Electricity and New Energy

Single-Phase AC Power Electronics

Courseware Sample

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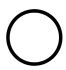
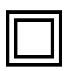
Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
⎓	Direct current
∿	Alternating current
⎓∿	Both direct and alternating current
3∿	Three-phase alternating current
⏚	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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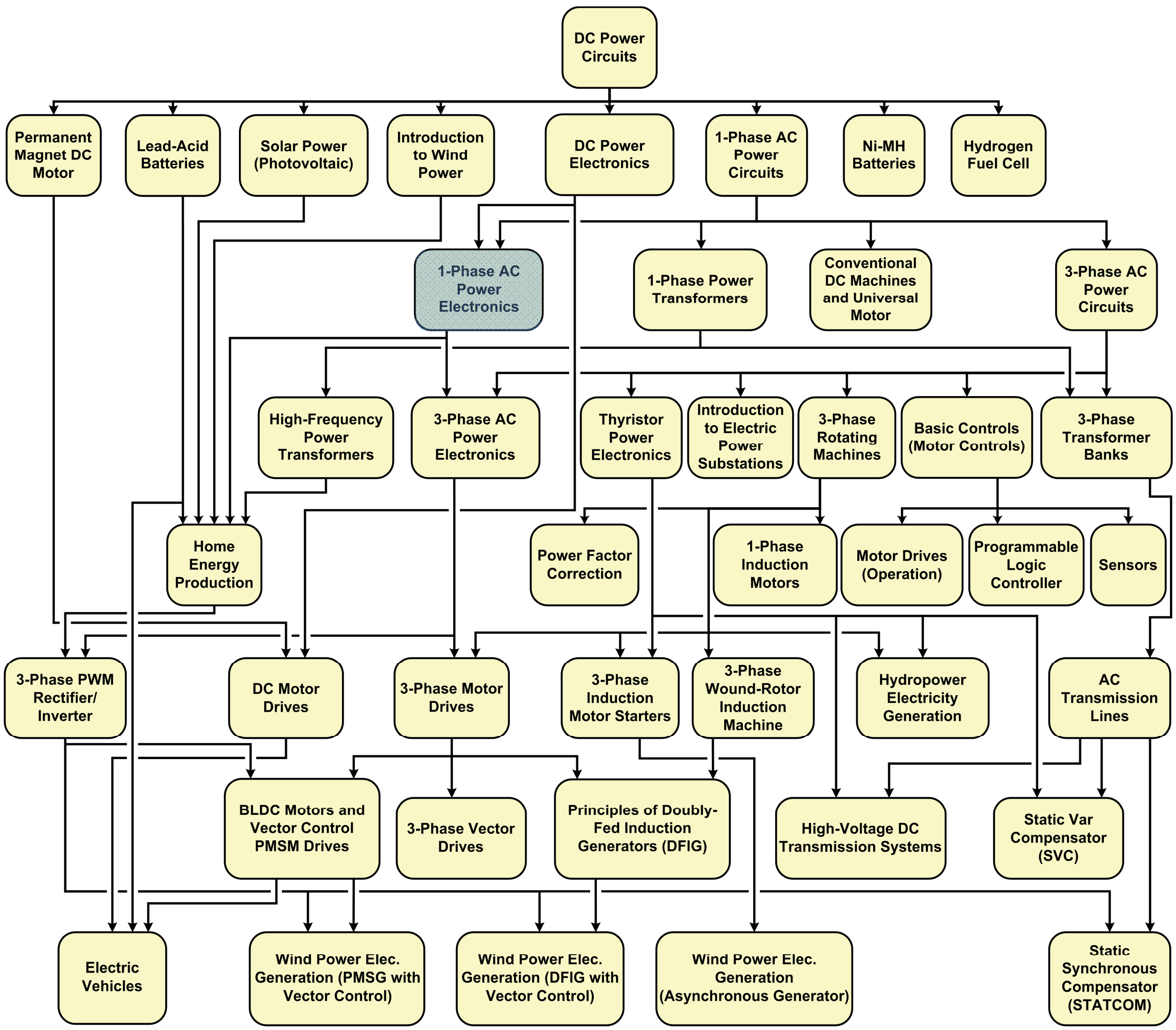
Preface

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, the Electric Power Technology Training Program was developed as 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 Electric Power Technology Training Program.

Preface

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.

Do you have suggestions or criticism regarding this manual?

If so, send us an e-mail at did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

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.

