of the duty-cycle control voltage up to 10 Hz while observing the voltage (after filtering) at the four-quadrant chopper output on the Oscilloscope display. Describe what happens.

24. In the Analog Output 1 window, set the frequency of the duty-cycle control signal to the frequency of your local ac power network. Set the amplitude of the control signal to 8 V.

In the Oscilloscope window, set the time base to 5 ms/div, and set the trigger controls so that the Oscilloscope triggers when the rising edge of the duty-cycle control signal (AI-1) of the four-quadrant chopper reaches 0 V.

25. Observe the voltage at the four-quadrant chopper output on the Oscilloscope display, and describe the voltage waveforms before and after filtering at the four-quadrant chopper output.

26. Explain why such a voltage waveform is obtained at the four-quadrant chopper output after filtering.
27. Is the four-quadrant chopper well suited to convert dc power into ac power, i.e., to operate as a single phase PWM inverter?

- Yes
- No

Relationship between output voltage, input voltage, and modulation index

In this part of the exercise, you will calculate the values of the modulation index and four-quadrant chopper output voltage for different amplitudes of the duty-cycle control voltage. You will then measure the four-quadrant chopper output voltage for the different amplitudes of the duty-cycle control voltage. You will compare your results to the calculated values.

28. For each amplitude of the duty-cycle control voltage shown in Table 3, calculate the modulation index $m$. Also calculate the amplitude of the voltage at the four-quadrant chopper output from the chopper input voltage (dc-bus voltage) and modulation index. Record your results in Table 3.

<table>
<thead>
<tr>
<th>Chopper input voltage [dc-bus voltage] (V)</th>
<th>Duty-cycle control voltage amplitude (V)</th>
<th>Modulation index $m$</th>
<th>Amplitude of the chopper output voltage [calculated] (V)</th>
<th>Amplitude of the chopper output voltage [measured] (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>8.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

29. In the Analog Output 1 window, successively set the duty-cycle control voltage to each amplitude shown in Table 3. For each value, measure the amplitude of the chopper output voltage $E_{O,max}$ (after filtering) and record the values in the table.

Are the amplitudes of the voltage measured at the four-quadrant chopper output equal to the calculated values, confirming that $E_{O,max} = E_I \times m$?

- Yes
- No

30. Stop the voltage source and the four-quadrant chopper.
Single-phase PWM inverter versus four-quadrant chopper

In this part of the exercise, you will compare the voltage and current waveforms of the four-quadrant chopper to those of the single-phase PWM inverter.

31. In the Chopper/Inverter Control window, set the switching frequency to 20,000 Hz. (Do not modify the setting of the other parameters in this window.)

32. In the Analog Output 1 window, set the amplitude of the duty-cycle control voltage to 8.0 V to obtain a modulation index $m$ of 0.8.

33. Start the voltage source and the four-quadrant chopper.

34. In the Oscilloscope window, make the following settings:
   - In the Oscilloscope Settings, set the Acquisition Filtering parameter to On.
   - Turn off Channels 1, 2, 3, 4, and 5, leaving only Channels 6 and 7 on to observe the four-quadrant chopper output voltage (after filtering) and current.
   - Make sure that the Continuous Refresh mode is selected, set the time base to 5 ms/div, and set the trigger controls so that the Oscilloscope triggers when the chopper output current ($i_1$) passes through 0 V with a positive slope.
   - Select convenient vertical scale and position settings to facilitate observation of the voltage and current at the four-quadrant chopper output (Channels 6, and 7).
   - Record the waveforms in memory M1.

35. Open the Harmonic Analyzer window and make the following settings:
   - Select Network as Type of fundamental frequency. This setting allows the total harmonic distortion of the four-quadrant chopper output voltage (after filtering) to be determined at the local network frequency.
   - Select $E3$ as input. This setting determines the signal to analyze.
   - Select % of 1f as Type of scale to display. With this setting, the total harmonic distortion is displayed in % of the signal fundamental frequency in the Harmonic Analyzer window.
36. Enter the total harmonic distortion (THD) of the voltage at the output of the four-quadrant chopper shown in the Distortion [%] section in the Harmonic Analyzer window.

