

Electricity and New Energy

Home Energy Production

Courseware Sample

86361-F0

Order no.: 86361-10
First Edition
Revision level: 01/2016

By the staff of Festo Didactic

© Festo Didactic Ltée/Ltd, Quebec, Canada 2012
Internet: www.festo-didactic.com
e-mail: did@de.festo.com

Printed in Canada
All rights reserved

ISBN 978-2-89640-462-9 (Printed version)

ISBN 978-2-89640-627-2 (CD-ROM)

Legal Deposit – Bibliothèque et Archives nationales du Québec, 2012

Legal Deposit – Library and Archives Canada, 2012

The purchaser shall receive a single right of use which is non-exclusive, non-time-limited and limited geographically to use at the purchaser's site/location as follows.

The purchaser shall be entitled to use the work to train his/her staff at the purchaser's site/location and shall also be entitled to use parts of the copyright material as the basis for the production of his/her own training documentation for the training of his/her staff at the purchaser's site/location with acknowledgement of source and to make copies for this purpose. In the case of schools/technical colleges, training centers, and universities, the right of use shall also include use by school and college students and trainees at the purchaser's site/location for teaching purposes.

The right of use shall in all cases exclude the right to publish the copyright material or to make this available for use on intranet, Internet and LMS platforms and databases such as Moodle, which allow access by a wide variety of users, including those outside of the purchaser's site/location.

Entitlement to other rights relating to reproductions, copies, adaptations, translations, microfilming and transfer to and storage and processing in electronic systems, no matter whether in whole or in part, shall require the prior consent of Festo Didactic.

Information in this document is subject to change without notice and does not represent a commitment on the part of Festo Didactic. The Festo materials described in this document are furnished under a license agreement or a nondisclosure agreement.

Festo Didactic recognizes product names as trademarks or registered trademarks of their respective holders.

All other trademarks are the property of their respective owners. Other trademarks and trade names may be used in this document to refer to either the entity claiming the marks and names or their products. Festo Didactic disclaims any proprietary interest in trademarks and trade names other than its own.

Safety and Common Symbols

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

Symbol	Description
	DANGER indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
	WARNING indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
	CAUTION indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
	CAUTION used without the <i>Caution, risk of danger</i> 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
	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

Table of Contents

Preface	IX
About This Manual	XI
To the Instructor	XIII
Introduction Home Energy Production	1
DISCUSSION OF FUNDAMENTALS	1
Home energy production: a definition	1
Stand-alone versus grid-tied home energy production	1
Grid-tied home energy production and the smart grid	2
Exercise 1 Stand-Alone Home Energy Production	5
DISCUSSION	5
Introduction	5
Frequency and rms value of the system's output voltage	7
Operation of the voltage feedback loop	8
Power limitation circuit	9
Battery under-voltage protection circuit	9
Insulated stand-alone inverter	11
PROCEDURE	13
Setup and connections	13
Operation of the single-phase stand-alone inverter	15
Operation of the protection circuit	20
Power limitation	20
Battery under voltage	21
Supplying power to an actual load	22
Operation with a power generation device (solar panel)	22
Operation with a power generation device (wind turbine)	27
Exercise 2 Single-Phase Grid-Tied Inverter (PWM Rectifier/Inverter)	35
DISCUSSION	35
Introduction to the single-phase grid-tied inverter	35
Active and reactive current commands	37
Controlling active power flow and reactive power flow in a single-phase grid-tied inverter	38
Operation of the current control loop	46
Feedforward voltage control	47
DC bus voltage versus the local ac power network voltage	49
PROCEDURE	52
Setup and connections	52
Active current command and active power flow control	54
Positive active-current command	55
Negative active-current command	59

Table of Contents

	Reactive current command and reactive power flow control	62
	Positive reactive-current command	62
	Negative reactive-current command.....	65
	Active and reactive power flow control	69
Exercise 3	Grid-Tied Home Energy Production Using a Solar or Wind Power Inverter without DC-to-DC Converter	77
	DISCUSSION	77
	Grid-tied home energy production using solar power or wind power.....	77
	Solar or wind power inverter implemented using the transformerless without dc-to-dc converter topology.....	80
	Solar or wind power inverter implemented using the LF transformer without dc-to-dc converter topology.....	83
	Operation of the MPP tracker in a solar power inverter implemented without a dc-to-dc converter.....	85
	PROCEDURE	87
	Set up and connections	87
	Grid-tied home energy production using a solar power inverter implemented with the LF transformer without dc-to-dc converter topology	89
Exercise 4	Grid-Tied Home Energy Production Using a Solar or Wind Power Inverter with DC-to-DC Converter	99
	DISCUSSION	99
	Solar or wind power inverter implemented using the transformerless with dc-to-dc converter topology.....	99
	Solar or wind power inverter implemented using the LF transformer with dc-to-dc converter topology.....	102
	Solar or wind power inverter implemented using the HF transformer topology.....	104
	Operation of a solar or wind power inverter using a dc-to-dc converter.....	107
	Operation of the MPP tracker in a solar or wind power inverter using a dc-to-dc converter	107
	PROCEDURE	111
	Setup and connections	111
	Grid-tied home energy production using a solar power inverter implemented with the HF transformer topology.....	114
	Grid-tied home energy production using a wind power inverter implemented with the HF transformer topology (optional).....	119

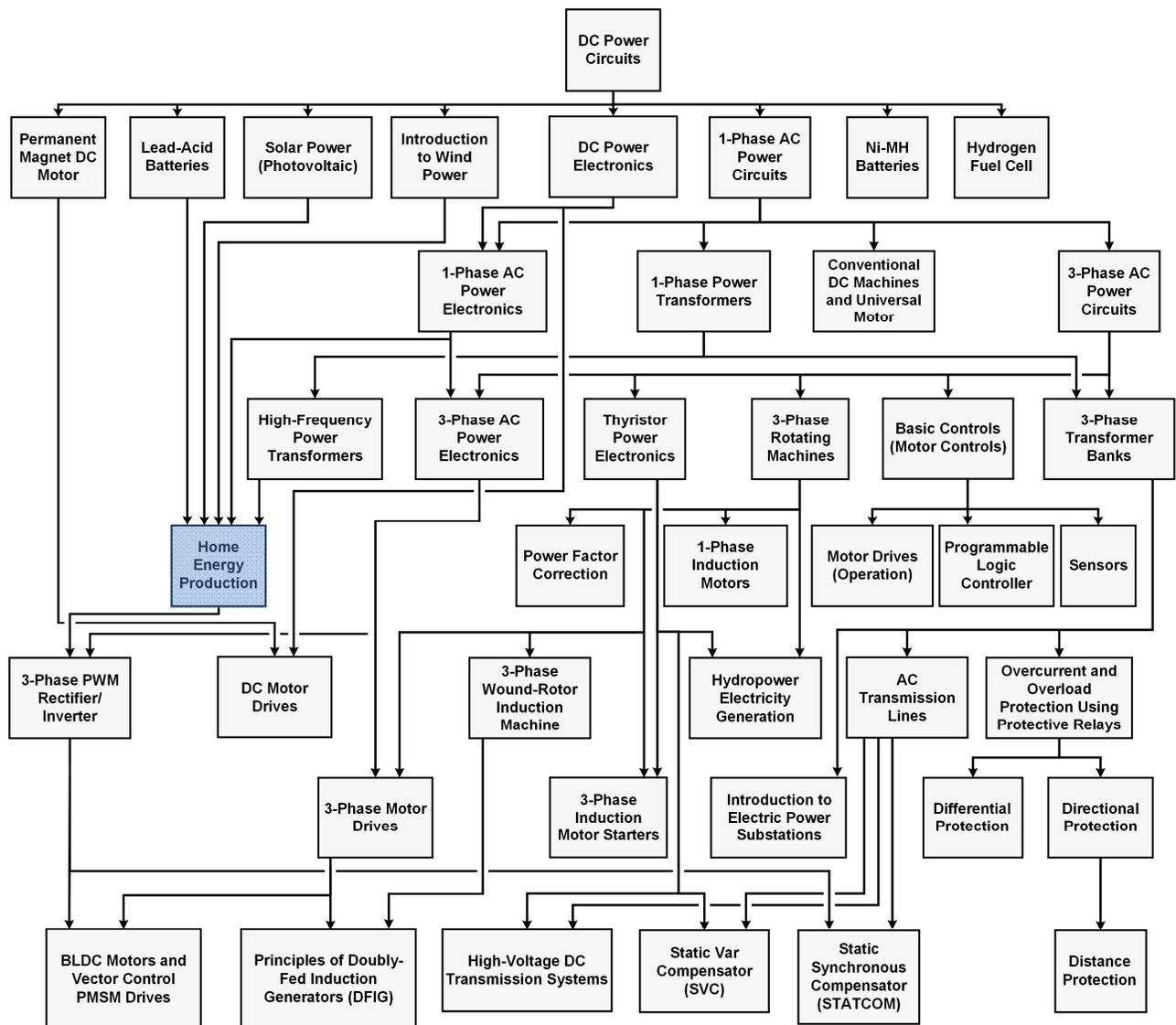
Table of Contents

Exercise 5	Large-Scale Energy Storage: A Step in the Implementation of the Smart Grid	129
	DISCUSSION	129
	Meeting the daily peak demand for electric power	129
	Grid-to-battery and battery-to-grid energy exchanges	130
	Using large-scale energy storage to help meet the daily peak power demand	131
	Using plug-in electric vehicles (PEVs) and plug-in hybrid electric vehicles (PHEVs) to implement large-scale energy storage in ac power networks.....	133
	PROCEDURE	133
	Setup and connections	134
	Battery Discharge.....	136
	Daytime and nighttime home power demands (without energy storage).....	137
	Daytime and nighttime home power demands (with energy storage).....	139
Appendix A	Equipment Utilization Chart.....	145
Appendix B	Glossary of New Terms	147
Appendix C	Impedance Table for the Load Modules	149
Appendix D	Circuit Diagram Symbols	151
Appendix E	Preparation of the Lead-Acid Battery Pack	157
	Charging procedure	157
	Sulfation test	158
	Battery maintenance.....	159
Appendix F	Setting the Maximum Charge Voltage of the Wind Turbine Controller.....	161
	Setup and connections	161
	Setting the maximum charge voltage of the wind turbine controller	162
	Index of New Terms.....	163
	Acronyms	165
	Bibliography	167

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

About the Home Energy Production course

The Home Energy Production course explains how to produce ac power from dc power produced using renewable natural resources (e.g., wind, sunlight, rain, etc.) or stored in batteries. The course first shows how to produce ac power for local use (typically at remote sites) from dc power produced using a solar panel or a wind turbine. In this case, any excess energy (i.e., energy produced but not consumed immediately) is stored in batteries to be used later. This is referred to as stand-alone home energy production. Then, the student learns how any excess energy produced locally can be returned to the local ac power network (i.e., the grid). This is referred to as grid-tied home energy production.

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 (p.n.) 86350, *Lead-Acid batteries*, p.n. 86351, *Solar Power*, p.n. 86352, *Introduction to Wind Power*, p.n. 86353, *DC Power Electronics*, p.n. 86356, *Single-Phase AC Power Circuits*, p.n. 86358, *Single-Phase AC Power Electronics*, p.n. 86359, *Single-Phase Power Transformers*, p.n. 86377, and *High-Frequency Power Transformers*, p.n. 86378.

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.

Samples Exercises
Extracted from
the Student Manual
and the Instructor Guide

Stand-Alone Home Energy Production

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with stand-alone home energy production.



The hands-on exercises in this manual require you to be familiar with the computer-based instruments included in this training system. Refer to the user guide titled Computer-Based Instruments for EMS (86718-E) to become familiar with the operation and use of the computer-based instruments.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction
- Frequency and rms value of the system's output voltage
- Operation of the voltage feedback loop
- Power limitation circuit
- Battery under-voltage protection circuit
- Insulated stand-alone inverter

DISCUSSION

Introduction

Stand-alone home energy production is the small-scale generation of electric power at a site that is not tied to the local ac power network. All energy produced is for local use only. Figure 4 shows a simplified diagram of a stand-alone home energy production system using a solar panel or a wind turbine. The main components of the system are: power generation device (solar panel or wind turbine in most cases), battery, boost chopper, and single-phase PWM inverter.

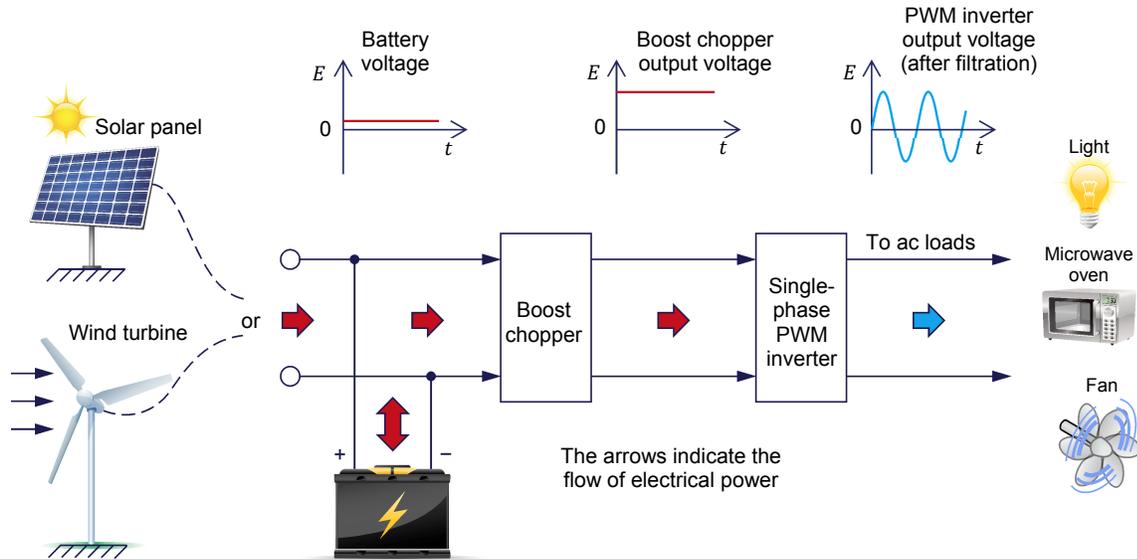


Figure 4. Simplified diagram of a stand-alone home energy production system using a wind turbine or a solar panel as a power generation device.

The wind turbine and/or the solar panel produce dc voltage suitable to charge the battery. A boost chopper increases the battery voltage to the value required for the single-phase PWM inverter to be able to produce a voltage sine wave whose rms value is equal to the ac power network voltage. The dc voltage required at the PWM inverter input depends on the value of ac power network voltage and the modulation index used in the inverter, as is explained later in this discussion.

The wind turbine and/or the solar panel generate dc power that is routed to the battery and boost chopper input. When no ac loads are connected to the PWM inverter output, all power generated is stored in the battery (until the battery is fully charged). When loads are connected to the inverter output, some of the power generated goes into the boost chopper to power the PWM inverter while the remaining power generated goes into the battery. When the power demand from the ac loads exceeds the dc power generated by the power generation device, dc power is drawn from the battery to provide the necessary amount of power to the boost chopper and PWM inverter.