Safety considerations

Safety symbols that may be used in this manual and on the 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.

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.

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).

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Equipment installation

In order for students to be able to perform the exercises in the Student Manual, the Electric Power Technology Training Equipment must have been properly installed, according to the instructions given in the user guide Electric Power Technology Training Equipment, part number 38486-E.

Sample Exercise

Extracted from

the Student Manual

and the Instructor Guide

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.

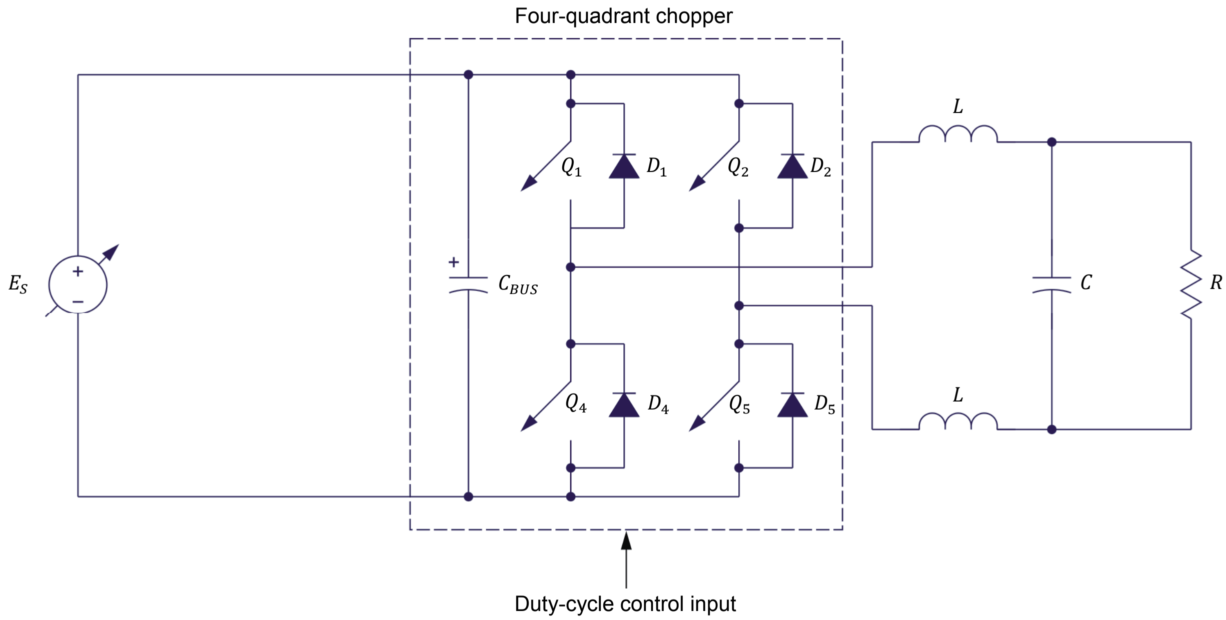


Figure 16. Using a four-quadrant chopper as an inverter.

A sine-wave signal modulates the duty cycles (α_{Q_1,Q_5} and α_{Q_2,Q_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.