Total harmonic distortion THD: _____

37. Observe the output voltage waveform of the four-quadrant chopper displayed on the Oscilloscope. Can you conclude that the waveform is closed to a pure sine wave?

☐ Yes  ☐ No

38. Stop the four-quadrant chopper.


40. In the Chopper/Inverter Control window, select the Single-Phase, PWM Inverter function.

Observe the schematic diagram, and note that the single-phase PWM inverter is in fact a four quadrant chopper.

Make the following settings in the Chopper/Inverter Control window:

– Make sure that the Switching Frequency parameter is set to 20 000 Hz.

– Make sure that the DC Bus parameter is set to Unipolar. This setting indicates that the dc bus of the Chopper/Inverter is supplied by a unipolar dc voltage source.

– Set the Frequency parameter to the frequency of your local ac power network.

– Set the Peak Voltage (% of DC Bus/2) parameter to 80. This setting determines the modulation index $m$. In the present case, this sets the modulation index to 0.8.

For comparison purposes, these parameters are set to the same values as those previously set in the four-quadrant chopper.

Start the single-phase PWM inverter.

41. Observe the voltage and current waveforms at the single-phase PWM inverter output on the Oscilloscope display.

Compare these waveforms with those obtained previously with the four-quadrant chopper and stored in memory M1.
Are the voltage and current waveforms identical, confirming that a single-phase PWM inverter is in fact a four-quadrant chopper?

☐ Yes  ☐ No

42. Stop the voltage source and the single-phase PWM inverter.

Close LVDAC-EMS, turn off all equipment, and remove all leads and cables.

**CONCLUSION**

In this exercise, you verified that dc power can be converted into ac power using a four-quadrant chopper in which the duty cycle of the switching control signals is modulated by a sine-wave signal. You observed that the frequency and the amplitude of the voltage and current at the four-quadrant chopper output are respectively proportional to the frequency and amplitude of the modulating sine-wave signal. You observed that the waveforms of the voltage and current at the four-quadrant chopper output are sinusoidal. You demonstrated that a single-phase PWM inverter is, in fact, a four-quadrant chopper.

**REVIEW QUESTIONS**

1. What is the main function of inverters?

2. Briefly explain how dc power can be converted into ac power using a four-quadrant chopper.

3. Explain why a filter is usually added at the output of single-phase inverters.

4. What is the average dc voltage at the input of a single-phase PWM inverter if the amplitude of the voltage at the output of the PWM inverter is 175 V and the modulation index $m$ equal to 0.5?
5. The rate at which the pulse width varies at the output of a four-quadrant chopper depends on the
   a. network frequency.
   b. switching frequency.
   c. frequency of the duty-cycle control signal.
   d. amplitude of the duty-cycle control signal.
## Equipment Utilization Chart

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>8131(^{(1)})</td>
<td>Workstation</td>
<td>1 1</td>
</tr>
<tr>
<td>8311</td>
<td>Resistive Load</td>
<td>1 1</td>
</tr>
<tr>
<td>8325-A</td>
<td>Filtering Inductors/Capacitors</td>
<td>1 1</td>
</tr>
<tr>
<td>8837-B</td>
<td>IGBT Chopper/Inverter(^{(2)})</td>
<td>1</td>
</tr>
<tr>
<td>8842-A</td>
<td>Rectifier and Filtering Capacitors</td>
<td>1</td>
</tr>
<tr>
<td>8951-L</td>
<td>Connection Leads</td>
<td>1 1</td>
</tr>
<tr>
<td>8960-C(^{(3)})</td>
<td>Four-Quadrant Dynamometer/Power Supply</td>
<td>1 1</td>
</tr>
<tr>
<td>8990</td>
<td>Host Computer</td>
<td>1 1</td>
</tr>
<tr>
<td>9063-C(^{(4)})</td>
<td>Data Acquisition and Control Interface</td>
<td>1 1</td>
</tr>
<tr>
<td>30004-2</td>
<td>24 V AC Power Supply</td>
<td>1 1</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Workstation model 8110-2 or model 8134-2 can also be used.
\(^{(2)}\) The prefix IGBT has been left out in this manual to identify the module.
\(^{(3)}\) Model 8960-C consists of the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, with functions 8968-1 and 8968-2.
\(^{(4)}\) Model 9063-C consists of the Data Acquisition and Control Interface, Model 9063, with functions 9069-1 and 9069-2.
Resistance Table for the Resistive Load Module

Table 4 gives resistance values which can be obtained by using the Resistive Load, model 8311. Other parallel combinations can be used to obtain the same resistance values listed. Figure 22 shows the load resistors and connection.