Figure 5 shows a block diagram of a stand-alone home energy production system. Observe that all major components shown in the simplified diagram in Figure 4 are present in the block diagram. Notice that several blocks forming a voltage feedback loop have been added to regulate the boost chopper output voltage. The purpose of this voltage feedback loop will be explained later in the exercise discussion. Also, notice that a filter (made of two inductors and a capacitor) is added at the PWM inverter output to filter the PWM rectangular voltage waveform produced in order to obtain a sinusoidal output voltage. The boost chopper, voltage feedback loop, and single-phase PWM inverter form what is often referred to as a stand-alone inverter.

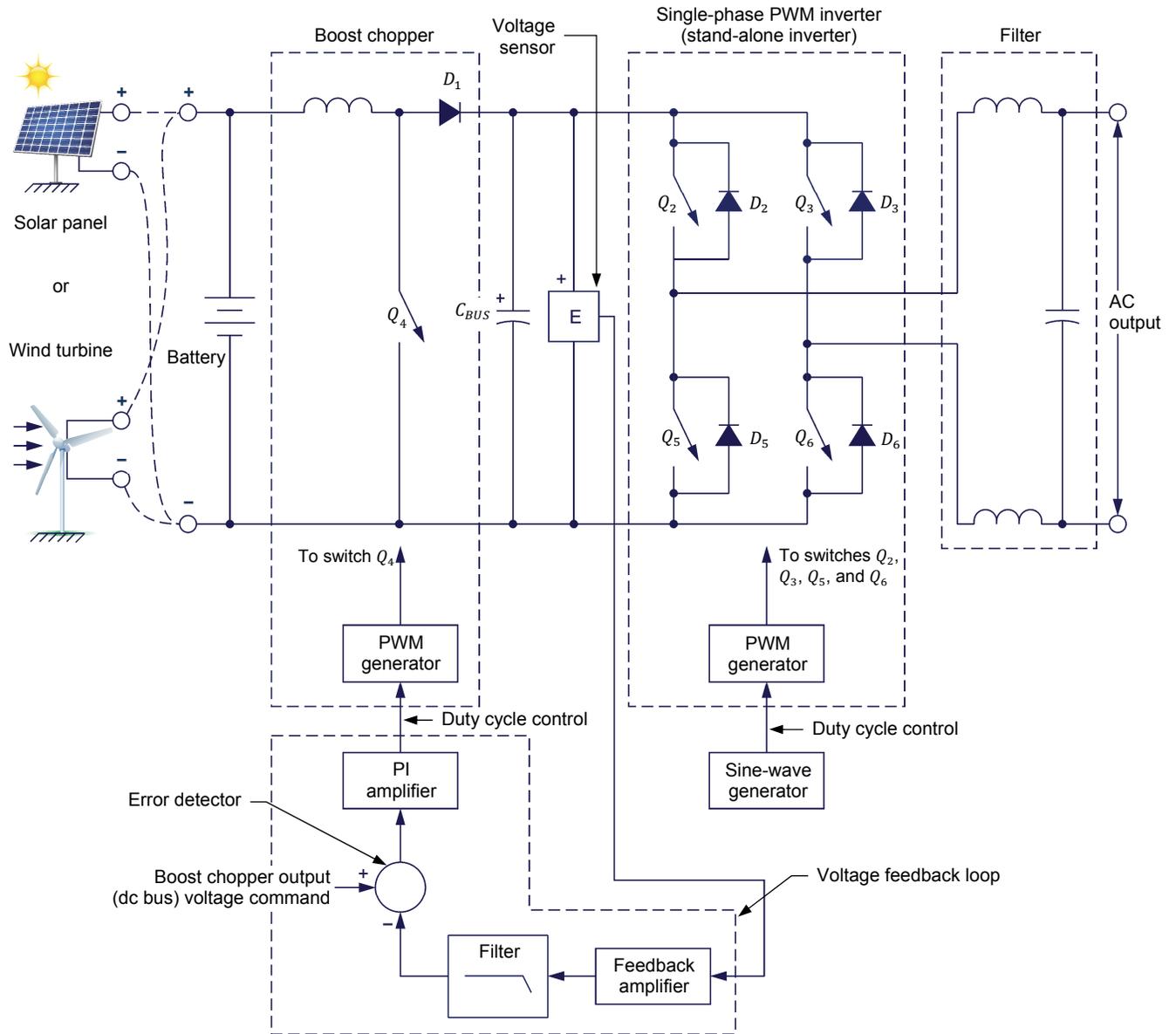


Figure 5. Block diagram of a stand-alone home energy production system using a wind turbine or a solar panel as power generation device.

Frequency and rms value of the system's output voltage

The frequency of the system's output voltage is set by making the output frequency parameter of the PWM inverter equal to the local ac power network frequency. The rms value of the system's output voltage is set equal to that of the local ac power network voltage. This is done by setting the modulation index of the PWM inverter to a fixed value (generally between 0.80 to 0.95) and adjusting the duty cycle of the boost chopper to obtain the dc voltage value required at the PWM inverter input. For instance, when the rms value of the system's output voltage is 220 V and the modulation index m of the PWM inverter is set to 0.9, a dc voltage of 346 V is required at the PWM inverter input (see calculation below).

If the battery voltage is 24 V, then the duty cycle of the boost chopper has to be set to 93.1% (see calculation below).

Calculation of the dc voltage required at the PWM inverter input to obtain an ac voltage of 220 V when the modulation index m of the PWM inverter is 0.9:

$$E_{BUS} = \frac{E_{O,rms} \times \sqrt{2}}{m} = \frac{220 \text{ V} \times \sqrt{2}}{0.9} = 345.7 \text{ V} \quad (1)$$

where E_{BUS} is the dc voltage applied at the PWM inverter input (i.e., dc voltage from the boost chopper output), expressed in volts (V)
 $E_{O,rms}$ is the rms value of the ac voltage at the PWM inverter output, expressed in volts (V)
 m is the modulation index expressed as a decimal

Calculation of the boost chopper duty cycle required to obtain a dc output voltage of 345.7 V when the dc voltage applied at the input of the boost chopper is 24 V:

$$\alpha = 1 - \frac{E_I}{E_{BUS}} = 1 - \frac{24 \text{ V}}{345.7 \text{ V}} = 0.9306 \quad (2)$$

where E_I is the dc voltage applied at the boost chopper input, expressed in volts (V)
 E_{BUS} is the dc voltage at the boost chopper output (i.e., dc voltage applied at the PWM inverter input), expressed in volts (V)
 α is the duty cycle expressed as a decimal

When the current drawn from the PWM inverter by the load increases, the system output voltage (i.e., the inverter output voltage) decreases due to the decrease in the battery voltage (this results in a decrease of the boost chopper output voltage) and the increase of voltage drops in the system. To limit the decrease of the system's output voltage with load, a voltage feedback loop is used to maintain the boost chopper output voltage (i.e., the PWM inverter input voltage) constant.

Operation of the voltage feedback loop

The operation of the voltage feedback loop is as follows: a boost-chopper output voltage command (also referred to as the dc bus voltage command) is set in the system. A voltage sensor (labeled E in Figure 5) measures the voltage at the boost chopper output. An error detector subtracts the value of the voltage measured at the boost chopper output from the dc bus voltage command. Whenever the boost chopper output voltage differs from the dc bus voltage command, the error detector produces an output signal, which after some proportional and integral (PI) amplification, readjusts the duty cycle of the boost chopper in order to correct the error. For instance, when the boost chopper output voltage is less than the dc bus voltage command, the error detector signal is positive, thereby increasing the duty cycle of the boost chopper. This increases

the boost chopper output voltage (i.e., the PWM inverter input voltage) until the error is corrected. At this point, the error detector signal is zero and the PI amplifier produces a fixed signal that sets the duty cycle of the boost chopper to the exact value required to maintain equilibrium.

Power limitation circuit

The power delivered to the load must be limited to a certain maximum value to avoid damage to the battery and stand-alone inverter. To do so, a current sensor measures the output current of the single-phase PWM inverter. When the measured current corresponds to an amount of power exceeding the maximum value allowed, the power limitation circuit disables the PWM generators of the boost chopper and PWM inverter. This turns off all electronic switches in the boost chopper and PWM inverter, thereby interrupting current flow in the system. The load must be decreased and the stand-alone inverter reset to resume normal operation.

Battery under-voltage protection circuit

When the battery voltage decreases to a certain minimum value, the stand-alone inverter must be stopped to stop discharging the battery and prevent permanent damage to the battery. The battery under-voltage protection circuit in a stand-alone inverter uses a voltage sensor to measure the battery voltage. When the measured voltage reaches the minimum value allowed, the battery under-voltage protection circuit disables the PWM generators of the boost chopper and PWM inverter. This turns off all electronic switches in the boost chopper and PWM inverter, thereby interrupting current flow in the system. The battery must be charged and the stand-alone inverter reset to resume normal operation.

The power limitation circuit and battery under-voltage protection circuit are often combined in a single protection circuit. This protection circuit monitors both the power delivered to the load (i.e., the load current) and the battery voltage. It disables the PWM generators when the power delivered to the load exceeds the maximum value allowed or when the battery voltage reaches the minimum value allowed. Figure 6 shows the block diagram of a single-phase, stand-alone inverter including a combined protection circuit.

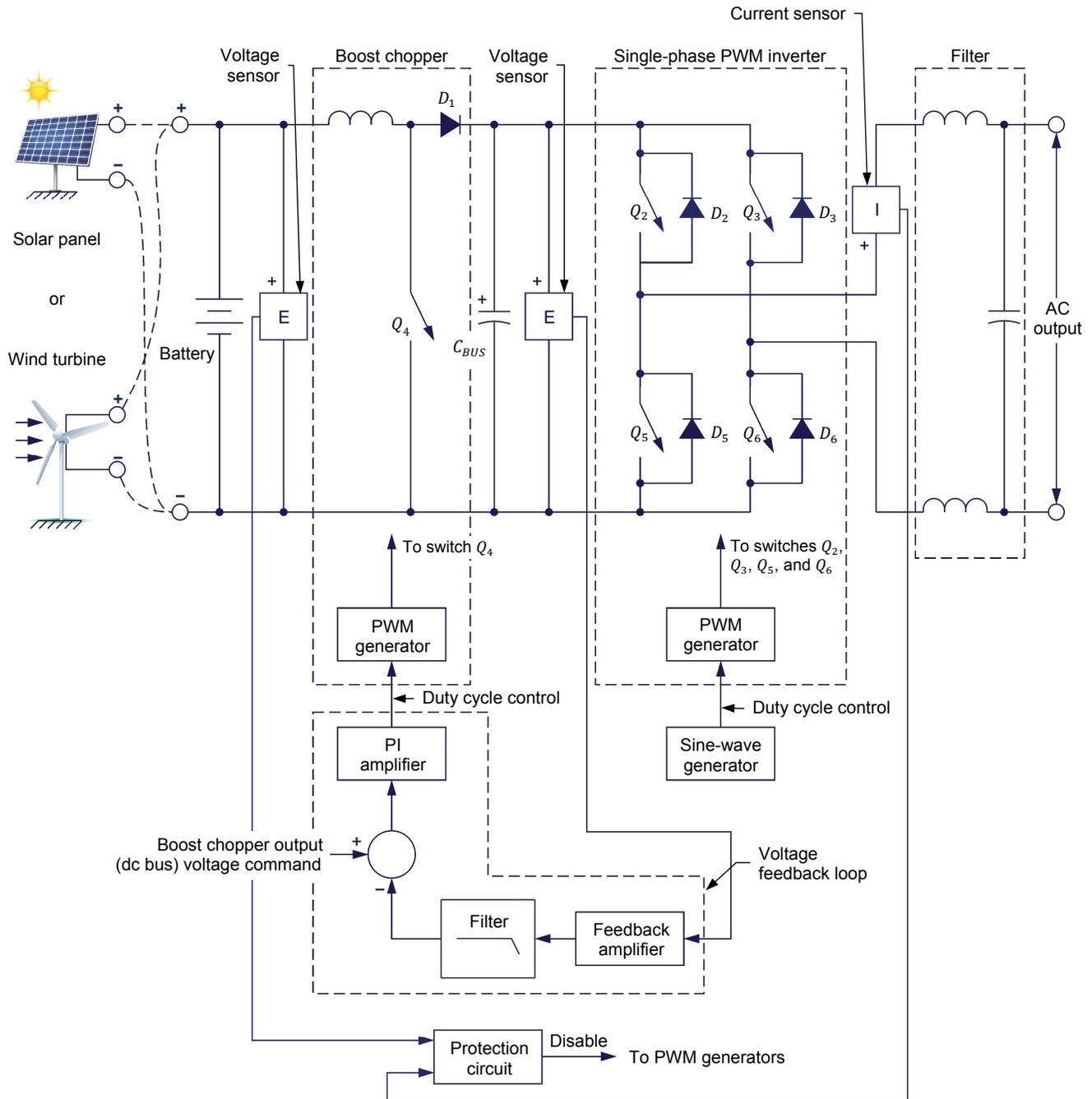


Figure 6. Block diagram of a stand-alone inverter including the protection circuit.

Insulated stand-alone inverter

In the stand-alone inverter shown in Figure 6, there is no electrical insulation (galvanic isolation) between the dc power input and the ac power output. Consequently, this topology of stand-alone inverter is not suitable when galvanic isolation between the dc and ac sides of the inverter is required (regulations in certain countries require galvanic isolation between the dc and ac sides of the inverter in certain applications). A different topology of stand-alone inverter must then be used.

A topology of a stand-alone inverter providing galvanic isolation between the dc and ac sides of the inverter is shown in Figure 7. Such an inverter is sometimes referred to as an insulated stand-alone inverter. With the topology shown in Figure 7, the boost chopper found in the stand-alone inverter shown in Figure 6 is replaced with an insulated dc-to-dc converter implemented with a high-frequency (HF) power transformer to provide galvanic isolation between the dc power input and the ac power output of the inverter. The HF power transformer is of the boost type in order to obtain the dc voltage (dc bus voltage) necessary for the PWM inverter to be able to produce a voltage sine-wave at the ac power network voltage value.