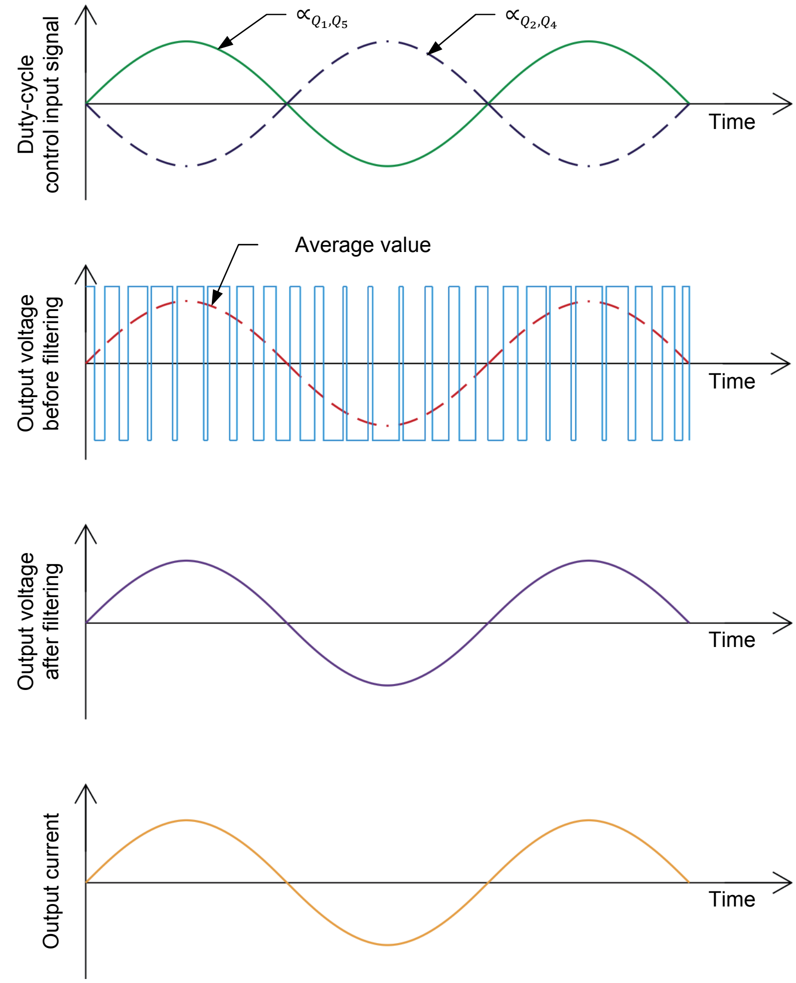


Figure 17. Voltage and current waveforms at the four-quadrant chopper output.

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.

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

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.

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

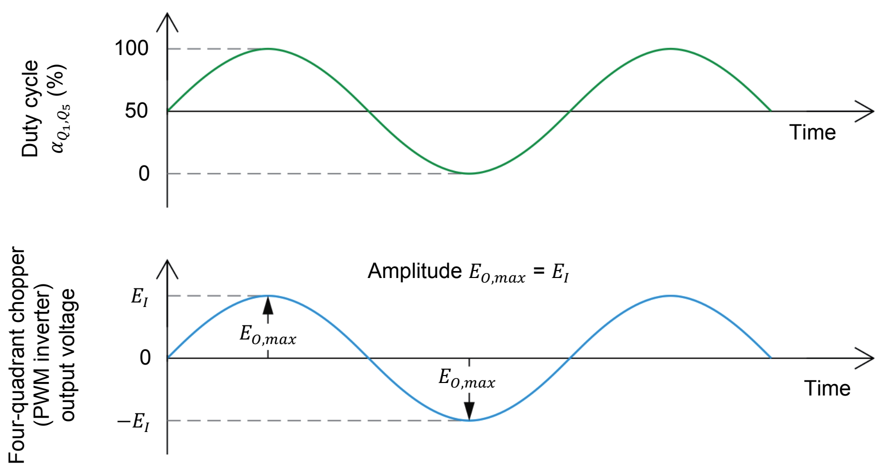


Figure 18. When a sine-wave signal is used to make the duty cycle α_{Q_1,Q_5} vary between 0% and 100%, the resulting output voltage (after filtering) is a sine-wave having an amplitude $E_{O,max}$ equal to E_I.

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 α is expressed as a percentage, or using Equation (3) when the duty cycle α is expressed as a decimal.

$$m = \frac{\alpha_{max} - \alpha_{min}}{100\%} \tag{2}$$

where m is the modulation index (pure number).

α_{max} is the maximum value of the duty cycle, expressed as a percentage.

α_{min} is the minimum value of the duty cycle, expressed as a percentage.

$$m = \alpha_{max} - \alpha_{min} \tag{3}$$

where m is the modulation index (pure number).

α_{max} is the maximum value of the duty cycle, expressed as a decimal.

α_{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.

