Electricity and New Energy

Three-Phase AC Power Electronics

Courseware Sample

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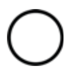
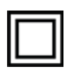
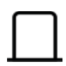
Safety and Common Symbols

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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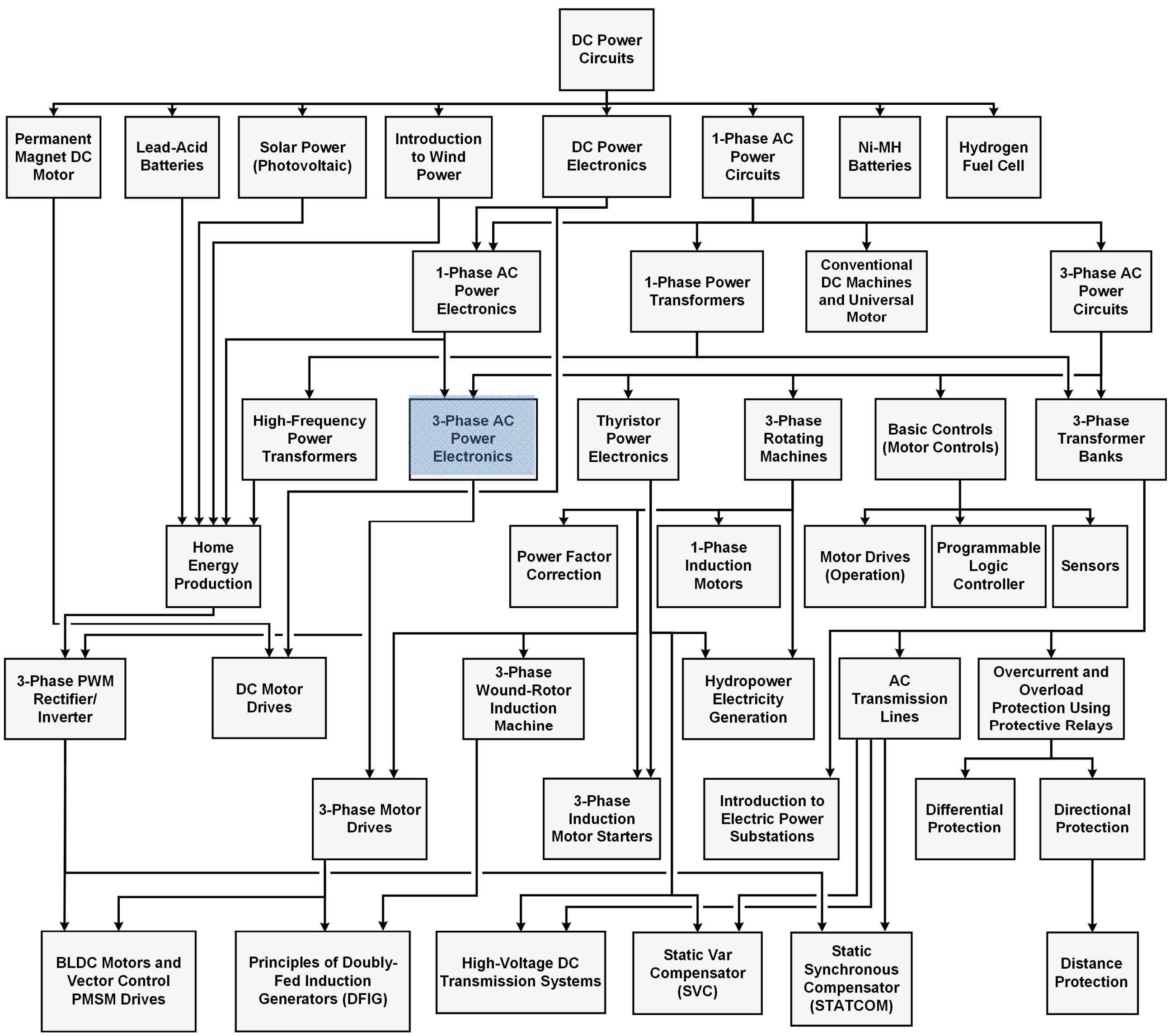
Preface

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.

We invite readers of this manual to send us their tips, feedback, and suggestions for improving the book.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

This manual, *Three-Phase AC Power Electronics*, introduces the student to the student to power electronic circuits (rectifiers and inverters) used to perform ac/dc power conversion in three-phase circuits. The course begins with the study of three-phase diode rectifiers. The student then becomes familiar with the operation of the single-phase PWM inverter built with a dual-polarity dc bus. The course continues with the operation of the three-phase PWM inverter built with a single-polarity or dual-polarity dc bus. The course concludes with the study of the three-phase PWM inverter.

The equipment for the course mainly consists of the IGBT Chopper/Inverter module. The operation of the IGBT Chopper/Inverter module is controlled by the LVDAC-EMS software. The Resistive Load, Filtering Inductors/Capacitors, Three-Phase Filter, Power Supply, Rectifier and Filtering Capacitors, and the Data Acquisition and Control Interface are also used to perform the exercises in this manual

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 manuals titled *DC Power Circuits*, part number 86350, *DC Power Electronics*, part number 86356, *Single-Phase AC Power Circuits*, part number 86358, *Single-Phase AC Power Electronics*, part number 86359, and *Three-Phase AC Power Circuits*, part number 86360.

Systems of units

Units are expressed using the International System of Units (SI) followed by 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.

Sample Exercise

Extracted from

the Student Manual

and the Instructor Guide

The Three-Phase PWM Inverter

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

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

- Operation of the three-phase PWM inverter
- Current in the neutral conductor

DISCUSSION

Operation of the three-phase PWM inverter

Basically, the three-phase PWM inverter consists of three single-phase PWM inverters powered by a dual-polarity dc bus. As Figure 21 shows, the three-phase PWM inverter contains three pairs of electronic switches (Q_1 and Q_4, Q_2 and Q_5, and Q_3 and Q_6), six free-wheeling diodes (D_1 to D_6), and a switching control signal generator.