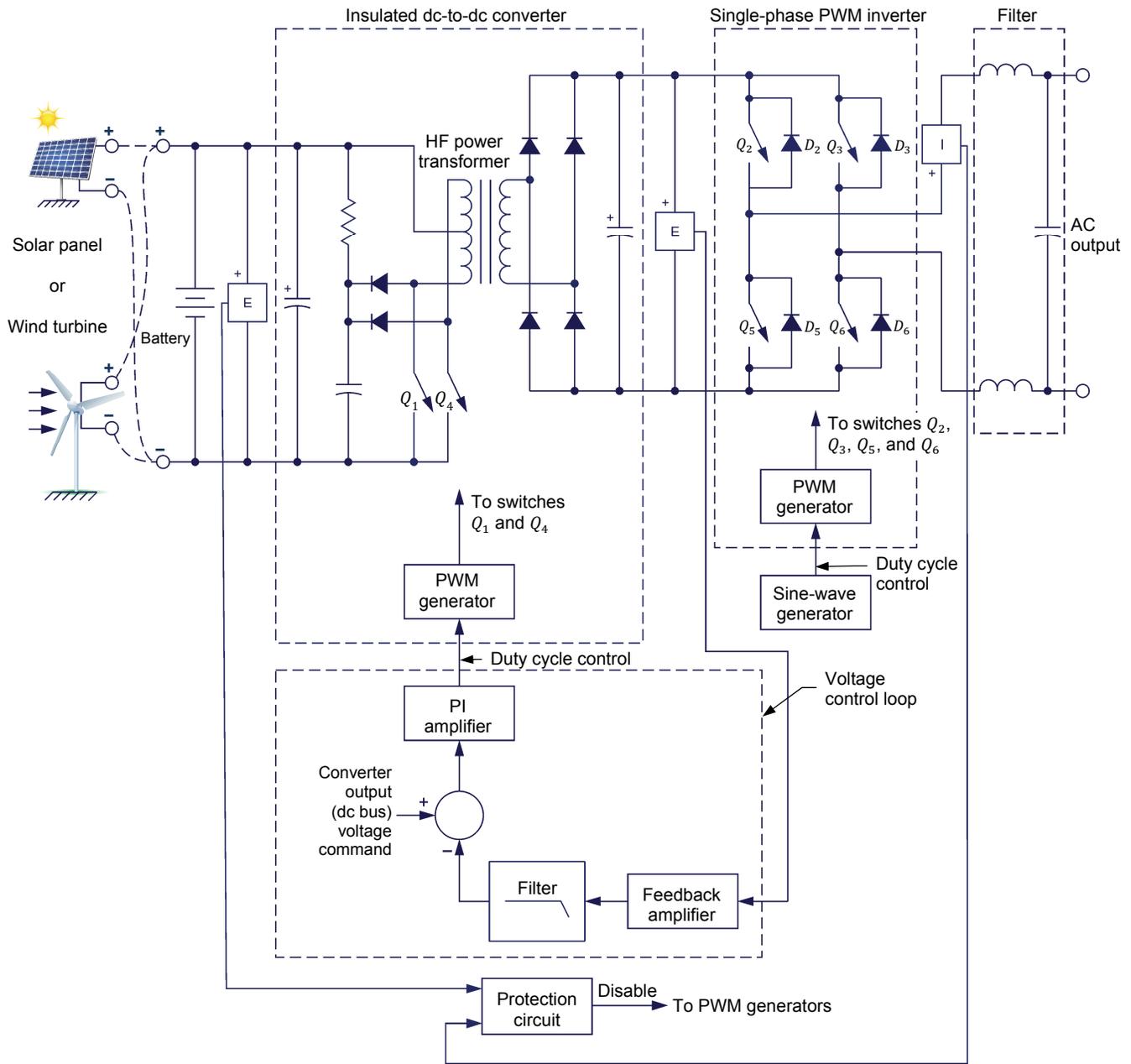


Figure 7. Insulated stand-alone inverter.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Operation of the single-phase stand-alone inverter
- Operation of the protection circuit
- Supplying power to an actual load
- Operation with a power generation device (solar panel)
- Operation with a power generation device (wind turbine)

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 the exercise.

Install the equipment in the [Workstation](#).



If the optional [Wind Turbine Generator/Controller, Model 8216](#), is used in the last part of the exercise, make sure that it is installed to the right of the [Four-Quadrant Dynamometer/Power Supply](#), then mechanically couple the [Four-Quadrant Dynamometer/Power Supply](#) to the [Wind Turbine Generator/Controller](#) using a timing belt.



Before beginning this exercise, measure the open-circuit voltage across the [Lead-Acid Battery Pack, Model 8802](#), using a multimeter. If the open-circuit voltage is lower than 51.2 V, ask your instructor for assistance as the [Lead-Acid Battery Pack](#) is probably not fully charged. Appendix E of this manual indicates how to prepare (fully charge) the [Lead-Acid Battery Pack](#) before each laboratory period.

2. Make sure that the main power switch on the [Four-Quadrant Dynamometer/Power Supply](#) is set to the **O** (off) position, then connect its [Power Input](#) to an ac power outlet.
3. Connect the [Power Input](#) of the [Data Acquisition and Control Interface \(DACI\)](#) 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 (DACI)** 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.

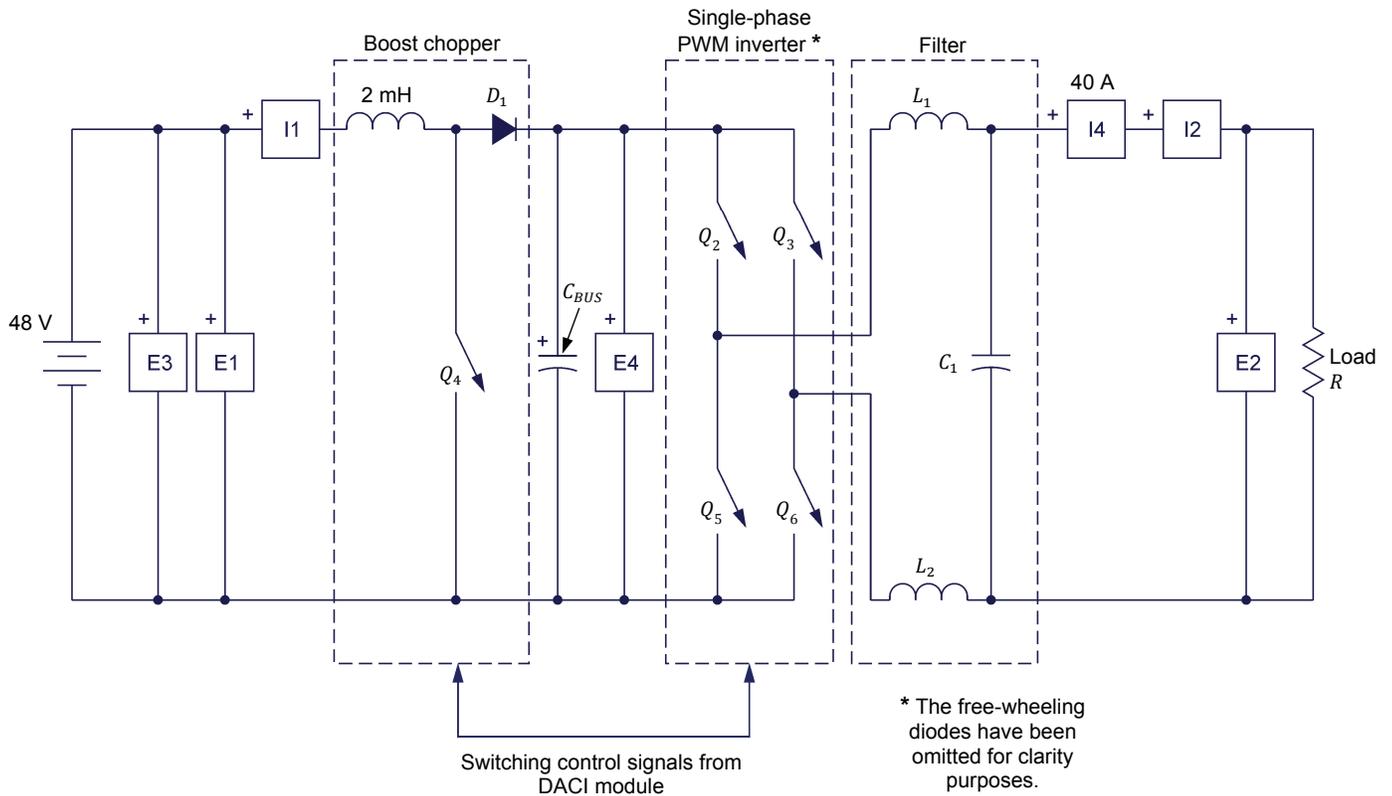
5. Turn the **Four-Quadrant Dynamometer/Power Supply** on, then set the **Operating Mode** switch to **Power Supply**.
6. Turn the host computer on, then start the **LVDAC-EMS** software.

In the **LVDAC-EMS Start-Up** window, make sure that the **Data Acquisition and Control Interface** and the **Four-Quadrant Dynamometer/Power Supply** are detected. Make sure that the **Computer-Based Instrumentation** and **Home Energy Production Control** functions for the **Data Acquisition and Control Interface** are available. Also make sure that the **Standard Functions (C.B. control)** and **Solar Panel Emulator** functions for the **Four-Quadrant Dynamometer/Power Supply** 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.

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

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.

8. Set up the circuit shown in Figure 8 Use the **Lead-Acid Battery Pack** as a voltage source. Use the inductor in the **AC Power Network Interface** to implement the boost chopper inductor L_1 . Open all switches on the **Resistive Load**. The resistance of load resistor R will be set later in the exercise. Use the **Filtering Inductors/Capacitors** to implement the inverter output filter; the inductance and capacitance values to be used for L_1 , L_2 , and C_1 depend on your local ac power network (see table in the diagram).



Local ac power network		L_1, L_2 (mH)	C_1 (μ F)
Voltage (V)	Frequency (Hz)		
120	60	2	5.0
220	50	8	1.5
240	50	8	1.5
220	60	8	1.5

Figure 8. Single-phase stand-alone inverter.

Operation of the single-phase stand-alone inverter

In this part of the exercise, you will calculate the dc bus voltage required to make the rms value of the PWM inverter output voltage equal to that of the local ac power network voltage when the modulation index of the PWM inverter is set to 0.85. You will validate your prediction, and observe the voltage and current waveforms at the inverter output. You will measure the power drawn from the battery and the load power to determine the power efficiency of the system. Then you will observe how the duty cycle of the boost chopper, dc bus voltage, battery voltage, and load voltage vary when the load power increases.



The *Four-Quadrant Dynamometer/Power Supply* is not used in this part of the exercise although it is mechanically coupled to the *Wind Turbine Generator/Controller*.

9. Calculate the dc bus voltage (i.e., the voltage at the PWM inverter input) required to make the rms value of the PWM inverter output voltage equal to that of the local ac power network voltage when the modulation index of the PWM inverter is set to 0.85.

DC bus voltage $E_{BUS} = \underline{\hspace{2cm}}$ V

$$E_{BUS} = \frac{E_{O,rms} \times \sqrt{2}}{m} = \frac{120 \text{ V} \times \sqrt{2}}{0.85} = 199.7 \text{ V}$$

10. In LVDAC-EMS, open the **Home Energy Production Control** window, then make the following settings:
- Make sure that the *Function* parameter is set to *Single-Phase Stand-Alone Inverter*.
 - Make sure that the *Output Power Limit* parameter is set to 250 W.
 - Make sure that the *Battery Minimum Voltage* parameter is set to 44 V.
 - Make sure that the *Peak Output Voltage (% of DC Bus)* of the PWM inverter is set to 85% of the dc bus. This sets the modulation index of the PWM inverter to 0.85.
 - Make sure that the *Output Frequency* of the PWM inverter is set to the frequency of the local ac power network.
 - Set the *DC Bus Voltage Command* parameter to the dc bus voltage calculated in the previous step (dc bus voltage required to make the rms value of the PWM inverter output voltage equal to that of the local ac power network voltage when the modulation index of the PWM inverter is set to 0.85).
11. In LVDAC-EMS, open the **Metering** window. Configure meters *E1* and *I1* to measure the battery voltage and current, respectively. Configure a meter to measure the power drawn from or supplied to the battery (i.e., the battery power). Configure meters *E2* and *I2* to measure the rms values of the load voltage and current, respectively. Configure a meter to measure the active power supplied to the resistive load.
12. In LVDAC-EMS, open the **Oscilloscope** window and make the settings required to observe the load voltage and current waveforms.
13. In the **Home Energy Production Control** window, start the *Single-Phase Stand-Alone Inverter*.

Set the load resistance so that the active power to the load is about 100 W.

Measure the dc bus voltage (indicated by the *DC Bus Voltage* meter in the *Home Energy Production Control* window) and the load voltage.

DC bus voltage: _____ V

Load voltage: _____ V

DC bus voltage: 200.0 V

Load voltage: 112.4 V

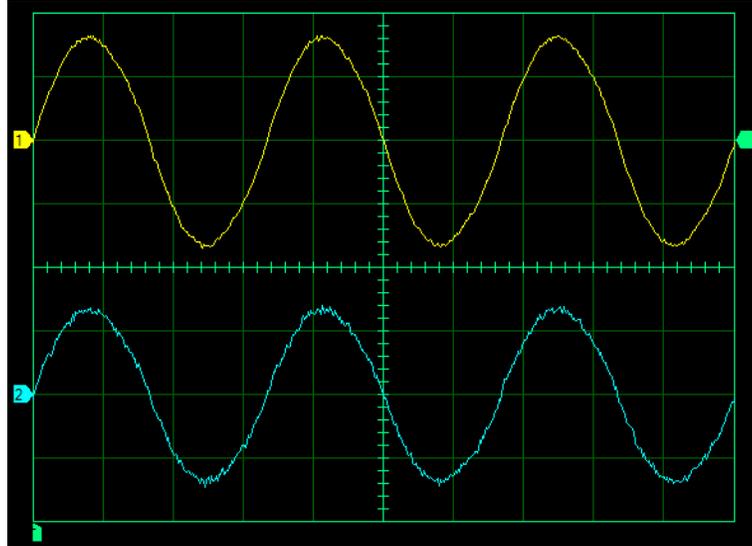
- 14.** Do the dc bus voltage and load voltage measured in the previous step correspond exactly to the expected values? If not, explain why.

The dc bus voltage corresponds to the expected value, but the load voltage is slightly lower than the expected value because of the voltage drop across the inverter and filter.

15. Describe the load voltage and current waveforms displayed on the oscilloscope screen.

Both the load voltage and current waveforms are sine waves, as shown in the following figure.

Oscilloscope Settings
 Channel-1 Input E2
 Channel-1 Scale 100 V/div
 Channel-1 Coupling AC
 Channel-2 Input I2
 Channel-2 Scale 1.0 A/div
 Channel-2 Coupling DC
 Time Base 5 ms/div
 Trigger Source Ch1
 Trigger Level 0
 Trigger Slope Rising



Waveforms of the load voltage and current.

16. In the Home Energy Production Control window, increase the *DC Bus Voltage Command* parameter by 5% to take account of the voltage drop across the inverter and filter. This increase of the *DC Bus Voltage Command* parameter makes the PWM output voltage higher than the local ac power network voltage when the load is null or very small, and lower than the local ac power network voltage when the load is maximum. Momentarily stop the *Single-Phase Stand-Alone Inverter* while you change the setting of the *DC Bus Voltage Command* parameter.

Measure the dc bus voltage (indicated by the *DC Bus Voltage* meter in the Home Energy Production Control window) and the load voltage.