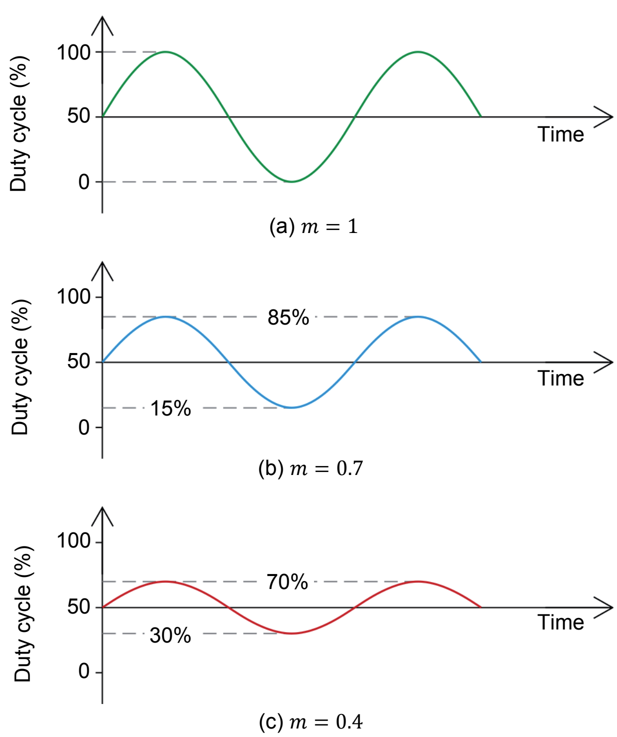


Figure 19. Duty cycles having modulation indexes m of 1.0, 0.7, and 0.4.

When a four-quadrant chopper is used as a single-phase PWM inverter, the amplitude $E_{O,max}$ of the voltage sine wave at the inverter output depends on both the input voltage E_I and the modulation index m. The amplitude $E_{O,max}$ of the voltage sine wave at the single-phase PWM inverter output can be calculated using the following equation:

$$E_{O,max} = E_I \times m \tag{4}$$

where $E_{O,max}$ 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.

$$E_{O,rms} = \frac{E_I \times m}{\sqrt{2}} \tag{5}$$

As an example, Table 1 shows the amplitude ($E_{O,max}$) and the rms value ($E_{O,rms}$) 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.

DC voltage at the PWM inverter input (V)	Modulation index	Voltage at the PWM inverter output	
		Amplitude $E_{O,max}$ (1) (V)	rms value $E_{O,rms}$ (2) (V)
48 V	$m = 1.0$	48.0	34.0
48 V	$m = 0.8$	38.4	27.2
48 V	$m = 0.3$	14.4	10.2

(1) Calculated using the equation $E_{O,max} = E_I \times m$

(2) Calculated using the equation $E_{O,rms} = (E_I \times m)/\sqrt{2}$

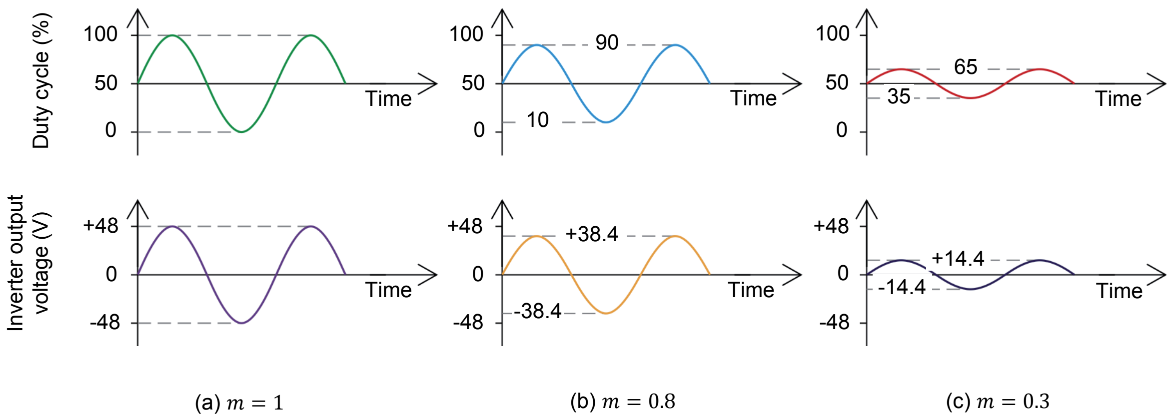


Figure 20. Duty cycle and inverter output voltage variations for modulation indexes m of 1.0, 0.8, and 0.3.

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.