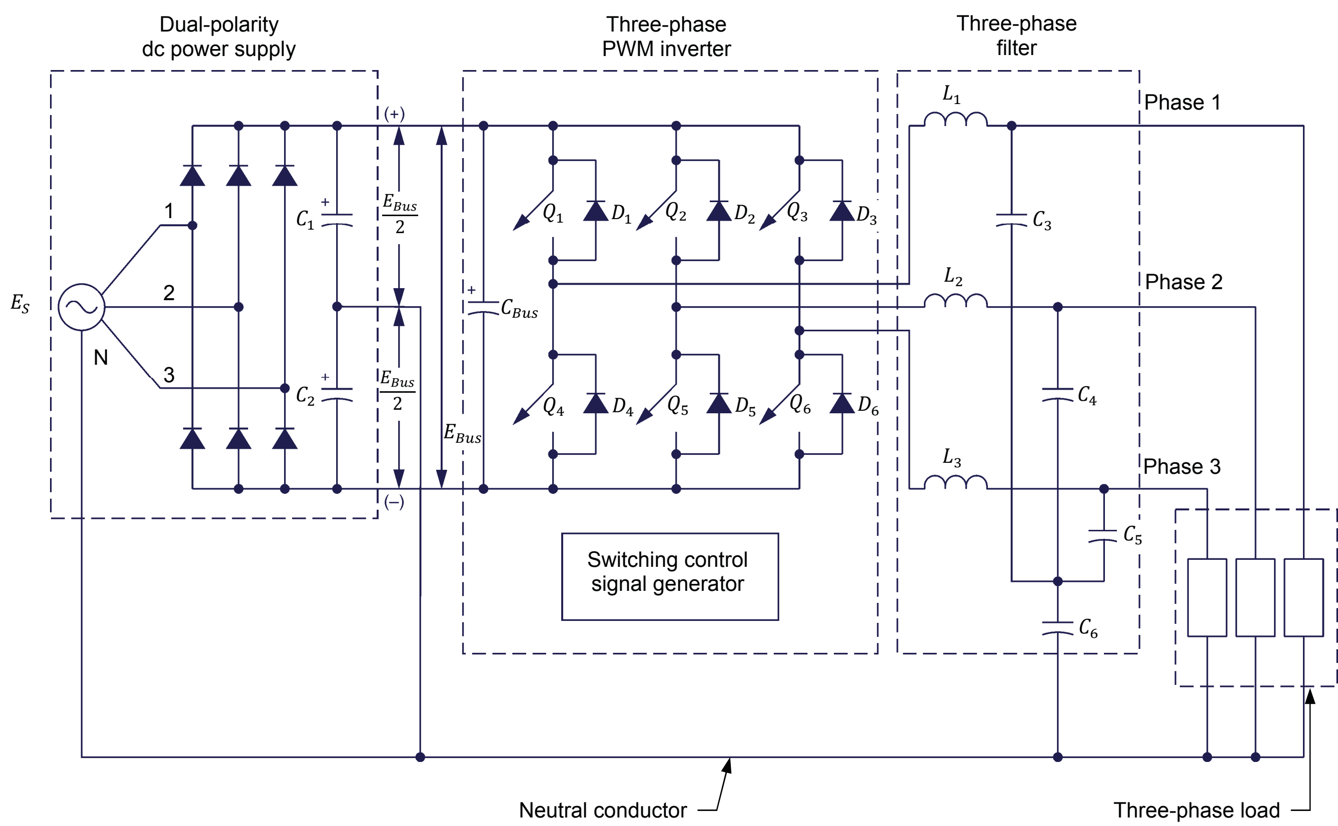


Figure 21. The three-phase PWM inverter consists of three single-phase PWM inverters.

The two signals that the switching control signal generator produces for each pair of electronic switches are complementary rectangular pulses to ensure that when one electronic switch in a pair is on, the other electronic switch in this pair is off, and vice versa. Each of the three pairs of electronic switches operates the same way: a positive voltage ($+E_{BUS}/2$) is applied to the load when the upper electronic switch (Q_1, Q_2 or Q_3) is on, whereas a negative voltage (-$E_{BUS}/2$) is applied to the load when the lower electronic switch (Q_4, Q_5 or Q_6) is on.

The voltage waveform at the outputs of the three-phase PWM inverter depends on the waveform of the signal that modulates the duty cycle of the switching control signals. When a sine-wave signal is used to modulate the duty cycle of the switching control signals, the voltage waveform at the three-phase PWM inverter outputs consists of three trains of rectangular bipolar pulses whose width varies in accordance with the instantaneous voltage of the modulating sine-wave signal. The average voltage of each on-off cycle of the rectangular bipolar pulse trains at the inverter outputs thus also varies sinusoidally.

As for the single-phase inverter, a filter made of inductors and capacitors (see example in Figure 25) is usually added at the outputs of the three-phase-PWM inverter to smooth the voltage and current waveforms. This results in sinusoidal voltage waveforms (when a sine-wave signal is used to modulate the duty cycle of the switching control signals and ideal filtering is assumed) at the outputs of the three-phase PWM inverter. The three-pairs of complementary switching control signals used with the three pairs of electronic switches in the thee-phase PWM inverter are phase shifted by 120° with respect to each other. Consequently, the sinusoidal voltage waveforms at the outputs of the three-phase PWM inverter are also phase shifted by 120° with respect to each other as shown by voltage waveforms $E_{Phase\,1}$, $E_{Phase\,2}$, and $E_{Phase\,3}$ in Figure 22. Note that ideal filtering at the PWM inverter outputs is assumed in Figure 22 as the voltage waveforms shown are pure sine waves. The current waveforms are similar to the voltage waveforms when the load is purely resistive as shown by current waveforms $I_{Line\,1}$, $I_{Line\,2}$, and $I_{Line\,3}$ in Figure 22. The outputs of the three-phase PWM inverter are usually connected to loads that are both balanced and similar in nature.

The amplitude of the sinusoidal voltages at the outputs of the three-phase PWM inverter can be varied by varying the amplitude of the sine-wave signal modulating the duty cycle of the switching control signals. The amplitude of the voltage at each output of the three-phase PWM inverter $E_{O,max}$ is the same as with a single-phase PWM inverter with dual-polarity dc bus, it is proportional to the modulation index.