Table 4. Combinations of switch positions required to obtain various resistance values.

<table>
<thead>
<tr>
<th>Resistance (Ω)</th>
<th>Position of the switches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left-hand section</td>
</tr>
<tr>
<td>1200</td>
<td>I</td>
</tr>
</tbody>
</table>
Figure 22. Location and connection of the load resistors on the Resistive Load.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>anode</strong></td>
<td>An electrode through which electric current flows into a polarized electrical device. In a semiconductor diode, the anode is the P-doped layer of the PN junction which initially supplies holes to the junction.</td>
</tr>
<tr>
<td><strong>cathode</strong></td>
<td>A cathode is an electrode through which electric current flows out of a polarized electrical device. In a semiconductor diode, the cathode is the N–doped layer of the PN junction.</td>
</tr>
<tr>
<td><strong>characteristic curve</strong></td>
<td>A representation of certain electrical characteristics of a device or component.</td>
</tr>
<tr>
<td><strong>diode</strong></td>
<td>Two-terminal semiconductor device that acts similar to a switch which has no movable parts. The main function of a diode is to allow electric current to flow in one direction and to block current in the opposite direction.</td>
</tr>
<tr>
<td><strong>duty cycle</strong></td>
<td>The ratio of the pulse duration to the duration of one cycle. It can be expressed as a decimal or a percentage.</td>
</tr>
<tr>
<td><strong>forward-biased</strong></td>
<td>A voltage applied across a rectifying junction with a polarity that provides a low-resistance conducting path.</td>
</tr>
<tr>
<td><strong>inverter</strong></td>
<td>An electrical device that converts direct current to alternating current. The converted ac voltage can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits. A device which performs the opposite function (converting ac to dc) is known as a rectifier.</td>
</tr>
<tr>
<td><strong>knee voltage</strong></td>
<td>The voltage at which a curve joins two relatively straight portions of a characteristic curve.</td>
</tr>
<tr>
<td><strong>leakage current</strong></td>
<td>A current which, in the absence of a fault, flows to earth or to extraneous conductive parts in a circuit.</td>
</tr>
<tr>
<td><strong>N-type</strong></td>
<td>A semiconductor with extra electrons is called N-type material, since it has extra negatively-charged particles. In N-type material, free electrons move from a negatively-charged area to a positively charged area.</td>
</tr>
<tr>
<td><strong>P-type</strong></td>
<td>A semiconductor with extra holes is called P-type material, since it effectively has extra positively-charged particles. Electrons can jump from hole to hole, moving from a negatively-charged area to a positively-charged area. As a result, the holes themselves appear to move from a positively-charged area to a negatively-charged area.</td>
</tr>
<tr>
<td><strong>peak inverse voltage</strong></td>
<td>The maximum voltage that a diode can withstand in the reverse direction without breaking down or avalanching. If this voltage is exceeded, the diode may be destroyed. Diodes must have a peak inverse (reverse) voltage rating that is higher than the maximum reverse bias voltage that will be applied to them in a given application.</td>
</tr>
</tbody>
</table>
**rectifier**  
An electrical device that converts alternating current to direct current. Rectifiers are commonly used in dc power supplies. A device which performs the opposite function (converting dc to ac) is known as an inverter.

**reverse-biased**  
A voltage applied across a rectifying junction with a polarity that causes the junction to block normal current.