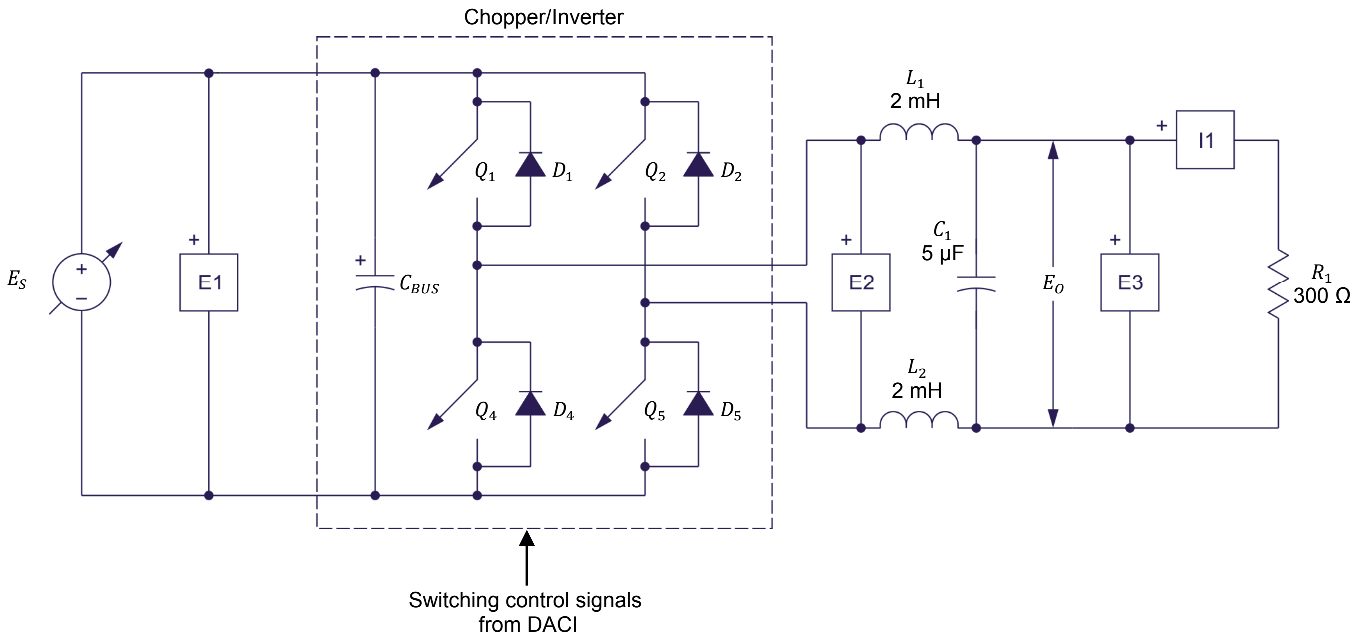


Figure 21. Four-quadrant chopper circuit.

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_I at the input of the inverter (*E1*), the voltage E_O at the inverter output before filtering (*E2*) and after filtering (*E3*), and the current I_O 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

Yes

13. Successively set the duty-cycle control voltage to each of the values shown in Table 2. For each value, measure the duty cycle α_{Q_1,Q_5} and the average voltage after filtering (*E3*) at the four-quadrant chopper output.

Table 2. Duty cycle and average output voltage (after filtering) versus duty-cycle control voltage.

Duty-cycle control voltage (V)	Duty cycle α_{Q_1,Q_5}	Average output voltage (V)
-10		
-8		
-6		
-4		
-2		
0		
+2		
+4		
+6		
+8		
+10		

Table 2. Duty cycle and average output voltage (after filtering) versus duty-cycle control voltage.

Duty-cycle control voltage (V)	Duty cycle α_{Q_1,Q_5}	Average output voltage (V)
-10	0	-98.1
-8	0.1	-78.8
-6	0.2	-59.6
-4	0.3	-40.0
-2	0.4	-20.4
0	0.5	-0.6
+2	0.6	19.1
+4	0.7	38.8
+6	0.8	58.5
+8	0.9	77.7
+10	1.0	97.0

14. Describe the relationship between the duty cycle α_{Q_1,Q_5} (*AI-2*) and the duty-cycle control voltage.

The duty cycle α_{Q_1,Q_5} varies from 0% to 100% (0 to 1) when the duty-cycle control voltage varies from -10 V to +10 V. The duty cycle α_{Q_1,Q_5} is minimum when the duty-cycle control voltage is minimum (-10 V), while it is maximum when the duty-cycle control voltage is maximum (+10 V).

15. Describe the relationship between the average voltage at the four-quadrant chopper output and the duty-cycle control voltage.

The average voltage at the four-quadrant chopper output is minimum when the duty-cycle control voltage is minimum (-10 V). Conversely, the average voltage at the four-quadrant chopper output is maximum when the duty-cycle control voltage is maximum (+10 V). The average voltage at the four-quadrant chopper output is virtually null when the duty cycle α_{Q_1,Q_5} control voltage is null (this corresponds to a duty cycle of 50% or 0.5).