The frequency of the voltages at the output of the three-phase PWM inverter can be varied by varying the frequency of the sine-wave signal modulating the duty cycle of the switching control signals.

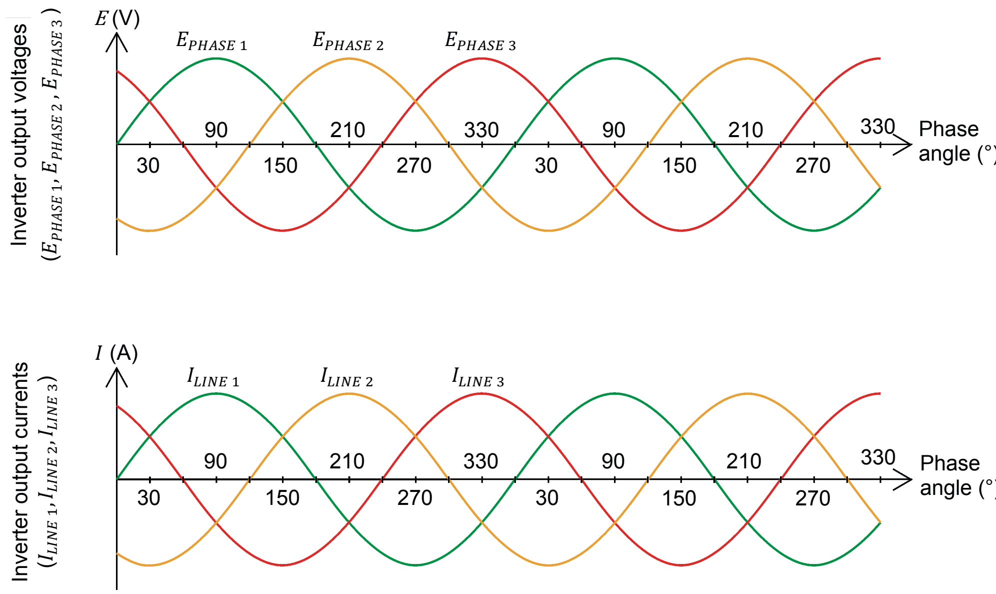


Figure 22. Voltage and current waveforms at the outputs of a three-phase PWM inverter (ideal filtering is assumed).

Current in the neutral conductor

When ideal filtering at the outputs of a three-phase PWM inverter is assumed, the line currents are pure sine waves that have the same amplitude, same frequency, and are phase-shifted by 120° with respect to each other, and their sum is null as shown in the phasor diagram of Figure 23. The neutral conductor can thus be removed without disturbing the operation of the three-phase PWM inverter.

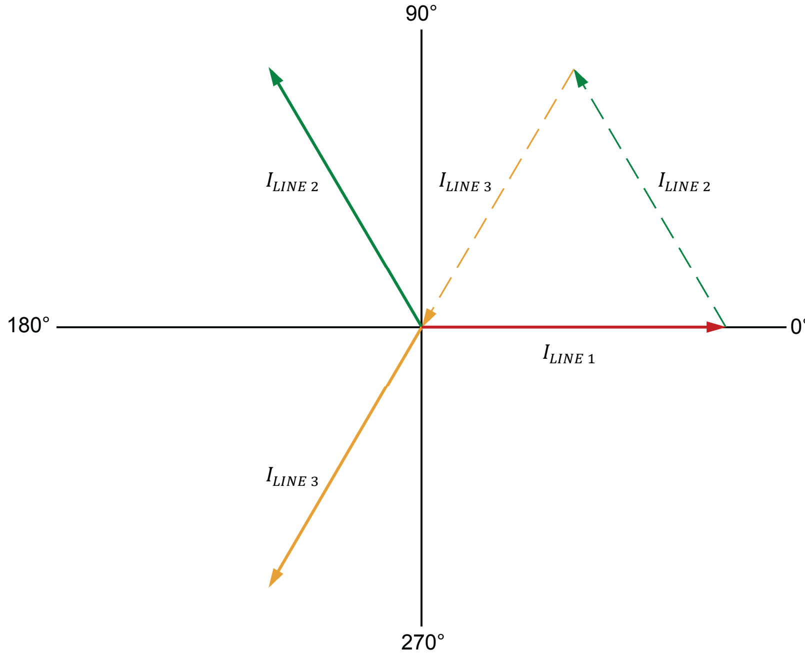


Figure 23. Phasor diagram showing that the sum of the line currents in a three-phase PWM inverter is null (ideal filtering assumed at the PWM inverter outputs).

Actual filters used in the three-phase PWM inverters, however, are not ideal. Consequently, the voltage and current waveforms at the three-phase PWM inverter outputs are slightly distorted sine waves. This also causes a residual current to flow into the neutral conductor. However, since the residual current in the neutral conductor is useless from an operational point of view, this does not prevent the neutral conductor from being removed. In fact, removing the neutral conductor eliminates the residual current and improves the voltage and current waveforms at the three-phase PWM inverter outputs.

Removing the neutral conductor also eliminates the need for a dual-polarity dc power supply. Figure 24 shows a diagram of a three-phase PWM inverter without a neutral conductor and powered by a single-polarity dc power supply.