DC bus voltage: _____ V

Load voltage: _____ V

DC bus voltage: 210.0 V

Load voltage: 118.2 V

17. Measure the power delivered by the battery.

Power delivered by the battery: _____ W

Power delivered by the battery: 111.4 W

18. Using the power delivered by the battery measured in the previous step and the power supplied to the load displayed by meter PQS2 (E2, I2), calculate the power efficiency of the system.

Power efficiency: _____ %

Power efficiency: 86.3%

$$\text{Power efficiency} = \frac{96.1 \text{ W}}{111.4 \text{ W}} \times 100\% = 86.3\%$$

19. Adjust the load resistance so that the load power varies between 25 W and 150 W, approximately, in six steps. While doing this, observe the duty cycle of the boost chopper (it is indicated by the *Duty Cycle* meter in the *Home Energy Production Control* window), dc bus voltage, battery voltage, load voltage, load current, and load power. For each load resistance, record the results using the *Data Table*.



The display of Meter I1 may become yellow when the load power is 150 W to indicate that the measured current (i.e., the battery current) momentarily exceeds 4 A.

Stop the *Single-Phase Stand-Alone Inverter*.

The results are presented in the following table.

Boost chopper duty cycle, dc bus voltage, battery voltage, load voltage, load current, and load power for various load resistance values.

Duty cycle (%)	DC bus voltage (V)	Battery voltage (V)	Load voltage (V)	Load current (A)	Load power (W)
77.0	209.8	51.1	122.4	0.21	25.5
77.0	210.1	50.7	120.6	0.31	36.9
77.0	209.9	50.6	119.2	0.41	48.4
78.0	209.9	50.3	117.7	0.60	70.2
78.0	210.3	49.8	115.7	0.97	112.0
79.0	210.4	49.0	114.0	1.34	152.7

20. How do the duty cycle, dc bus voltage, battery voltage, and load voltage vary as the load power increases? Explain why.

As the load power increases from approximately 25 W to 150 W, the duty cycle increases slightly, the dc bus voltage remains constant, and the battery voltage and the load voltage both decrease slightly.

21. Explain why the dc bus voltage remains constant as the battery voltage decreases slightly.

The dc bus voltage is maintained constant by the voltage feedback loop that adjusts (increases) the duty cycle of the boost chopper as the battery voltage decreases slightly, thereby minimizing variation in the load voltage.

22. Explain why the load voltage decreases as the load power increases even if the dc bus voltage is maintained at a constant value.

The load voltage decreases as the load power increases, even if the dc bus voltage is maintained at a constant value, because of the increasing voltage drop across the inverter and filter.



The voltage control loop in the stand-alone inverter regulates the dc bus voltage (consequently, it does not measure the load voltage) and thus the decrease in the load voltage, as the load power increases that is due to the voltage drop across the PWM inverter and the filter, is not compensated. Using the load voltage as the feedback voltage (and of course, setting the voltage command to the ac power network voltage value) would allow the voltage drop across the PWM inverter and the filter to be compensated.

23. Set the load resistance so that the load power is about 25 W.

Operation of the protection circuit

Power limitation

In this part of the exercise, you will observe the operation of the protection circuit when the load power at the output of the single-phase stand-alone inverter exceeds the output power limit set.

24. In the Home Energy Production Control window, set the *Output Power Limit* parameter to 100 W, and start the *Single-Phase Stand-Alone Inverter*.

Gradually decrease the load resistance until the load power is about 150 W. Describe what happens when the load power is increased up to 150 W, and explain why.

The stand-alone inverter stops operating after a while. This is due to the action of the power limitation circuit that detects a load power higher than the output power limit set (100 W) for ten seconds, and stops the stand-alone inverter by disabling the two PWM generators.

Battery under voltage

In this part of the exercise, you will observe the operation of the protection circuit when the battery voltage reaches the battery minimum voltage set.

25. In the **Home Energy Production Control** window, set the **Output Power Limit** parameter back to 250 W. Momentarily stop the **Single-Phase Stand-Alone Inverter** while you change the setting of the **Output Power Limit** parameter.

Set the load resistance so that the active power is about 150 W.

Measure the battery voltage using the **Battery Voltage** meter in the **Home Energy Production Control** window.

Battery voltage: _____ V

Battery voltage: 49.3 V

26. In the **Home Energy Production Control** window, set the **Battery Minimum Voltage** to the measured battery voltage plus about 0.2 V, and let the system operate.

Describe what happens after a while, and explain why.

The stand-alone inverter stops operating after a while. This is due to the action of the battery under-voltage protection circuit that detects a battery voltage lower than the battery minimum voltage set, and stops the stand-alone inverter by disabling the two PWM generators.

27. Open all switches on the **Resistive Load** module. In the **Home Energy Production Control** window, set the **Battery Minimum Voltage** back to 44 V.

Supplying power to an actual load

In this part of the exercise, you will supply power to an actual ac load using a battery.

- 28.** Connect the ac output of the single-phase stand-alone inverter to terminals *L* and *N* of the **AC Power Outlet** (standard ac power outlet) on the front panel of the **AC Power Network Interface**, Model 8622.

Connect an actual load (e.g., a table lamp with an incandescent bulb, a fan, etc.) of about 100 W to the ac power outlet on the **AC Power Network Interface**.



If no actual load is available, go to the next section: Operation with a power generation device (solar panel).

- 29.** Start the *Single-Phase Stand-Alone Inverter*.

Does the system work (i.e., a real ac powered device is powered from dc power stored in a battery)?

Yes No

Yes

- 30.** Stop the *Single-Phase Stand-Alone Inverter*.

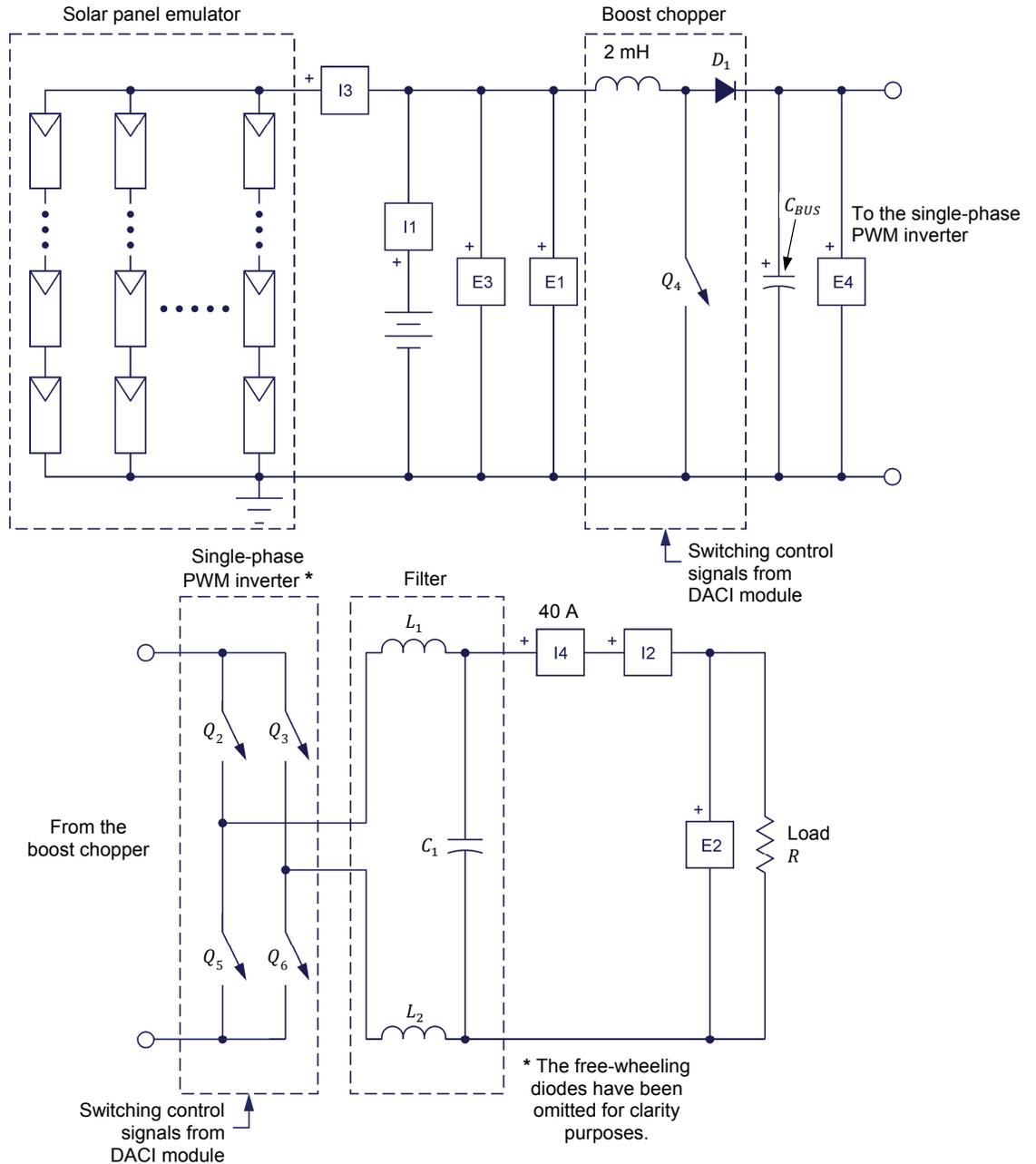
Operation with a power generation device (solar panel)

In this part of the exercise, you will use the solar panel emulator as a power generation device. You will observe that the solar panel emulator delivers power to both the load and the battery when the solar irradiance is high. You will also observe the operation of the circuit when the current flowing in the battery is null, and when the solar irradiance is not sufficient for the solar panel emulator to deliver all the power required by the load.



Optionally, a wind turbine can be used as a power generation device. If you choose to do so, go to the next section Operation with a power generation device (wind turbine).

- 31.** Disconnect the actual load and rearrange the circuit as shown in Figure 9. In this circuit, the solar panel emulator is connected in parallel with the battery. Meter *I3* measures the current supplied by the solar panel emulator, and meter *I1* measures the current flowing through the battery. The inductance and capacitance values to be used for L_1 , L_2 , and C_1 depend on your local ac power network (see table in the diagram).



Local ac power network		L_1, L_2 (mH)	C_1 (μF)
Voltage (V)	Frequency (Hz)		
120	60	2	5.0
220	50	8	1.5
240	50	8	1.5
220	60	8	1.5

Figure 9. Single-phase stand-alone inverter using a solar panel as power generation device.

- 32.** In **LVDAC-EMS**, open the **Four-Quadrant Dynamometer/Power Supply** window, then make the following settings:
- Set the **Function** parameter to **Solar Panel Emulator**. This function makes the power supply in the **Four-Quadrant Dynamometer/Power Supply** operate like a solar panel.
 - Set the **Solar Irradiance** parameter to 1000 W/m².
 - Set the **Number of PV modules in series** parameter to 7. This setting allows the solar panel emulator to generate an open-circuit voltage (E_{OC}) of 67.9 V (7 PV modules × 9.7 V/PV module).
 - Set the **Number of PV modules in parallel** parameter to 38. This setting allows the solar panel emulator to deliver a short-circuit current (I_{SC}) of 4 A (38 PV modules × 0.106 A/PV module).

Do not start the **Solar Panel Emulator** for now.

- 33.** In the **Metering** window, configure meter **I3** to measure the average (dc) value of the emulated solar panel output current. Configure a meter to measure the active power delivered by the emulated solar panel; i.e., use function **PQS (E1,I3)**.
- 34.** In the **Home Energy Production Control** window, start the **Single-Phase Stand-Alone Inverter**.
- 35.** Set the load resistance so that the active power is about 100 W. Record the active power supplied to the load as well as the battery power.

Active power supplied to the load: _____ W

Battery power: _____ W

Active power supplied to the load: 104.7 W

Battery power: 120.8 W

- 36.** In the **Four-Quadrant Dynamometer/Power Supply** window, start the **Solar Panel Emulator** while observing the various power meters.

Record the active power supplied to the load, the battery power, and the power delivered by the solar panel emulator.

Active power supplied to the load: _____ W

Battery power: _____ W

Power delivered by the solar panel emulator: _____ W

Active power supplied to the load: 104.7 W

Battery power: -36.5 W (this value may vary substantially depending on the state of battery charge).

Power delivered by the solar panel emulator: 155.4 W (this value may vary substantially depending on the state of battery charge).

37. Compare the active power supplied to the load when the solar panel emulator is not operating to that supplied when it is operating. Describe how the active power supplied to the load varies, and explain why.

The active power supplied to the load when the solar panel emulator is not operating is the same as that supplied when the solar panel emulator is operating because the load has not changed.

38. Compare the battery power measured when the solar panel emulator is not operating to that measured when it is operating. Describe how the battery power varies, and explain why.

The battery power passes from a positive value to a negative value when the solar panel emulator is turned on. This indicates that power is now fed to the battery by the solar panel emulator (because the solar irradiation is high) instead of being drawn from the battery. This also indicates that all power supplied to the load is delivered by the solar panel emulator and that the excess power produced by the solar panel emulator charges the battery.

39. In the **Four-Quadrant Dynamometer/Power Supply** window, gradually decrease the *Solar Irradiance* parameter until the current flowing in the battery is approximately 0 A.

Record the active power supplied to the load, the battery power, and the power delivered by the solar panel emulator.

Active power supplied to the load: _____ W

Battery power: _____ W

Power delivered by the solar panel emulator: _____ W

Active power supplied to the load: 104.7 W

Battery power: -0.4 W

Power delivered by the solar panel emulator: 120.5 W

40. Determine which proportion of the power supplied to the load is drawn from the battery and which proportion of the power supplied to the load is delivered by the solar panel emulator when the current flowing in the battery is null.

When the current flowing in the battery is null, the battery is neither charging nor delivering power. Therefore, all power supplied to the load is delivered by the solar panel emulator. The solar irradiation at this moment corresponds to the exact value required so that the solar panel emulator produces just the amount of power required to supply the load.

41. In the **Four-Quadrant Dynamometer/Power Supply** window, decrease the **Solar Irradiance** parameter to 250 W/m² while observing the various power meters.

Record the active power supplied to the load, the battery power, and the power delivered by the solar panel emulator.

Active power supplied to the load: _____ W

Battery power: _____ W

Power delivered by the solar panel emulator: _____ W

Active power supplied to the load: 104.7 W

Battery power: 73.6 W

Power delivered by the solar panel emulator: 46.5 W

42. Describe how the various power values changed when the solar irradiance decreased to 250 W/m². Explain briefly.

The active power supplied to the load has not changed since the load value is the same. The battery power increased substantially and is positive. This indicates that power is now drained from the battery to contribute to the power that is supplied to the load. The power delivered by the solar panel emulator decreased substantially when the solar irradiation decreased. This low level of solar irradiation does not allow the solar panel emulator to produce enough power to supply the load.