16. From your observations, is it possible to convert dc power into ac power using a four-quadrant chopper? If so, explain how.

Yes. DC power can be converted into ac power using a four-quadrant chopper by varying the duty cycle around 50% using an alternating control voltage.

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 α_{Q_1,Q_5} will be affected by the duty-cycle control voltage produced by the function generator.

The duty cycle α_{Q_1,Q_5} will be maximum when the amplitude of the sinusoidal voltage produced by the function generator is maximum (+10 V). Conversely, the duty cycle α_{Q_1,Q_5} will be minimum when the sinusoidal voltage produced by the function generator is minimum (-10 V).

20. In the main window of LVDAC-EMS, set the range of *E3* 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

Yes

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

The voltage obtained at the four-quadrant chopper output after filtering varies gradually and changes polarity twice every second.

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.

The voltage obtained at the four-quadrant chopper output after filtering varies more rapidly, i.e., the frequency of the ac waveform at the four-quadrant chopper output follows the frequency of the duty-cycle control voltage produced by the function generator.

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.

Before filtering, the voltage waveform consists of a rectangular pulse train that is pulse-width modulated. After filtering, the voltage waveform at the four-quadrant chopper output is a sine wave with some slight distortion.

26. Explain why such a voltage waveform is obtained at the four-quadrant chopper output after filtering.

A voltage sine wave is obtained at the four-quadrant chopper output after filtering because the duty cycle of the chopper is made to vary sinusoidally by the sine-wave control signal.

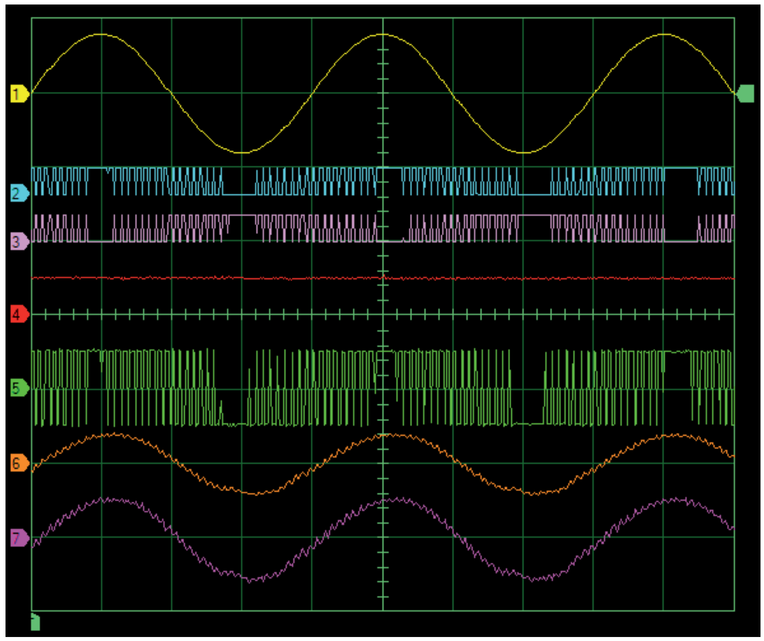
27. Is the four-quadrant chopper well suited to convert dc power into ac power, i.e., to operate as a single phase PWM inverter?

❑ Yes ❑ No

Yes

For a 50 Hz ac power network:

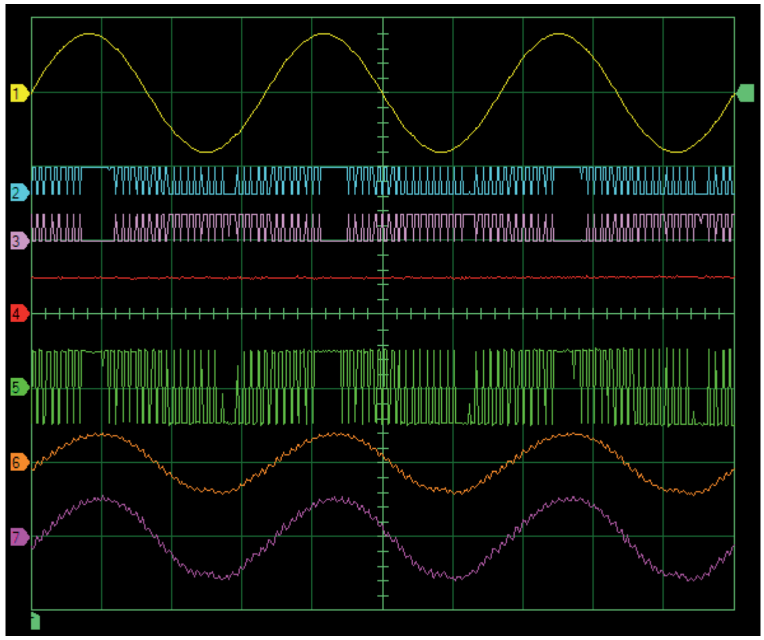
Oscilloscope Settings
Channel-1 Input AI-1
Channel-1 Scale .... 10 V/div
Channel-1 Coupling .... DC
Channel-2 Input AI-2
Channel-2 Scale .... 10 V/div
Channel-2 Coupling .... DC
Channel-3 Input AI-3
Channel-3 Scale .... 10 V/div
Channel-3 Coupling .... DC
Channel-4 Input E1
Channel-4 Scale .... 200 V/div
Channel-4 Coupling .... DC
Channel-5 Input E2
Channel-5 Scale .... 200 V/div
Channel-5 Coupling .... DC
Channel-6 Input E3
Channel-6 Scale .... 200 V/div
Channel-6 Coupling .... DC
Channel-7 Input I1
Channel-7 Scale .... 0.5 A/div
Channel-7 Coupling .... DC
Time Base............................. 5 ms/div
Trigger Source Ch1
Trigger Level 0
Trigger Slope .... Rising



Waveforms of the single-phase full-wave rectifier voltages and currents.

For a 60 Hz ac power network:

Oscilloscope Settings
Channel-1 Input AI-1
Channel-1 Scale .... 10 V/div
Channel-1 Coupling ....DC
Channel-2 Input AI-2
Channel-2 Scale .... 10 V/div
Channel-2 Coupling ....DC
Channel-3 Input AI-3
Channel-3 Scale .... 10 V/div
Channel-3 Coupling ....DC
Channel-4 Input E1
Channel-4 Scale .... 200 V/div
Channel-4 Coupling ....DC
Channel-5 Input E2
Channel-5 Scale .... 200 V/div
Channel-5 Coupling ....DC
Channel-6 Input E3
Channel-6 Scale .... 200 V/div
Channel-6 Coupling ....DC
Channel-7 Input I1
Channel-7 Scale .... 0.5 A/div
Channel-7 Coupling ....DC
Time Base............................. 5 ms/div
Trigger Source Ch1
Trigger Level.....................................0
Trigger Slope ....Rising



Waveforms of the single-phase full-wave rectifier voltages and currents.

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 3. Relationship between the output voltage, input voltage, and modulation index m.

Chopper input voltage [dc-bus voltage] (V)	Duty-cycle control voltage amplitude (V)	Modulation index m	Amplitude of the chopper output voltage [calculated] (V)	Amplitude of the chopper output voltage [measured] (V)
100	10.0			
100	8.0			
100	6.0			
100	4.0			
100	2.0			
100	1.0			

Table 3. Relationship between the output voltage, input voltage, and modulation index m.

Chopper input voltage [dc-bus voltage] (V)	Duty-cycle control voltage amplitude (V)	Modulation index m	Amplitude of the chopper output voltage [calculated] (V)	Amplitude of the chopper output voltage [measured] (V)
100	10.0	1.0	100	99.0
100	8.0	0.8	80	79.7
100	6.0	0.6	60	60.0
100	4.0	0.4	40	40.0
100	2.0	0.2	20	20.0
100	1.0	0.1	10	10.0

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

Yes

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: _____

Total harmonic distortion THD: approximately 3.5 %

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

Yes

38. Stop the four-quadrant chopper.

39. On the Data Acquisition and Control Interface, disconnect *Analog Output 1* from *Analog Input 1*.

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.