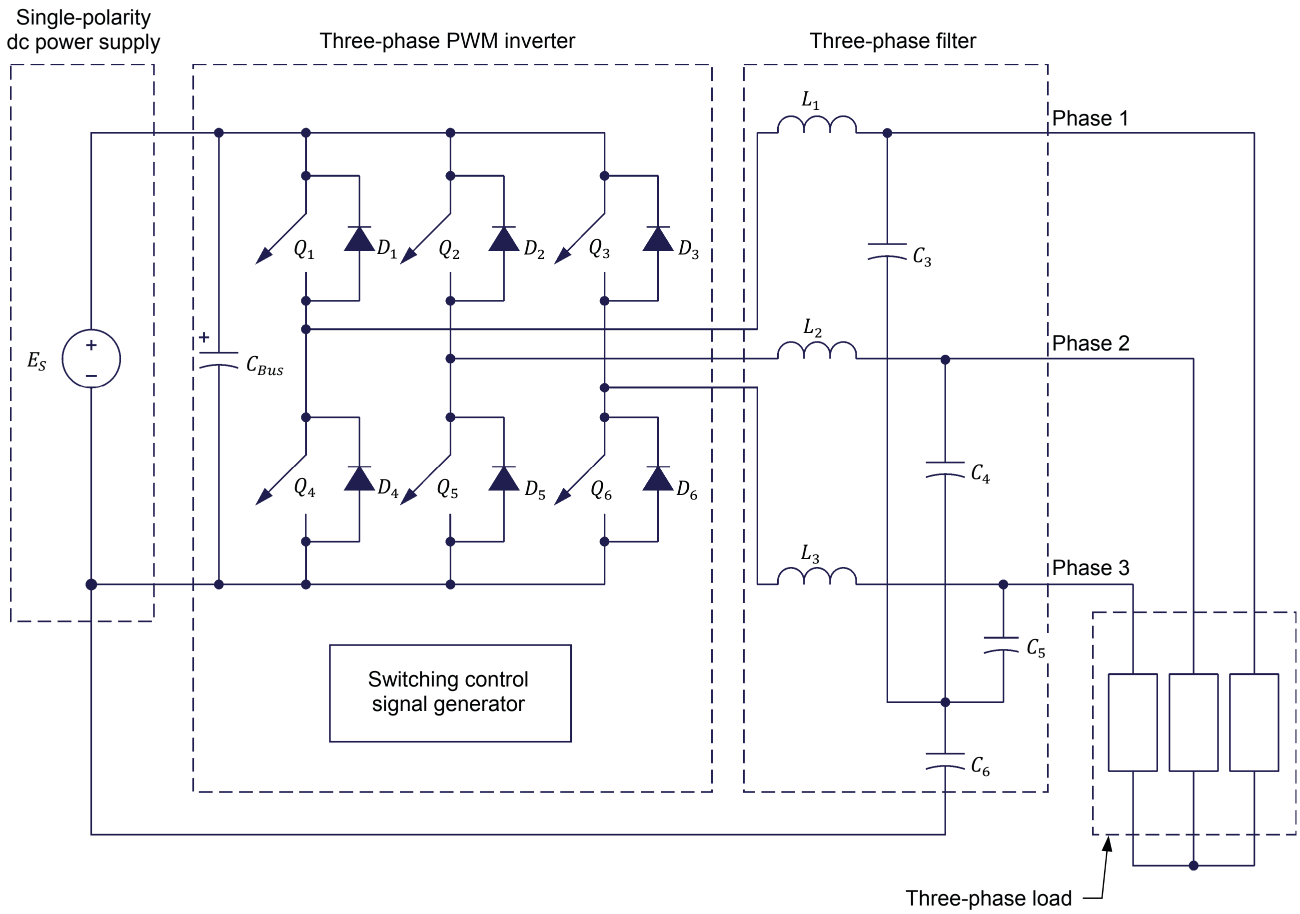


Figure 24. Three-phase PWM inverter without neutral conductor and supplied by a single-polarity dc power supply.

Procedure Outline

The Procedure is divided into the following sections:

- Setup and connections
- Operation of a three-phase PWM inverter powered by a dual-polarity dc power supply
- Effect of the neutral conductor on the voltage and current waveforms at the output of the three-phase PWM inverter

Procedure

⚠ WARNING

High voltages are present in this laboratory exercise. Do not make of 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 the exercise.

Install the equipment in the Workstation.

2. Make sure that the ac and dc power switches on the Power Supply are set to the O (off) position, then connect the Power Supply to a three-phase ac power outlet.

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

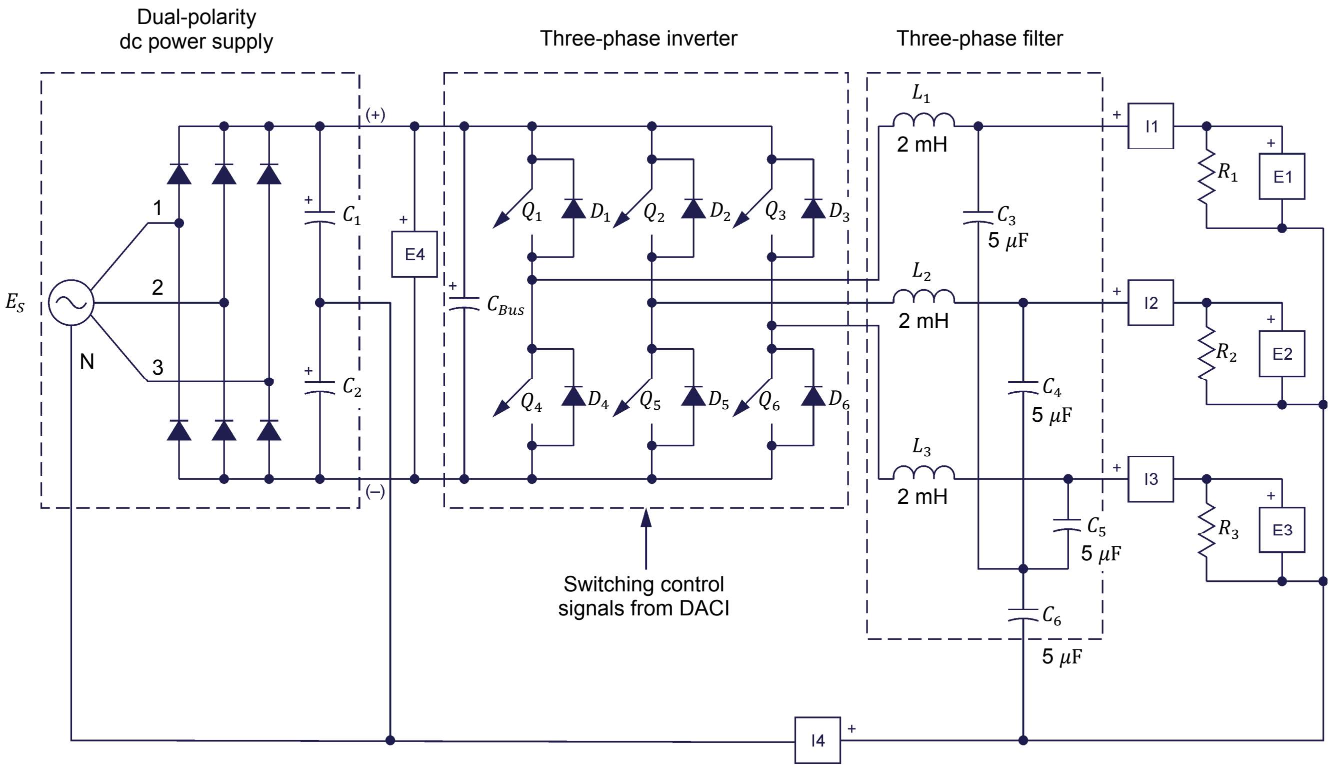
Connect the *Low Power Input* of the Chopper/Inverter to the *Power Input* of the Data Acquisition and Control Interface. Turn the 24 V ac power supply on.