43. If you do not perform the next section of the procedure, which uses a wind turbine as a power generation device, close **LVDAC-EMS**, then turn off all equipment. Remove all leads and cables, and go to the Conclusion of this exercise.

Operation with a power generation device (wind turbine)

In this part of the exercise, you will use the Wind Turbine Generator/Controller, Model 8216, as a power generation device. You will observe that the wind turbine delivers power to both the load and the battery when the wind speed is high. You will also observe the operation of the circuit when the current flowing in the battery is null, and when the wind speed is not sufficient for the wind turbine to deliver the power required by load.



This section of the Procedure requires optional equipment (Wind Turbine Generator/Controller, Model 8216, and Wind-Turbine Emulator function, Model 8968-3).



Before performing the next steps, set the maximum charge voltage of the wind turbine controller to 56.5 V. See Appendix F for a procedure that describes how to set the maximum charge voltage of the wind turbine controller.

- 44.** In the [Home Energy Production Control](#) window, make sure that the [Single-Phase Stand-Alone Inverter](#) is stopped.

- 45.** Connect the circuit as shown in Figure 10. In this circuit, the [Wind Turbine Generator/Controller](#) is connected in parallel with the battery. Meter [I3](#) measures the current supplied by the wind turbine, and meter [I1](#) measures the current flowing in the battery. The inductance and capacitance values to be used for L_1 , L_2 , and C_1 depend on your local ac power network (see table in the diagram).

On the [Wind Turbine Generator/Controller](#), make sure that the [Controller](#) switch is set to [Charge](#).

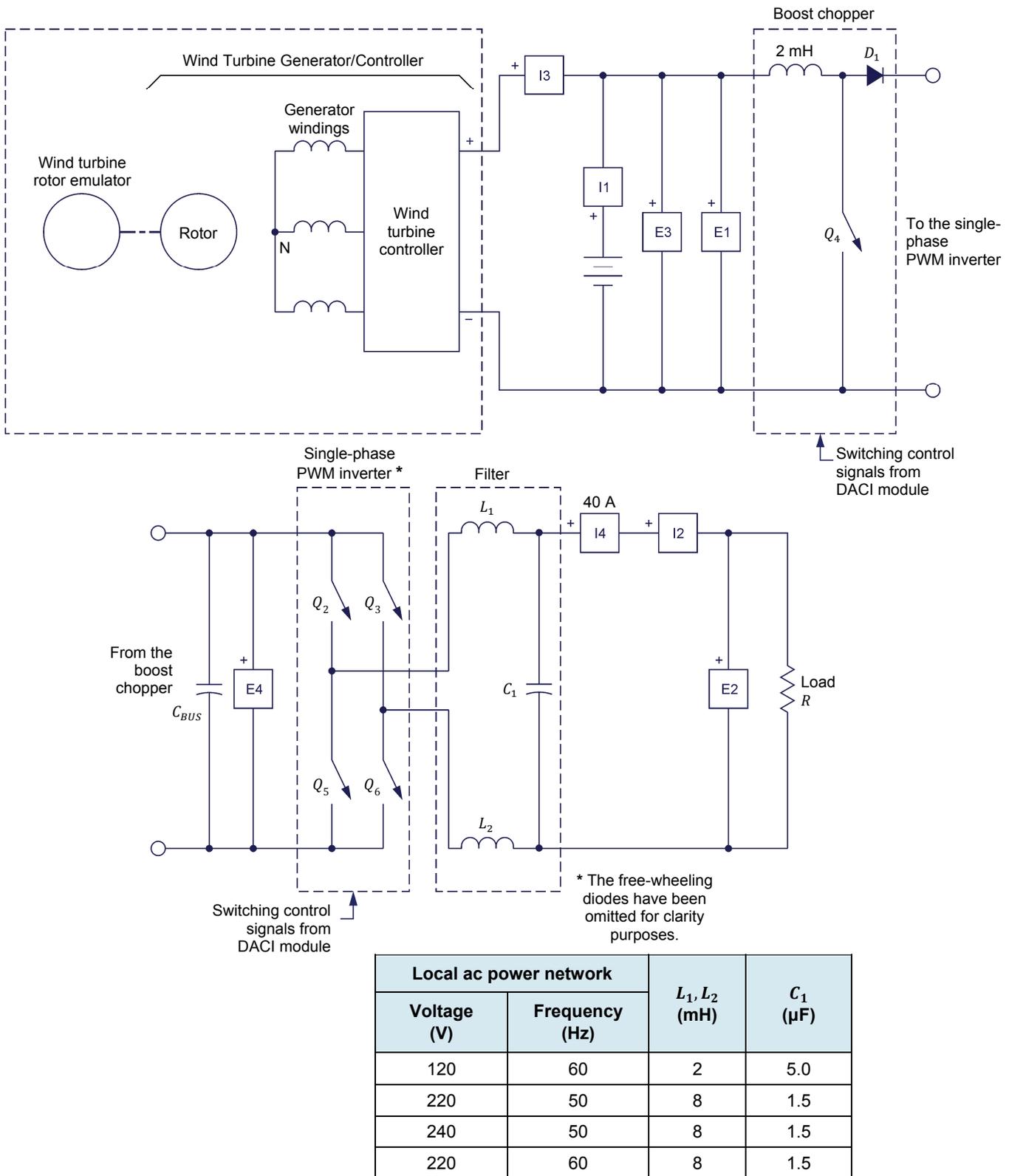


Figure 10. Single-phase stand-alone inverter using a wind turbine as power generation device.

46. On the **Four-Quadrant Dynamometer/Power Supply**, set the *Operating Mode* switch to *Dynamometer*.
47. In **LVDAC-EMS**, open the **Four-Quadrant Dynamometer/Power Supply** window, then make the following settings:
- Set the *Function* parameter to *Wind-Turbine Emulator*. This function makes the motor in the **Four-Quadrant Dynamometer/Power Supply** emulate a wind turbine rotor when subjected to wind.
 - Set the *Wind Speed* parameter to 9.5 m/sec.

Do not start the wind turbine now.

48. In the **Metering** window, configure meter *I3* to measure the average (dc) value of the wind turbine output current. Configure a meter to measure the active power delivered by the wind turbine; i.e., use function *PQS (E1,I3)*.
49. In the **Home Energy Production Control** window, start the *Single-Phase Stand-Alone Inverter*.
50. Set the load resistance so that the active power is about 100 W. Record the active power supplied to the load and the battery power.

Active power supplied to the load: _____ W

Battery power: _____ W

Active power supplied to the load: 100.4 W

Battery power: 115.2 W

51. In the **Four-Quadrant Dynamometer/Power Supply** window, start the *Wind-Turbine Emulator* while observing the various power meters. Make sure that the battery voltage does not exceed 54.5 V (slightly decrease the wind speed if necessary).

Record the active power supplied to the load, the battery power, and the power delivered by the wind turbine.

Active power supplied to the load: _____ W

Battery power: _____ W

Power delivered by the wind turbine: _____ W

Active power supplied to the load: 100.8 W

Battery power: -32.9 W (this value may vary substantially depending on the state of battery charge).

Power delivered by the wind turbine: 189.7 W (this value may vary substantially depending on the state of battery charge).

52. Compare the active power supplied to the load when the wind turbine is not operating to the active power supplied when it is operating. Describe how the active power supplied to the load varies, and explain why.

The active power supplied to the load when the wind turbine is not operating is the same as that supplied when the wind turbine is operating because the load has not been changed.

53. Compare the battery power measured when the wind turbine is not operating to that measured when it is operating. Describe how the battery power varies, and explain why.

The battery power passes from a positive value to a negative value when the wind turbine enters into operation. This indicates that power is now fed to the battery by the wind turbine (because the wind speed is high) instead of being drawn from the battery. This also indicates that all power supplied to the load is delivered by the wind turbine and that the excess power produced by the wind turbine charges the battery.

54. In the **Four-Quadrant Dynamometer/Power Supply** window, gradually decrease the *Wind Speed* parameter until the current flowing in the battery is approximately 0 A.

Record the active power supplied to the load, the battery power, and the power delivered by wind turbine.

Active power supplied to the load: _____ W

Battery power: _____ W

Power delivered by wind turbine: _____ W

Active power supplied to the load: 100.7 W

Battery power: 0.8 W

Power delivered by the wind turbine: 144.5 W

55. Determine which proportion of the power supplied to the load is drawn from the battery and which proportion of the power supplied to the load is delivered by the wind turbine when the current flowing in the battery is null.

When the current flowing in the battery is null, the battery is neither charging nor delivering power. Therefore, all power supplied to the load is delivered by the wind turbine. The wind speed at this moment corresponds to the exact value required so that the wind turbine produces just the amount of power required to supply the load.

56. In the *Four-Quadrant Dynamometer/Power Supply* window, decrease the *Wind Speed* parameter to 5 m/sec while observing the various power meters.

Record the active power supplied to the load, the battery power, and the power delivered by the wind turbine.

Active power supplied to the load: _____ W

Battery power: _____ W

Power delivered by the wind turbine: _____ W

Active power supplied to the load: 100.7 W

Battery power: 103.2 W

Power delivered by the wind turbine: approximately 21.6 W

57. Describe how the various power values changed when the wind speed decreased to 5 m/sec. Explain briefly.

The active power supplied to the load has not changed since the load value is the same. The battery power increased substantially and is positive. This indicates that the battery now contributes to the power that is supplied to the load. The power delivered by the wind turbine decreased substantially when the wind speed decreased. This low value of wind speed does not allow the wind turbine to produce enough power to supply the load.

58. Stop the *Wind-Turbine Emulator* and the *Single-Phase Stand-Alone Inverter*.

59. Close *LVDAC-EMS*, then turn off all equipment. Remove all leads and cables.

CONCLUSION

In this exercise, you learned that the main components of a stand-alone home energy system are the power generation device, battery, boost chopper, and single phase PWM inverter. You learned that the boost chopper increases the dc voltage from the battery or power generation device to the value required by the single-phase PWM inverter to produce a voltage sine wave whose rms value is equal to the ac power network voltage. You saw that when no loads are connected to the PWM inverter output, the power generated by the power generation device is stored in the battery until the battery is fully charged and that when loads are connected to the inverter output, some of the generated power goes into the boost chopper to power the PWM inverter while the remaining power goes into the battery. When the power demand from the loads exceeds the power generated by the power generation device, power is drawn from the battery to provide the necessary amount of power to the boost chopper and PWM inverter.

You learned that the frequency of the system's output voltage is set by making the output frequency parameter of the PWM inverter equal to the local ac power network frequency and that the rms value of the system's output voltage is set equal to that of the local ac power network voltage by setting the modulation index of the PWM inverter to a fixed value and adjusting the duty cycle of the boost chopper to obtain the dc voltage value required at the PWM inverter input.

You were also introduced to the operation of the voltage feedback loop, which allows the dc bus voltage to be maintained at the exact value set by the dc bus voltage command. You learned that the power limitation protection circuit limits the load power to a certain maximum value to avoid damages to the battery and stand-alone inverter, and that the battery under-voltage protection circuit stops the stand-alone inverter if the battery voltage decreases under a certain minimum value.

You also saw that the stand-alone inverter shown in Figure 6 does not provide electrical insulation between the dc and ac sides of the stand-alone inverter. Consequently, an insulated stand-alone inverter such as the one shown in Figure 7 must be used when galvanic isolation between the dc and ac sides of the inverter is required.

REVIEW QUESTIONS

1. What is the function of the boost chopper in a stand-alone home energy production system?

The boost chopper increases the dc voltage produced by the power generation device or battery to the value required for the single-phase PWM inverter to be able to produce a voltage sine wave whose rms value is equal to the ac power network voltage.

2. What happens when the power demand from the load connected to the output of a stand-alone inverter exceeds the power produced by the power generation device?

When the power demand from the load connected to the output of a stand-alone inverter exceeds the power produced by the power generation device, dc power is drawn from the battery to provide the necessary amount of power to the boost chopper and PWM inverter.

3. In the single-phase stand-alone inverter using a solar panel as a power generation device shown in Figure 9, how is the power delivered by the solar panel emulator distributed when the solar irradiance is high (i.e., close to 1000 W/m²) and the battery is not fully charged?

The power delivered by the solar panel emulator provides the necessary amount of power which the boost chopper and PWM inverter require to supply the load, and the remaining power produced by the solar panel emulator goes to the battery.

4. Determine the duty cycle of the boost chopper, in a single-phase stand-alone inverter, if the rms value of the system output voltage is 240 V, the modulation index m of the PWM inverter is set to 0.9, and the battery voltage is 36 V.

Duty cycle: 0.9

Voltage required at the PWM inverter input to obtain 240 V at the output of the inverter:

$$E_{BUS} = \frac{E_{O,rms} \times \sqrt{2}}{m} = \frac{240 \text{ V} \times \sqrt{2}}{0.9} = 377.1 \text{ V}$$

Duty cycle of the boost chopper required to obtain 377.1 V at the PWM inverter input:

$$\alpha = 1 - \frac{E_I}{E_{BUS}} = 1 - \frac{36 \text{ V}}{377.1 \text{ V}} = 0.9$$

5. What is the battery under-voltage protection circuit used for? Briefly describe the operation of the battery under-voltage protection circuit in the stand-alone inverter shown in Figure 6.

The battery under-voltage protection circuit is used to stop discharging the battery before it is fully discharged to prevent permanent damage to the battery. The battery under-voltage protection circuit uses a voltage sensor to measure the battery voltage. When the measured voltage reaches the minimum value allowed, the battery under-voltage protection circuit disables the PWM generators of the boost chopper and PWM inverter. This turns off all electronic switches in the boost chopper and PWM inverter, therefore interrupting current flow in the system.

Single-Phase Grid-Tied Inverter (PWM Rectifier/Inverter)

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the single-phase grid-tied inverter.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to the single-phase grid-tied inverter
- Active and reactive current commands
- Controlling active power flow and reactive power flow in a single-phase grid-tied inverter
- Operation of the current control loop
- DC bus voltage versus the local ac power network voltage

DISCUSSION

Introduction to the single-phase grid-tied inverter

A single-phase PWM inverter produces a sine-wave voltage E_{AC} from dc voltage. The amplitude A (which in turn sets the rms value of voltage E_{AC}), frequency f , and phase angle θ of the sine-wave voltage E_{AC} are determined by control parameters in the inverter controller (a mere sine-wave generator in most cases). On the other hand, the amplitude (rms value) and phase angle of current I_{AC} at the inverter output depends on the impedance Z_L of the load connected to the inverter output as illustrated in Figure 11. The role of the filter shown in Figure 11 is to convert the PWM rectangular pulse train at the inverter output into sine-wave voltage and current.