**semiconductor**  
A semiconductor is a material with electrical conductivity due to electron flow. The conductivity can be varied between that of a conductor and that of an insulator by adjusting the magnitude of the electron flow.
Various symbols are used in the circuit diagrams of this manual. Each symbol is a functional representation of a particular electrical device that can be implemented using Lab-Volt equipment. The use of these symbols greatly simplifies the number of interconnections that need to be shown on the circuit diagram, and thus, makes it easier to understand the circuit operation.

For each symbol other than those of power sources, resistors, inductors, and capacitors, this appendix gives the name of the device which the symbol represents, as well as the equipment and the connections required to properly connect the device to a circuit. Notice that the terminals of each symbol are identified using circled letters. The same circled letters identify the corresponding terminals in the Equipment and Connections diagram. Also notice that the numbers (when present) in the Equipment and Connections diagrams correspond to terminal numbering used on the actual equipment.

When a current at inputs I1, I2, I3, or I4 exceeds 4 A (either permanently or momentarily), use the corresponding 40 A input terminal and set the Range parameter of the corresponding input to High in the Data Acquisition and Control Settings window of LVDAC-EMS.
Appendix D

Circuit Diagram Symbols

Symbol

A
B
C

Induction machine

Three-phase induction machine

A
B
C

Induction machine

Three-phase induction machine

D
A
B
C

Synchronous motor

Three-phase synchronous motor

Equipment and Connections

Four-Pole Squirrel Cage Induction Motor (8221-0)

A
B
C

1
2
3
4
5
6

N

Three-Phase Induction Machine (8221-B)

A
B
C

1
2
3

N

Synchronous Motor / Generator (8241-2)

A
B
C

1
2
3
4
5
6
7
8

D
E

N

D
E

single-Phase AC Power Electronics
Appendix D  Circuit Diagram Symbols

Symbol

Equipment and Connections

Synchronous Generator (8241-2)

Three-Phase Wound-Rotor Induction Machine (8231-B)
Appendix D

Circuit Diagram Symbols

Symbol

Permanent Magnet Synchronous Machine (PMSM)

Power diode three-phase full-wave rectifier

Power thyristor three-phase bridge

Equipment and Connections

Permanent Magnet Synchronous Machine (8245)

Rectifier and Filtering Capacitors (8842-A)

Power Thyristors (8841)
Appendix D

Circuit Diagram Symbols

Symbol

Equipment and Connections

Three-phase inverter

IGBT Chopper / Inverter
(8837-B)
## Index of New Terms

The bold page number indicates the main entry. Refer to the Glossary of New Terms for definitions of new terms.

<table>
<thead>
<tr>
<th>Term</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>anode</td>
<td>3</td>
</tr>
<tr>
<td>cathode</td>
<td>3</td>
</tr>
<tr>
<td>characteristic curve</td>
<td>5</td>
</tr>
<tr>
<td>diode</td>
<td>3</td>
</tr>
<tr>
<td>duty cycle</td>
<td>23</td>
</tr>
<tr>
<td>forward biased</td>
<td>5</td>
</tr>
<tr>
<td>inverters</td>
<td>23</td>
</tr>
<tr>
<td>knee voltage</td>
<td>6</td>
</tr>
<tr>
<td>leakage current</td>
<td>6</td>
</tr>
<tr>
<td>N-type</td>
<td>4</td>
</tr>
<tr>
<td>peak inverse voltage</td>
<td>8</td>
</tr>
<tr>
<td>P-type</td>
<td>4</td>
</tr>
<tr>
<td>rectifier</td>
<td>1, 3, 4</td>
</tr>
<tr>
<td>reverse biased</td>
<td>4</td>
</tr>
<tr>
<td>semiconductor</td>
<td>1, 3</td>
</tr>
</tbody>
</table>
Acronyms

The following acronyms are used in this manual:

AVG average
DACI Data Acquisition and Control Interface
DB9 common type of electrical connector having 9 pins
EMS Electromechanical System
GHG greenhouse gas
IGBT insulated-gate bipolar transistor
LVDAC Lab-Volt Data Acquisition and Control
MOSFET metal-oxide-semiconductor field-effect transistor
PIV peak inverse (reverse) voltage
PWM pulse-width modulation
USB universal serial bus
UPS uninterruptible power supply
Bibliography


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services@labvolt.com

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