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

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 25. Use the diodes and capacitors in the Rectifier and Filtering Capacitors to implement rectifier and capacitors C_1 and C_2. Use the IGBT Chopper/Inverter to implement the Three-phase inverter. Use the inductors and capacitors of the Three-Phase Filter to implement inductors L_1, L_2, and L_3 as well as capacitors C_3, C_4, C_5, and C_6. Resistors R_1, R_2, and R_3 are implemented with the Resistive Load module. The resistance value to be used for these resistors depends on your local ac power network voltage (see table in diagram).



Local ac power network		R_1, R_2, R_3 (Ω)
Voltage (V)	Frequency (Hz)	
120	60	171
220	50	629
240	50	686
220	60	629

Figure 25. Three-phase PWM inverter.

7. Connect the *Digital Outputs* of the Data Acquisition and Control Interface (DACI) to the *Switching Control Inputs* of the Chopper/Inverter using a DB9 connector cable.

   Connect *Switching Control Inputs 1* to *6* of the Chopper/Inverter to *Analog Inputs 1* to *6* 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 Chopper/Inverter.

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

On the Chopper/Inverter, set the *Dumping* switch to the O (off) position. The *Dumping* switch is used to prevent overvoltage on the dc bus of the Chopper/Inverter. It is not required in this exercise.

Operation of a three-phase PWM inverter powered by a dual-polarity dc power supply

In this part of the exercise, you will use the circuit shown in Figure 25 to observe the operation of a three-phase PWM inverter powered by a dual-polarity dc power supply. You will observe the switching control signals of the electronic switches, and the waveforms of the voltages and currents at the output of the inverter with and without the neutral conductor.

8. In the Chopper/Inverter Control window of LVDAC-EMS, make the following settings:

   – Set the *Function* parameter to *Three-Phase, PWM Inverter*. This setting allows the Data Acquisition and Control Interface to generate the switching control signals required by a three-phase PWM inverter.

   – Set the *Switching Frequency* parameter to 400 Hz. This will allow observation of the switching control signals in the three-phase PWM inverter, using the Oscilloscope.

   – Set the *Phase Sequence* parameter to *Fwd (1-2-3)*. This parameter sets the phase sequence [*Fwd (1-2-3)* or *Rev (1-3-2)*]. The phase sequence *Fwd (1-2-3)* causes a three-phase motor supplied by the three-phase PWM inverter to rotate in the forward direction.

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

   – Set the *Peak Voltage* parameter to 90%. This parameter sets the modulation index, i.e., it sets the amplitude of the signal that modulates the duty cycle of the switching control signals. When the *Peak Voltage* parameter is set to 90%, the amplitude of the modulating signal is set to make the duty cycle vary to obtain a peak output voltage corresponding to 90% of the half dc bus voltage (45% of E_{BUS}).

   – Make sure that parameters *Q1* to *Q6* are set to *PWM*.

9. Turn the Power Supply on.

   If the breaker of the Power Supply trips when you turn it on, set its power switch to on another time (to let the DC bus voltage charge).

   In the Chopper/Inverter Control window of LVDAC-EMS, start the *Three-Phase, PWM Inverter*.

10. In LVDAC-EMS, open the Oscilloscope window and use channels 1 through 6 to display the switching control signals of electronic switches Q_1 (*AI-1*) to Q_6 (*AI-6*).

Select the *Continuous Refresh* mode, set the time base to 5 ms/div, and set the trigger controls so that the Oscilloscope triggers on the rising edge of the switching control signal of electronic switch Q_1 (Ch1).

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

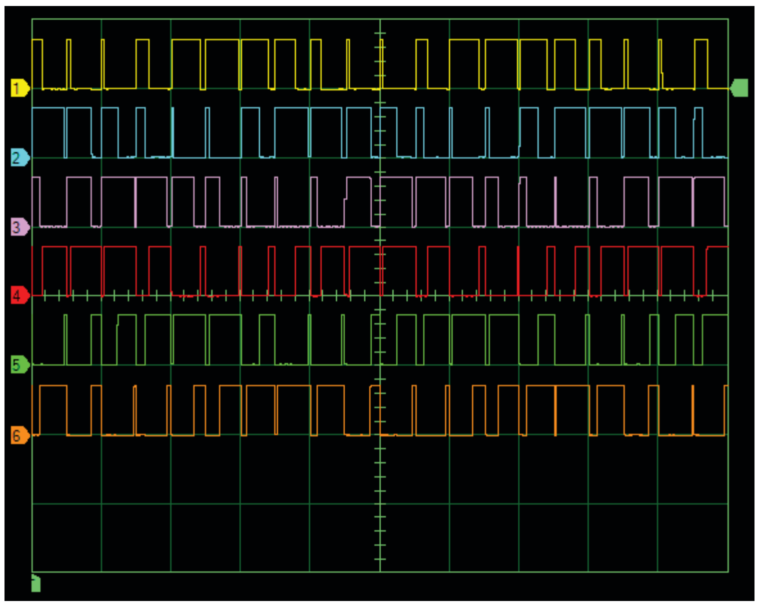
Finally, set the Oscilloscope so that the waveforms are displayed on the screen using staircase steps (squared display mode).