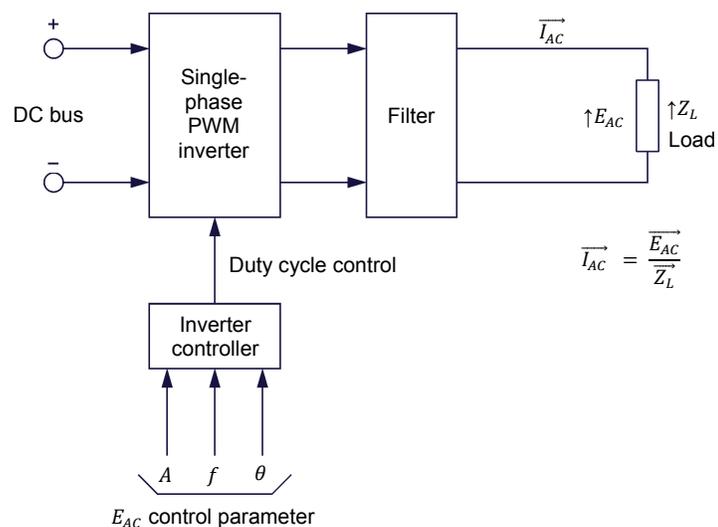


Figure 11. Single-phase PWM inverter.

The arrow beside E_{AC} , I_{AC} , and Z_L in Figure 11 (as well as in subsequent figures in this discussion) indicates that each of these parameters is a phasor with an amplitude and a phase angle. In the case of a voltage phasor, the arrow head indicates which of the two circuit points at which voltage is measured is at the higher potential (i.e., the point that is positive with respect to the other point) when the polarity of voltage E is positive. Similarly, in the case of a current phasor, the arrow head indicates the direction of current flow when the polarity of current I is positive.

When the output of a single-phase PWM inverter is connected to the local ac power network, the PWM inverter is commonly referred to as a **single-phase grid-tied inverter**. In this situation, the PWM inverter no longer has any control on the amplitude A , frequency f , and phase angle θ of the sine-wave voltage E_{AC} at its output since the values of these parameters are imposed by the local ac power network which acts as a voltage source. However, the PWM inverter can exercise control over the amplitude A and phase angle θ of the current I_{AC} which flows between its output and the local ac power network by using a current control loop. In other words, a single-phase grid-tied inverter consists of a single-phase PWM inverter, a filter, and a current control loop (the current and voltage sensors are considered as being part of the current control loop), as shown in Figure 12.

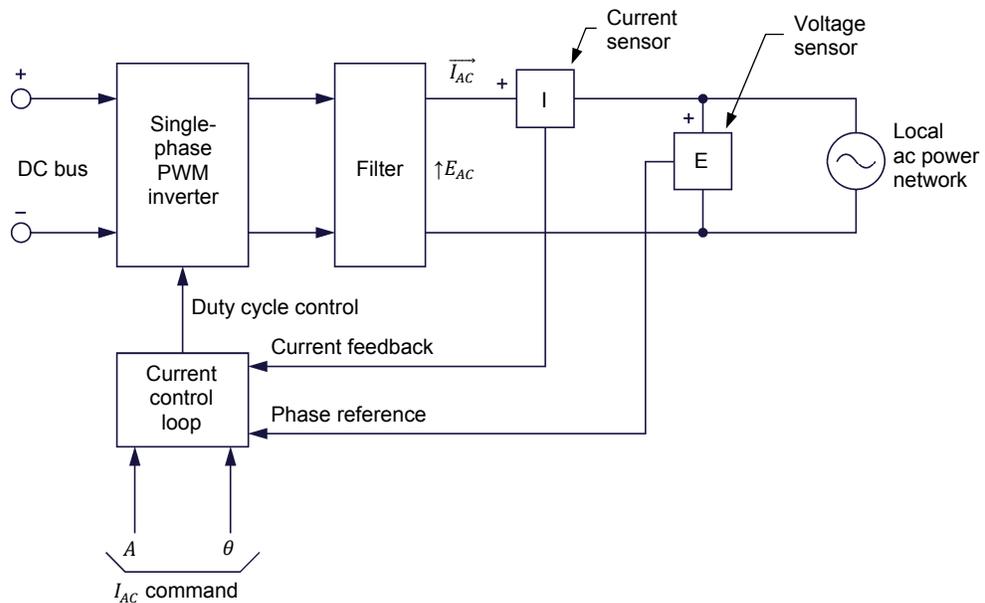


Figure 12. A single-phase grid-tied inverter consists of a single-phase PWM inverter, a filter, and a current control loop.

The current control loop in a single-phase grid-tied inverter continuously measures current I_{AC} via a current sensor and adjusts the duty cycle of the PWM inverter so that the amplitude A and phase angle θ of current I_{AC} remains equal to the inverter current command (I_{AC} command). Of course, the I_{AC} command is vectorial in nature; that is, it consists of an amplitude A and a phase angle θ . The current control loop also monitors voltage E_{AC} via a voltage sensor to be able to correctly adjust the phase angle of current I_{AC} .

Figure 13 shows a phasor diagram of voltage E_{AC} and current I_{AC} in a single-phase grid-tied inverter. In this example, the current command is set to $10\text{ A} \angle 30^\circ$. Consequently, current I_{AC} has an amplitude of 10 A and is leading voltage E_{AC} by 30° . The corresponding voltage and current sine waves are also shown in Figure 13.

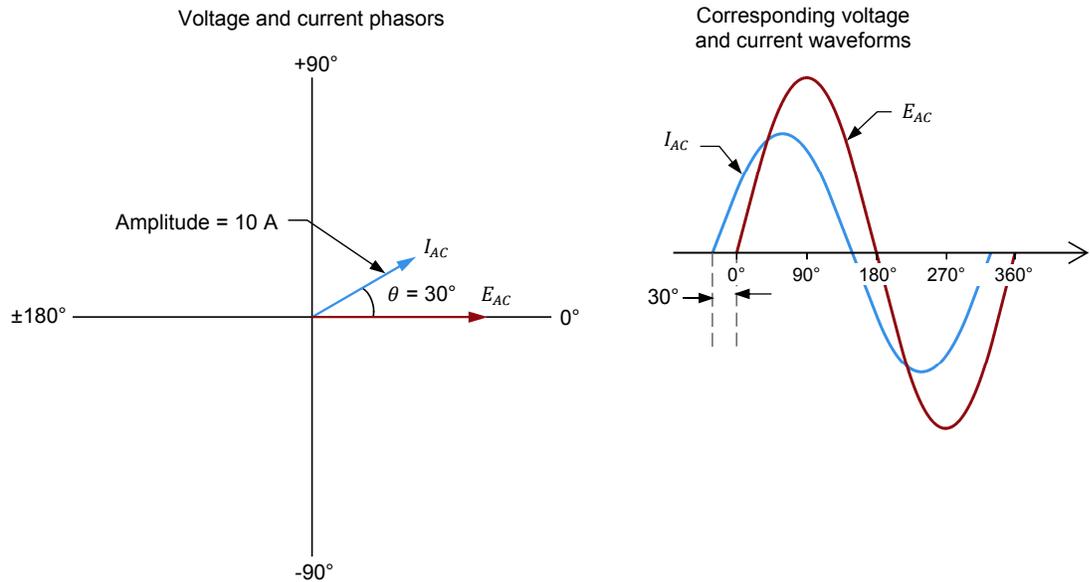


Figure 13. Phasor diagram of voltage E_{AC} and current I_{AC} in a single-phase grid-tied inverter.

Active and reactive current commands

The current phasor in Figure 13 is expressed in polar coordinates; that is with a magnitude (e.g., amplitude or rms value) and a phase angle. Current phasors can also be represented as vectors in a complex plane (i.e., in a rectangular coordinate system with a real axis and an imaginary axis). When represented in a complex plane, current phasors are of the form $x \pm jy$, where x and y are real numbers and j is an imaginary unit. For example, current phasor $10\text{ A} \angle 30^\circ$ shown in Figure 13 is equal to complex number $8.66\text{ A} + j5\text{ A}$ when expressed in a rectangular coordinate system. In other words, the current phasor $10\text{ A} \angle 30^\circ$ is the same as the sum of a current of 8.66 A in phase with voltage E_{AC} and a current of 5 A leading voltage E_{AC} by 90° . This is illustrated in the phasor diagram shown in Figure 14.

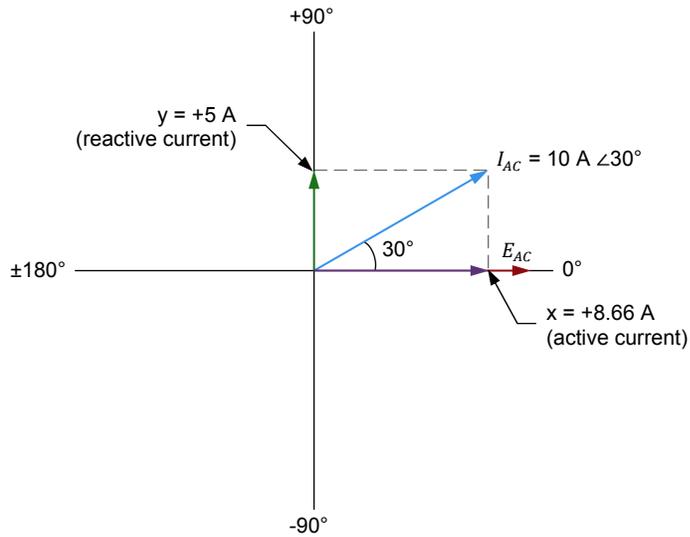


Figure 14. The current phasor $10\text{ A } \angle 30^\circ$ is the same as the sum of a current of 8.66 A in phase with voltage E_{AC} and a current of 5 A leading voltage E_{AC} by 90° .

In single-phase grid-tied inverters, it is common practice to express the current command (I_{AC} command) using rectangular coordinates. This is because the x-axis component of the current command determines the value of a current that is either in phase or phase shifted 180° with respect to voltage E_{AC} , depending on the polarity of the x-axis component. The value of the current determined by the x-axis component of the current command thus sets the amount of active power that is exchanged between the inverter and the ac power network. Consequently, the x-axis component of the current command is generally referred to as the **active current** command. Similarly, the y-axis component of the current command determines the value of a current that either leads or lags voltage E_{AC} by 90° , depending on the polarity of the y-axis component. The value of the current determined by the y-axis component of the current command thus sets the amount of reactive power that is exchanged between the inverter and the ac power network. Consequently, the y-axis component of the current command is generally referred to as the **reactive current** command. For instance, to obtain the current phasor $10\text{ A } \angle 30^\circ$ shown in Figure 14, the active and reactive current commands of a single-phase grid-tied inverter must be set to $+8.66\text{ A}$, and $+5\text{ A}$, respectively.

Controlling active power flow and reactive power flow in a single-phase grid-tied inverter

As seen in the previous section of the exercise, the active current command determines the value of a current that is either in phase or phase shifted 180° with the ac power network voltage E_{AC} . Consequently, the active current command determines the amount of active power that is exchanged between the single-phase grid-tied inverter and the ac power network. When the polarity of the active current command is positive and the reactive current command is set to zero, the current I_{AC} is in phase with voltage E_{AC} , and the polarity of the active power is positive when voltage phasor E_{AC} and current phasor I_{AC} are defined as in the diagram of a single-phase grid-tied inverter shown in Figure 12 (of course,

no reactive power exchange occurs in this situation). The positive polarity of the active power indicates that it is the grid-tied inverter which supplies active power to the ac power network. For instance, when the active current command is set to +5 A and the ac power network voltage is 220 V, the active power is +1100 W (i.e., the grid-tied inverter supplies 1100 W to the ac power network as shown in Figure 15). When active power is supplied to the ac power network, power is converted from dc to ac and the grid-tied inverter effectively works as an inverter.

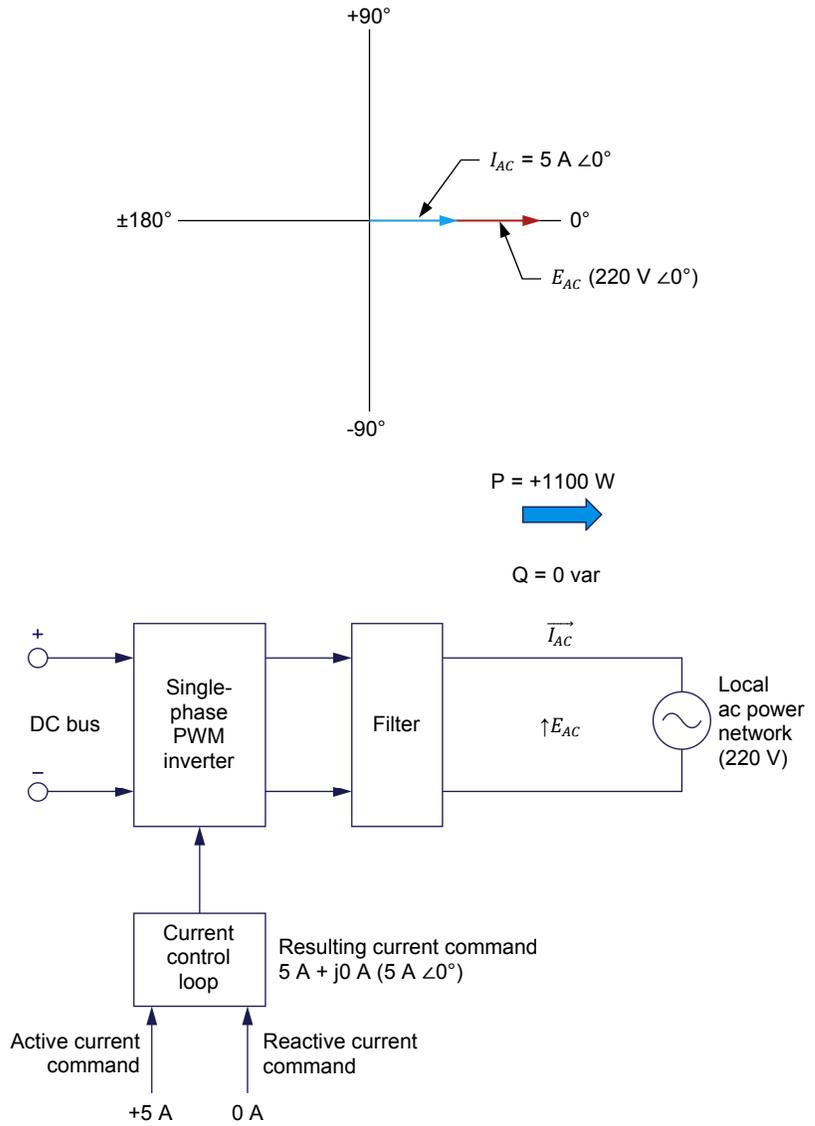


Figure 15. Power flow when the active current command is positive and the reactive current command is zero.

On the other hand, when the polarity of the active current command is negative and the reactive current command is set to zero, the current I_{AC} is phase shifted 180° with respect to voltage E_{AC} , and the polarity of the active power is negative when voltage phasor E_{AC} and current phasor I_{AC} are defined as in the diagram of a single-phase grid-tied inverter shown in Figure 12 (of course, no reactive power exchange occurs in this situation). The negative polarity of the active power indicates that it is the ac power network which supplies active power to the grid-tied inverter. For instance, when the active current command is set to -5 A and the ac power network voltage is 220 V , the active power is -1100 W (i.e., the ac power network supplies 1100 W to the grid-tied inverter as shown in Figure 16). When active power is received from the ac power network, power is converted from ac to dc and the grid-tied inverter therefore works as a rectifier.