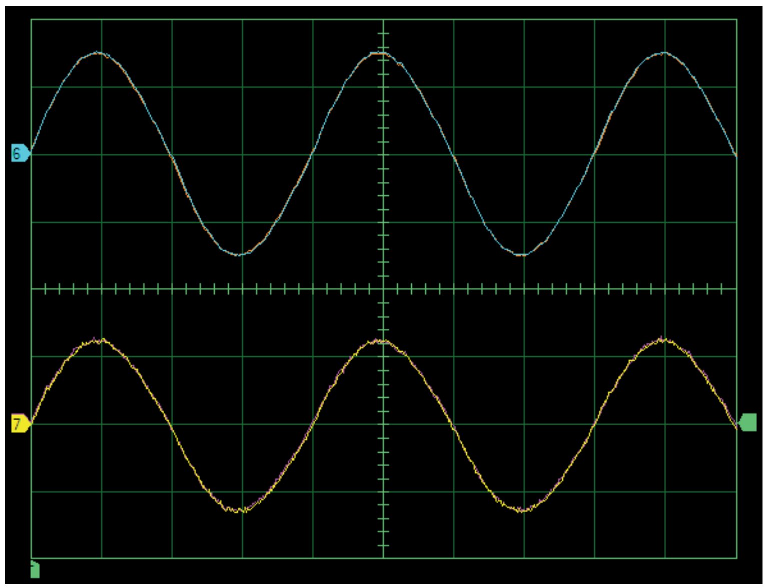
Are the voltage and current waveforms identical, confirming that a single-phase PWM inverter is in fact a four-quadrant chopper?

❑ Yes ❑ No

Yes

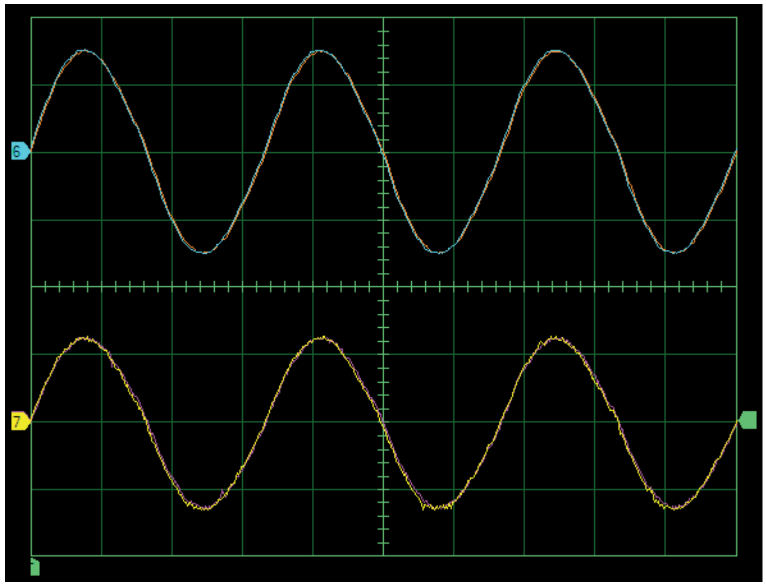
For a 50 Hz ac power network: the curves in the upper half of the Oscilloscope display show the voltage waveforms superimposed, and the curves in the lower half of the Oscilloscope display show the current waveforms superimposed.

Oscilloscope Settings
Channel-6 Input E3
Channel-6 Scale .... 50 V/div
Channel-6 Coupling .... DC
Channel-7 Input I1
Channel-7 Scale .... 0.2 A/div
Channel-7 Coupling .... DC
Time Base .... 5 ms/div
Trigger Source Ch7
Trigger Level 0
Trigger Slope .... Rising



For a 60 Hz ac power network: the curves in the upper half of the Oscilloscope display show the voltage waveforms superimposed, and the curves in the lower half of the Oscilloscope display show the current waveforms superimposed.

Oscilloscope Settings
Channel-6 Input E3
Channel-6 Scale ....50 V/div
Channel-6 Coupling ....DC
Channel-7 Input I1
Channel-7 Scale ....0.2 A/div
Channel-7 Coupling ....DC
Time Base............................ 5 ms/div
Trigger Source Ch7
Trigger Level......................................0
Trigger Slope ....Rising



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?

The main function of inverters is to produce ac power from dc power.

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

Since the voltage at the output of a four-quadrant chopper is negative when the duty cycle is lower than 50% and positive when the duty cycle is higher than 50%, an ac power can be produced by cyclically varying the duty cycle from a value lower than 50% to a value higher than 50%. For instance, controlling the duty cycle using a sine-wave voltage produces a sine-wave voltage at the output of a four-quadrant chopper.

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

Without filtration, the voltage waveform at the output of single phase inverters is a train of rectangular bipolar pulses, which affect the operation of many ac powered devices. A filter is added at the output of single-phase-inverters to smooth the voltage waveform, resulting in a sinusoidal voltage waveform.

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?

Average dc voltage at the input of the single-phase PWM inverter: 350 V. ($E_{O,max} = E_I \times m$)

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.

c

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