11. Print or save the waveforms displayed on the Oscilloscope screen for future reference. It is suggested that you include these waveforms in your lab report.

The resulting waveforms are shown below.

Oscilloscope Settings

Channel-1 Input	AI-1
Channel-1 Scale	5 V/div
Channel-1 Coupling	DC
Channel-2 Input	AI-2
Channel-2 Scale	5 V/div
Channel-2 Coupling	DC
Channel-3 Input	AI-3
Channel-3 Scale	5 V/div
Channel-3 Coupling	DC
Channel-4 Input	AI-4
Channel-4 Scale	5 V/div
Channel-4 Coupling	DC
Channel-5 Input	AI-5
Channel-5 Scale	5 V/div
Channel-5 Coupling	DC
Channel-6 Input	AI-6
Channel-6 Scale	5 V/div
Channel-6 Coupling	DC
Time Base	5 ms/div
Trigger Type	Software
Trigger Source	Ch1
Trigger Level	0
Trigger Slope	Rising



Waveforms of the switching control signals of the three-phase PWM inverter.

12. Do your observations confirm that the switching control signals in each pair of electronic switches Q_1-Q_4, Q_2-Q_5, and Q_3-Q_6 are complementary?

❑ Yes ❑ No

Yes

Do your observations confirm that the switching control signals of consecutive pairs of electronic switches seem to be phase shifted by 120°?

❑ Yes ❑ No

Yes

13. In the Chopper/Inverter Control window of LVDAC-EMS, make the following settings:

– Set the *Switching Frequency* parameter to 20 000 Hz

– Set the *Peak Voltage* parameter to 100%.

14. In the Oscilloscope window, set channels 1 through 3 to display the phase voltages at the three-phase PWM inverter outputs (*E1*, *E2*, and *E3*), channel 4 to display the dc bus voltage (*E4*), channels 5 through 7 to display the line currents at the inverter outputs (*I1*, *I2*, and *I3*), and channel 8 to display the current in the neutral conductor (*I4*).

Set the trigger controls so that the Oscilloscope triggers when the load voltage waveform (Ch1) passes through 0 V with a positive slope.

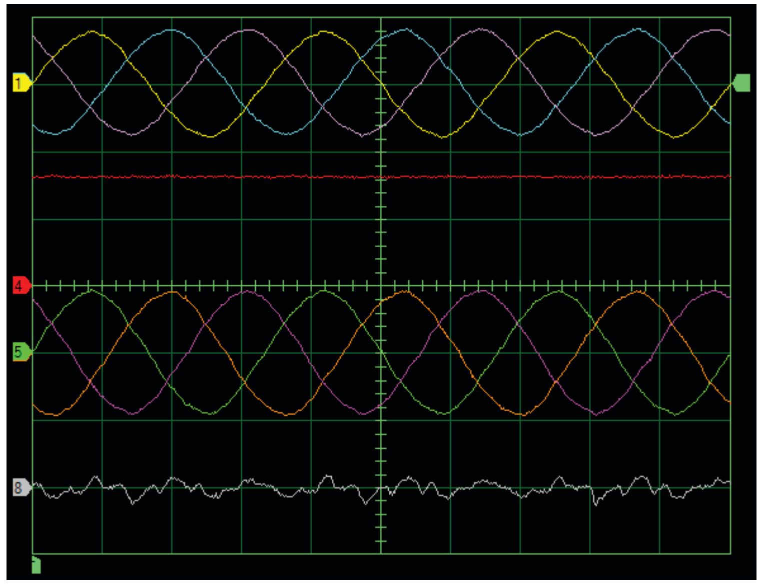
Make sure that the *Continuous Refresh* mode is selected. Select convenient vertical scale and position settings to facilitate observation of the waveforms.

Finally, set the Oscilloscope so that the waveforms are displayed as usual (normal display mode).

15. Print or save the waveforms displayed on the Oscilloscope screen for future reference. It is suggested that you include these waveforms in your lab report.

The resulting waveforms are shown below.

Oscilloscope Settings
Channel-1 Input E1
Channel-1 Scale .... 200 V/div
Channel-1 Coupling .... DC
Channel-2 Input E2
Channel-2 Scale .... 200 V/div
Channel-2 Coupling .... DC
Channel-3 Input E3
Channel-3 Scale .... 200 V/div
Channel-3 Coupling .... DC
Channel-4 Input E4
Channel-4 Scale .... 200 V/div
Channel-4 Coupling .... DC
Channel-5 Input I1
Channel-5 Scale .... 1 A/div
Channel-5 Coupling .... DC
Channel-6 Input I2
Channel-6 Scale .... 1 A/div
Channel-6 Coupling .... DC
Channel-7 Input I3
Channel-7 Scale .... 1 A/div
Channel-7 Coupling .... DC
Channel-8 Input I4
Channel-8 Scale .... 0.5 A/div
Channel-8 Coupling .... DC
Time Base .... 5 ms/div
Trigger Type .... Software
Trigger Source Ch1
Trigger Level 0
Trigger Slope .... Rising



Waveforms of the voltages and currents at the output of the three-phase PWM inverter (with neutral conductor).

16. Are the waveforms of the phase voltages at the output of the three-phase PWM inverter sinusoidal, balanced, and phase shifted by 120° with respect to each other?

❑ Yes ❑ No

Yes

17. In the Chopper/Inverter Control window, use the *Peak Voltage* control knob to slowly vary the *Peak Voltage* parameter from 10% to 100% while observing the phase voltages at the three-phase PWM inverter output.

Do your observations confirm that the *Peak Voltage* parameter (i.e., the modulation index m) controls the amplitude of the phase voltages at the output of the three-phase PWM inverter?

❑ Yes ❑ No

Yes

18. In the Chopper/Inverter Control window, set the *Peak Voltage* parameter to 40% of half the dc bus voltage (modulation index = 0.4).