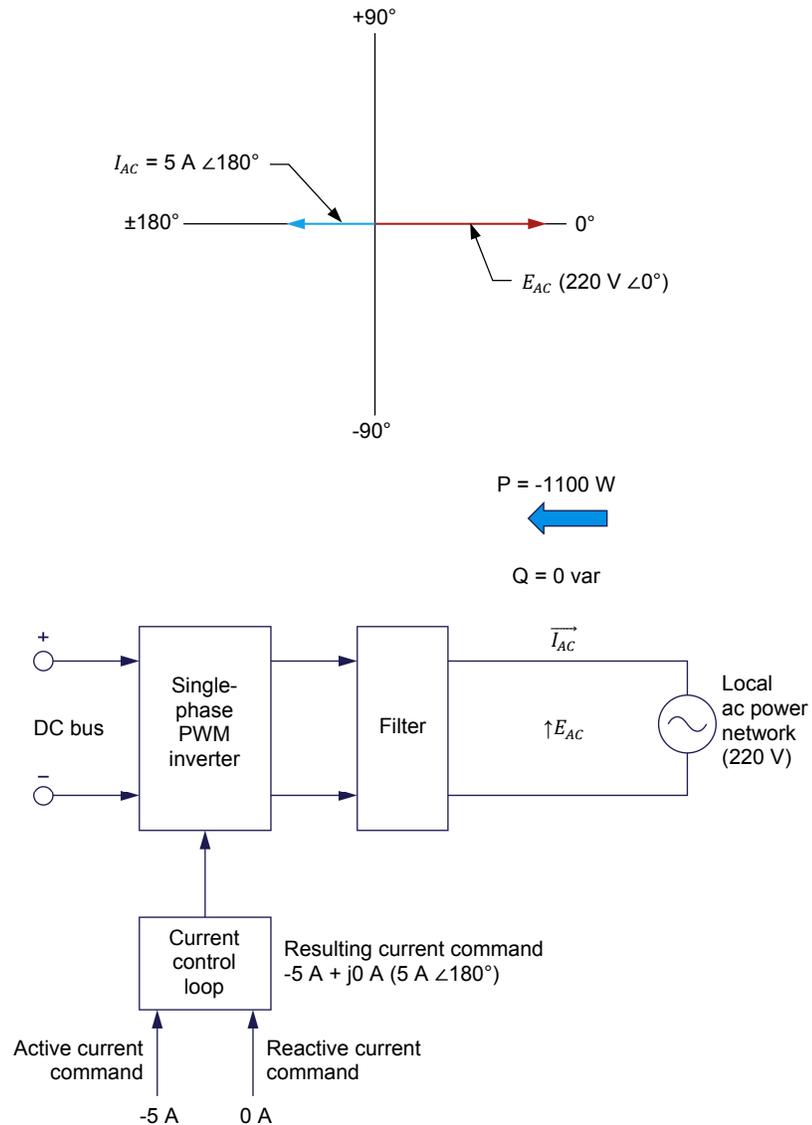


Figure 16. Power flow when the active current command is negative and the reactive current command is zero.

Because the PWM inverter in a single-phase grid-tied inverter can work as either a rectifier or an inverter, the single-phase grid-tied inverter is also referred to as a single-phase PWM rectifier/inverter.

It is generally accepted that inductive components absorb reactive power and capacitive components supply reactive power, although reactive components in fact exchange reactive power and neither absorb nor supply reactive power.

As seen in the previous section of the exercise, the reactive current command determines the value of a current that either leads or lags the ac power network voltage (E_{AC}) by 90° . Consequently, the reactive current command determines the amount of reactive power that is exchanged between the single-phase grid-tied inverter and the ac power network. When the polarity of the reactive current command is positive and the active current command is set to zero, the current I_{AC} leads voltage E_{AC} by 90° , and the polarity of the reactive power is negative when voltage phasor E_{AC} and current phasor I_{AC} are defined as in the diagram of a single-phase grid-tied inverter shown in Figure 12 (of course, no active power exchange occurs in this situation). The fact that the current I_{AC} leads the voltage E_{AC} by 90° indicates that the ac power network appears to the grid-tied inverter as a capacitor. Since a capacitor is generally considered a source (supplier) of reactive power, we can thus state that the ac power network supplies reactive power to the grid-tied inverter in this situation. In other words, when the reactive current command is positive, the polarity of the reactive power is negative, indicating that the ac power network supplies reactive power to the grid-tied inverter. For instance, when the reactive current command is set to +5 A and the ac power network voltage is 220 V, the reactive power is -1100 var (i.e., the ac power network supplies 1100 var to the grid-tied inverter as shown in Figure 17).

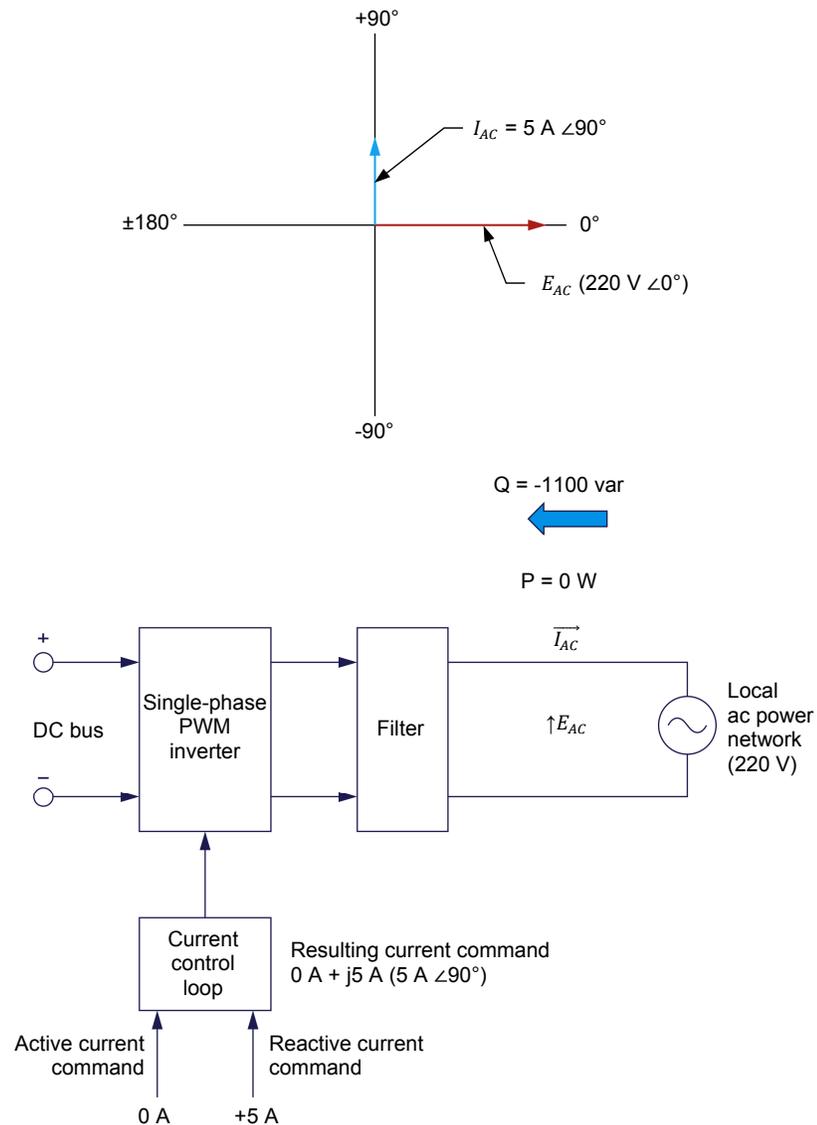


Figure 17. Power flow when the active current command is zero and the reactive current command is positive.

On the other hand, when the polarity of the reactive current command is negative and the active current command is set to zero, the current I_{AC} lags voltage E_{AC} by 90° , and the polarity of the reactive power is positive when voltage phasor E_{AC} and current phasor I_{AC} are defined as in the diagram of a single-phase grid-tied inverter shown in Figure 12 (of course, no active power exchange occurs in this situation). The fact that the current I_{AC} lags the voltage E_{AC} by 90° indicates that the ac power network appears to the inverter as an inductor. Since an inductor is generally considered as a consumer of reactive power, we can thus state that the grid-tied inverter supplies reactive power to the ac power network in this situation. In other words, when the reactive current command is negative, the polarity of the reactive power is positive, indicating that the grid-tied inverter supplies reactive power to the ac power network. For instance, when the reactive current command is set to -5 A and the ac power network voltage is 220 V , the

reactive power is +1100 var (i.e., the grid-tied inverter supplies 1100 var to the ac power network as shown in Figure 18).

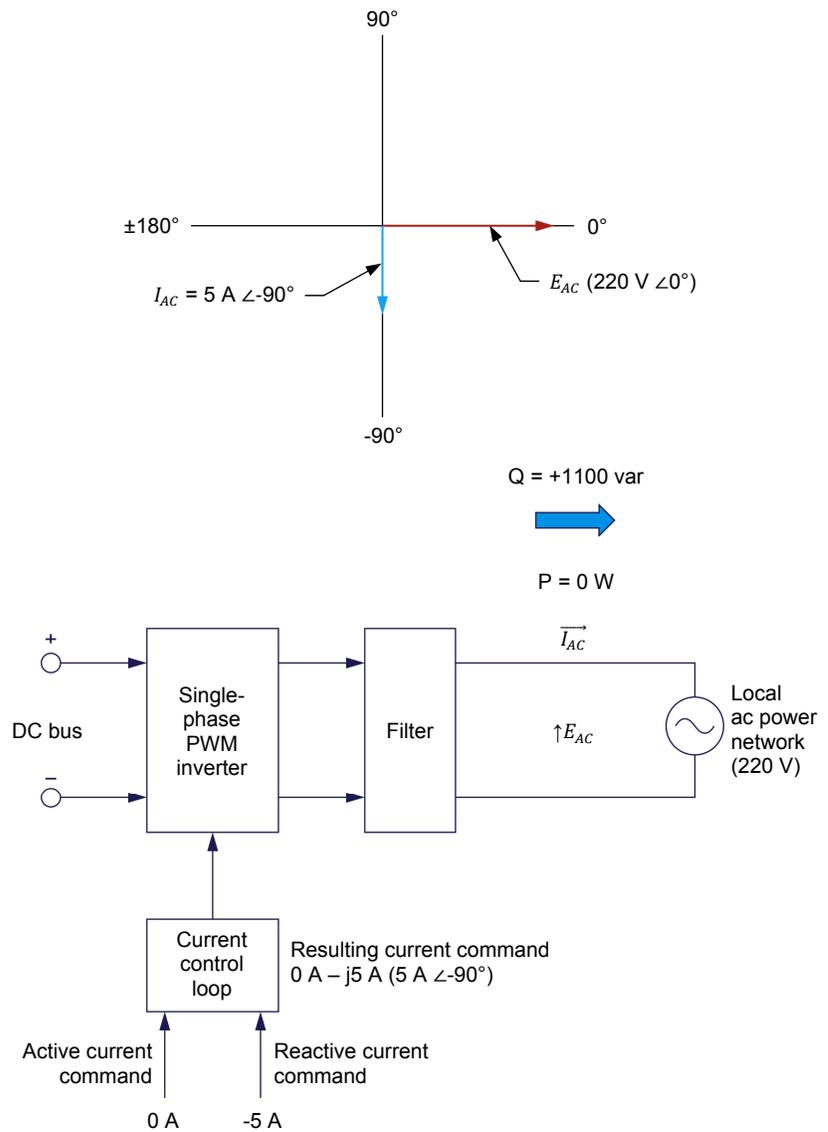
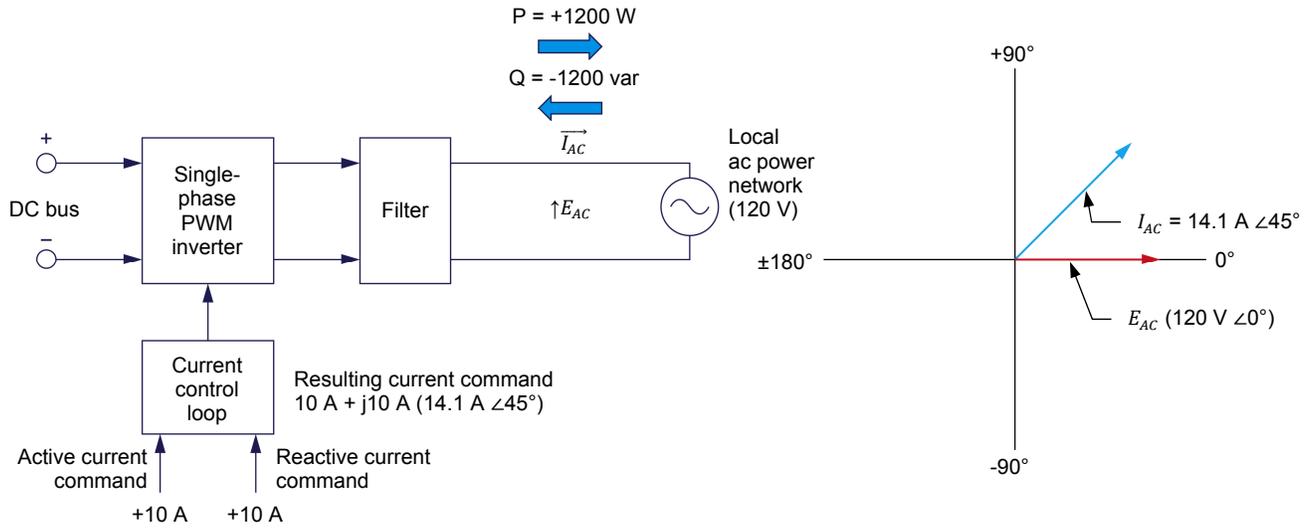
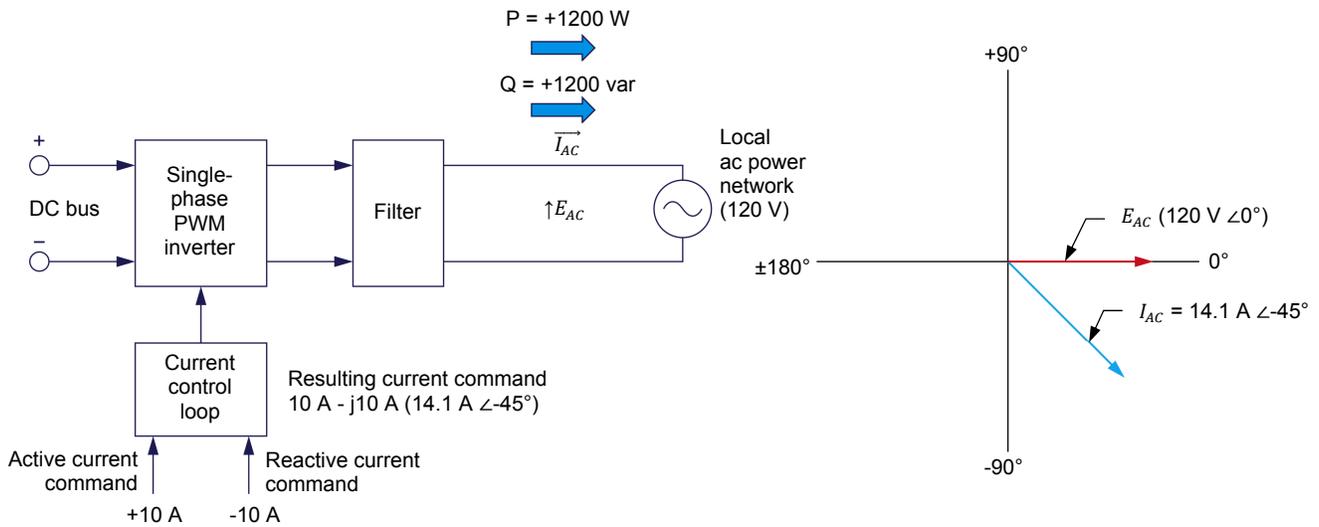


Figure 18. Power flow when the active current command is zero and the reactive current command is negative.