Using the *Frequency* control knob, slowly vary the *Frequency* parameter from 10 Hz to 120 Hz while observing the phase voltages at the output of the inverter.

Do your observations confirm that the *Frequency* parameter controls the frequency of the phase voltages at the output of the three-phase PWM inverter?

❑ Yes ❑ No

Yes

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

Measure the average (dc) value of the dc bus voltage, i.e., the voltage between the positive and negative terminals of the dc power supply.

DC bus voltage (E_{BUS}): _______ V

DC bus voltage (E_{BUS}): 337 V

20. Measure the amplitude of phase 1 voltage (Ch1) at the output of the three-phase PWM inverter (after filtering) and record the value.

Since the phase voltages at the output of the three-phase PWM inverter are identical, this observation can also be done using phase 2 and phase 3 voltages.

Amplitude of phase 1 voltage at the output of the three-phase PWM inverter (after filtering): _______ V

Amplitude of phase 1 voltage at the output of the three-phase PWM inverter (after filtering): 63 V

21. Compare the amplitude of phase 1 voltage at the output of the three-phase PWM inverter (after filtering) to the amplitude of the voltage at the output of the single-phase PWM inverter (after filtering) measured in the previous exercise when the modulation index is set to 0.4 (see Table 2). Do the values confirm that the amplitude of the voltage at each output of the three-phase PWM inverter is the same as the amplitude of the voltage at the output of a single-phase PWM inverter with dual-polarity dc bus?

❑ Yes ❑ No

Yes

Effect of the neutral conductor on the voltage and current waveforms at the output of the three-phase PWM inverter

In the next steps, you will compare the voltage and current waveforms at the output of the three-phase PWM inverter with and without neutral conductor between the load and the power supply.

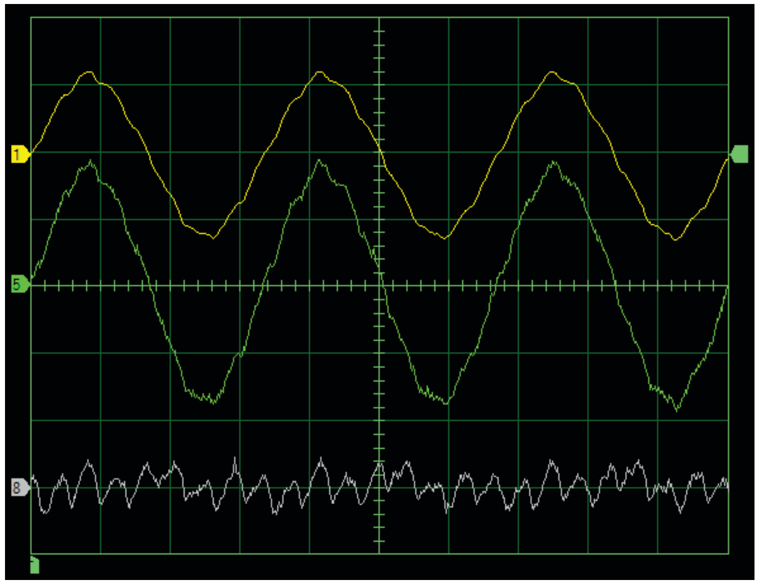
22. In the Oscilloscope window, close channels 2, 3, 4, 6, and 7 to display one of the phase voltage at the three-phase PWM inverter output and the corresponding line current as well as the current in the neutral conductor.

Position and set the scale of channels 1 and 5 so that each waveform covers approximately half of the Oscilloscope screen. Position channel 8 at the bottom of the Oscilloscope screen. These settings facilitate the observation of the waveforms at the inverter output in order to compare the effect the neutral conductor may have on the phase voltages and line currents.

23. Print or save the waveforms displayed on the Oscilloscope screen for future reference. It is suggested that you include these waveforms in your lab report.

The resulting waveforms are shown below.

Oscilloscope Settings
Channel-1 Input E1
Channel-1 Scale ....50 V/div
Channel-1 Coupling ....DC
Channel-5 Input I1
Channel-5 Scale ....0.2 A/div
Channel-5 Coupling ....DC
Channel-8 Input I4
Channel-8 Scale ....0.2 A/div
Channel-8 Coupling ....DC
Time Base............................ 5 ms/div
Trigger Type ....Software
Trigger Source Ch1
Trigger Level.....................................0
Trigger Slope ....Rising



Waveforms of the phase voltage and line current at the output of the three-phase PWM inverter as well as the waveform of the current in the neutral conductor.

24. Are the voltage and current at the three-phase PWM inverter output pure sine waves? Explain why some current flows through the neutral conductor?

The voltage and current at the three-phase PWM inverter output are not pure sine waves. A residual current flows in the neutral conductor because the line currents at the three-phase PWM inverter outputs are slightly distorted.

25. Turn the Power Supply off.

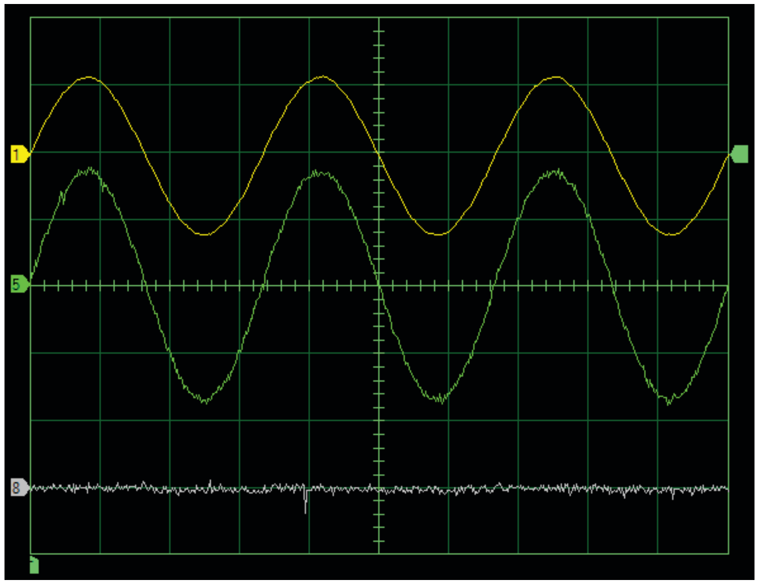
Remove the neutral conductor (represented by a red line in Figure 25) between the load and the positive terminal of input *I4* on the Data Acquisition and Control Interface.

Turn the Power Supply on.

26. Print or save the waveforms displayed on the Oscilloscope screen for future reference. It is suggested that you include these waveforms in your lab report.

The resulting waveforms are shown below.

Oscilloscope Settings
Channel-1 Input E1
Channel-1 Scale .... 50 V/div
Channel-1 Coupling .... DC
Channel-5 Input I1
Channel-5 Scale .... 0.2 A/div
Channel-5 Coupling .... DC
Channel-8 Input I4
Channel-8 Scale .... 0.2 A/div
Channel-8 Coupling .... DC
Time Base .... 5 ms/div
Trigger Type .... Software
Trigger Source Ch1
Trigger Level 0
Trigger Slope .... Rising



Waveforms of the phase voltage and line current at the output of the three-phase PWM inverter with the neutral conductor removed.

27. Compare the amplitude and frequency of the phase voltage and line current at the output of the three-phase PWM inverter with and without the neutral conductor. Do your observations confirm that the neutral conductor between the load and the power supply can be removed without affecting the amplitude and frequency of the phase voltages and line currents at the output of the inverter?

❑ Yes ❑ No

Yes

28. Compare the waveforms of the phase voltages and line currents at the output of the inverter with and without the neutral conductor. Describe how the waveforms are affected when the neutral conductor is removed.

The waveforms are improved (less distorted) when the neutral conductor is removed.

29. Does removing the neutral conductor improve the waveforms of the phase voltage and line current at the three-phase PWM inverter output?

❑ Yes ❑ No

Yes

30. Measure the average (dc) value of the dc bus voltage, i.e., the voltage between the positive and negative terminals of the dc power supply.

DC bus voltage (E_{BUS}): _______ V

DC bus voltage (E_{BUS}): 337 V

31. Measure the amplitude of phase 1 voltage at the output of the three-phase PWM inverter (after filtering) and record the value.

Amplitude of phase 1 voltage at the output of the three-phase PWM inverter (after filtering): _______ V

Amplitude of phase 1 voltage at the output of the three-phase PWM inverter (after filtering): 63 V

32. Compare the amplitude of phase 1 voltage at the output of the three-phase PWM inverter (after filtering) measured with and without neutral conductor (step 20 and step 31 respectively). Do the measured values confirm that the neutral conductor can be removed without negatively affecting the operation of the three-phase PWM inverter?

❑ Yes ❑ No

Yes

33. From the observations you made in this section of the exercise, can you conclude that a dual-polarity power supply is not required to supply a three-phase PWM inverter? Explain.

❑ Yes ❑ No

Yes, since the neutral conductor (common point of the dual-polarity power supply) can be removed without negatively affecting the operation of the three-phase PWM inverter.

34. Stop the voltage source and the *Three-Phase, PWM Inverter*.

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

Conclusion

In this exercise, you observed that the switching control signals of each pair of electronic switches in a three-phase PWM inverter are complementary and that the switching control signals of one pair is phase shifted by 120° with respect to those of the other pairs.

You observed that the waveforms of the phase (line-to-neutral) voltages at the outputs of the three-phase PWM inverter are phase shifted by 120° from one another. You also observed that when the load is purely resistive, the waveforms of the line currents at the outputs of the three-phase PWM inverter are similar to the phase voltage waveforms. You saw that the amplitude and frequency of the voltages at the output of the three-phase PWM inverter can be varied by respectively varying the amplitude (i.e., the modulation index) and frequency of the sine-wave signal modulating the duty cycle of the switching control signals.

You saw that residual current flows in the neutral conductor when a three-phase inverter is powered with a dual-polarity dc power supply. You also observed that removing the neutral conductor improves the waveforms of the phase voltages and line currents at the three-phase PWM inverter outputs (they become almost pure sine waves) without affecting the operation of the three-phase PWM inverter.

Review Questions

1. What is the phase shift between the waveforms of the phase voltages at the outputs of a three-phase PWM inverter?

   The phase shift between the waveforms of the phase voltages at the outputs of a three-phase PWM inverter is 120°.

2. What determines the voltage waveform at the outputs of a three-phase PWM inverter (after filtration)?

   The voltage waveform at the outputs of the three-phase PWM inverter depends on the waveform of the signal that modulates the duty cycle of the switching control signals.

3. How can the amplitude and frequency of the voltages at the output of a three-phase PWM inverter be varied?

   The amplitude and frequency of the voltages at the output of a three-phase PWM inverter can be varied by respectively varying the amplitude (i.e., the modulation index) and frequency of the sine-wave signal modulating the duty cycle of the switching control signals.

4. Why is the sum of the line currents at the outputs of a three-phase PWM inverter not null even when the load is balanced?

   The sum of the line currents at the outputs of a three-phase PWM inverter is not null because the line currents are slightly distorted.

5. Is it possible to remove the neutral conductor in a three-phase PWM inverter powered by a dual-polarity dc power supply? If so, does this have any effect on the waveforms of the phase voltages and line currents at the three-phase PWM inverter outputs? Briefly explain.

Yes, it is possible to remove the neutral conductor in a three-phase PWM inverter powered by a dual-polarity dc power supply because this does not affect the operation of the inverter. In fact, removing the neutral conductor slightly improves the waveforms (i.e., the waveforms become less distorted) of the phase voltages and line currents at the three-phase PWM inverter outputs.

Bibliography

Jackson, Herbert W, Introduction to Electric Circuits, 8th ed. Oxford: Oxford University Press, 2008, ISBN 0-19-542310-0.

Wildi, Theodore, Electrical Machines, Drives, and Power Systems, 6th ed. New Jersey: Pearson Prentice Hall, 2006, ISBN 0-13-177691-6.