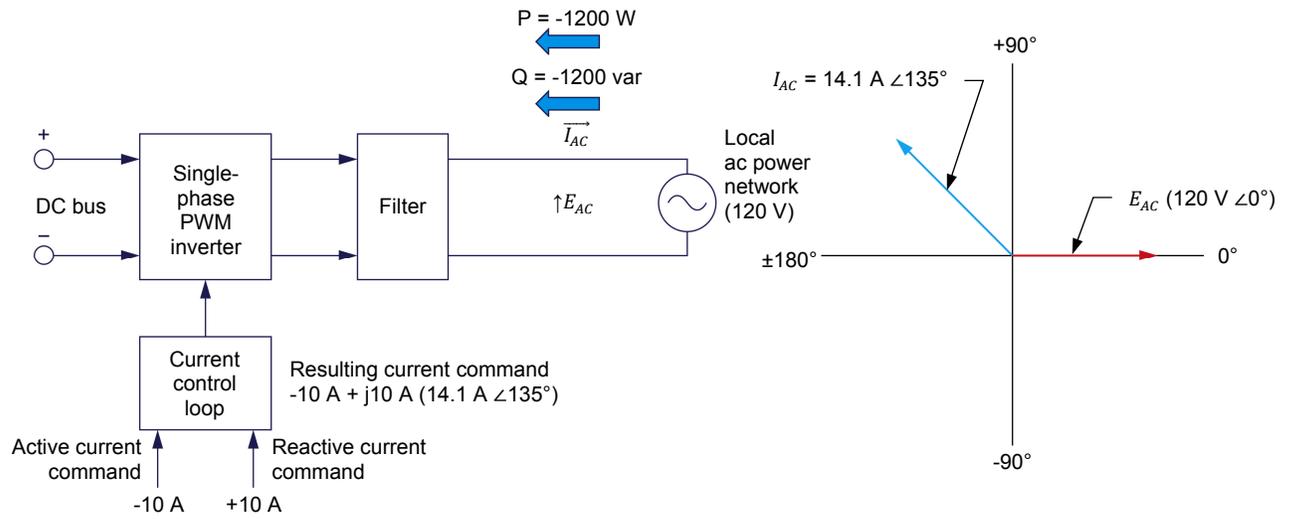
Any combination of active and reactive power can be exchanged between the single-phase grid-tied inverter and the ac power network by adjusting the polarity and magnitude (amplitude or rms value) of the active and reactive current commands accordingly. Figure 19 shows the four possible combinations of active power and reactive power flow.



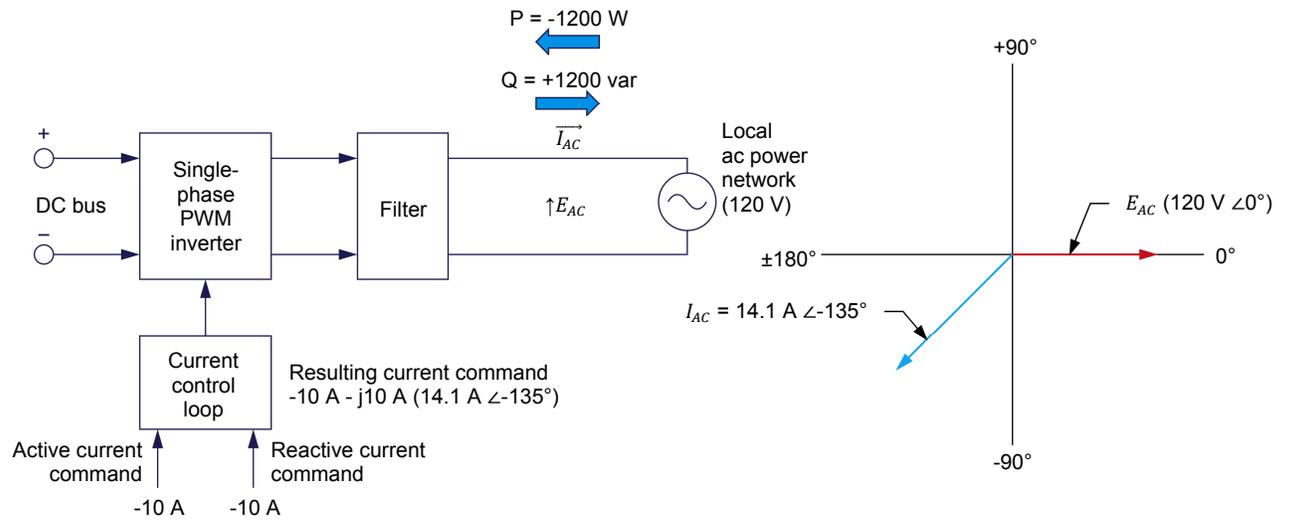
(a) Power flow when both the active and reactive current commands are positive.



(b) Power flow when the active current command is positive and the reactive current command is negative.



(c) Power flow when the active current command is negative and the reactive current command is positive.



(d) Power flow when both the active and reactive current commands are negative.

Figure 19. Combinations of active power and reactive power flow.

Operation of the current control loop

Figure 20 shows a block diagram of a single-phase grid-tied inverter. It consists of the major building blocks in the simplified block diagram shown in Figure 12 at the beginning of this discussion (i.e., a single-phase PWM inverter, a filter, a current control loop, a current sensor, and a voltage sensor).

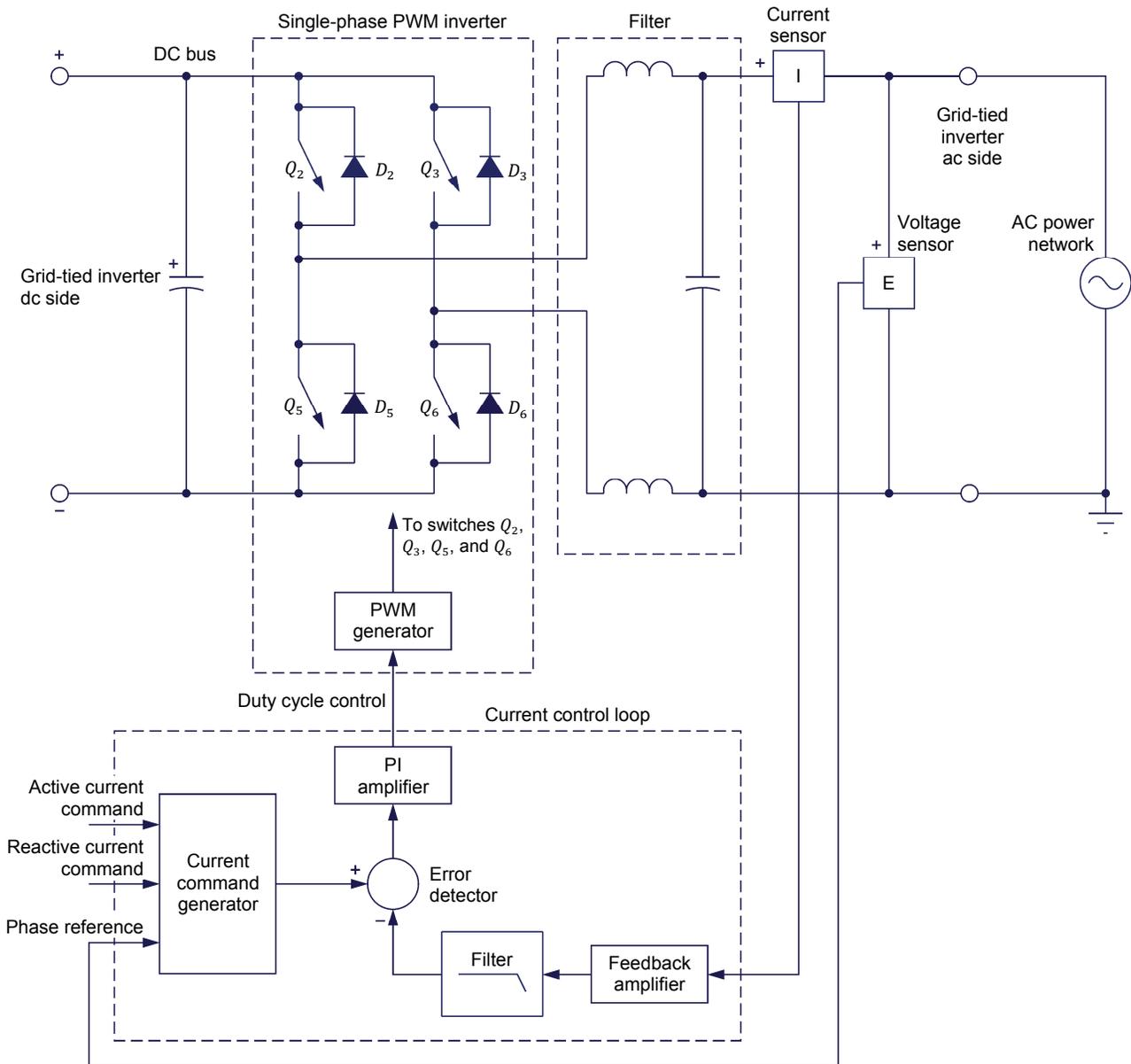


Figure 20. Block diagram of a single-phase grid-tied inverter.

The current command generator uses the active and reactive current commands as well as the ac power network voltage measured by the voltage sensor to produce the actual current command (I_{AC} command) used in the current control loop (i.e., the current command applied to the positive input of the error detector). The actual current command is a sine wave whose amplitude and phase angle

exactly correspond to the current phasor defined by the active and reactive current commands. For instance, when the amplitude of the active and reactive current commands are equal to 3.0 A and -3.0 A, respectively, the resulting actual current command is a sine wave with an amplitude of 4.24 A that is lagging the ac power network voltage (E_{AC}) by exactly 45° . This is illustrated in Figure 21.

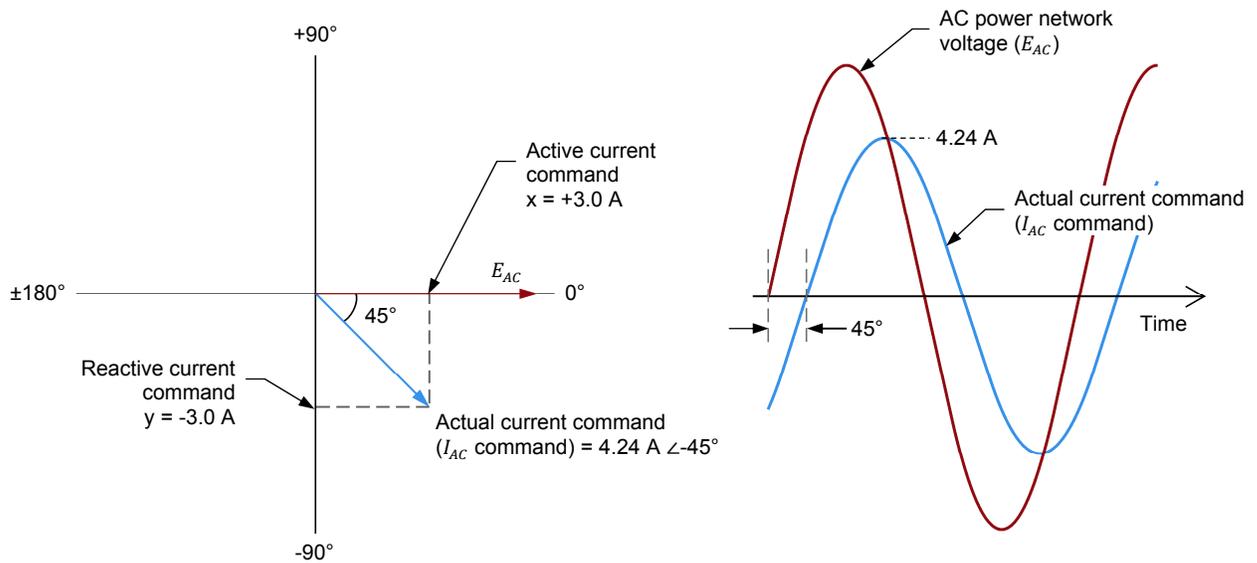


Figure 21. The current command generator uses the active and reactive current commands as well as the ac power network voltage measured by the voltage sensor to produce the actual current command used in the current control loop.

The error detector subtracts the value of the current I_{AC} (I_{AC} command) measured at the ac side of the PWM inverter from the actual current command produced by the current command generator. Whenever the current I_{AC} measured differs from the actual current command, the error detector produces an output signal which, after some proportional and integral (PI) amplification, readjusts the duty cycle of the PWM inverter in order to correct the error. For instance, when the current I_{AC} is lower than the actual current command, the error detector signal is positive, therefore increasing the duty cycle of the PWM inverter. This increases the PWM inverter output voltage, and thus causes current I_{AC} to increase until the error is corrected. Conversely, when the current I_{AC} is higher than the actual current command, the error detector signal is negative, therefore decreasing the duty cycle of the PWM inverter. This decreases the PWM inverter output voltage, and thus causes current I_{AC} to decrease until the error is corrected.

Feedforward voltage control

Because the actual current command and current I_{AC} at the ac side of the PWM inverter are both periodical signals, their amplitude varies continuously, and thus the current control has a tendency to be unstable.

To stabilize the operation of the current control loop, a circuit named *Feedforward voltage control* is generally added to the current control loop as shown in Figure 22. The **feedforward voltage control** circuit uses the ac power network voltage measured by the voltage sensor to adjust the duty cycle control

signal sent to the PWM generator in order to virtually zero current I_{AC} when the actual current command is zero. By doing so, the rest of the current control loop only has to perform minor corrections on the duty cycle of the PWM inverter in order to maintain current I_{AC} at the desired value.

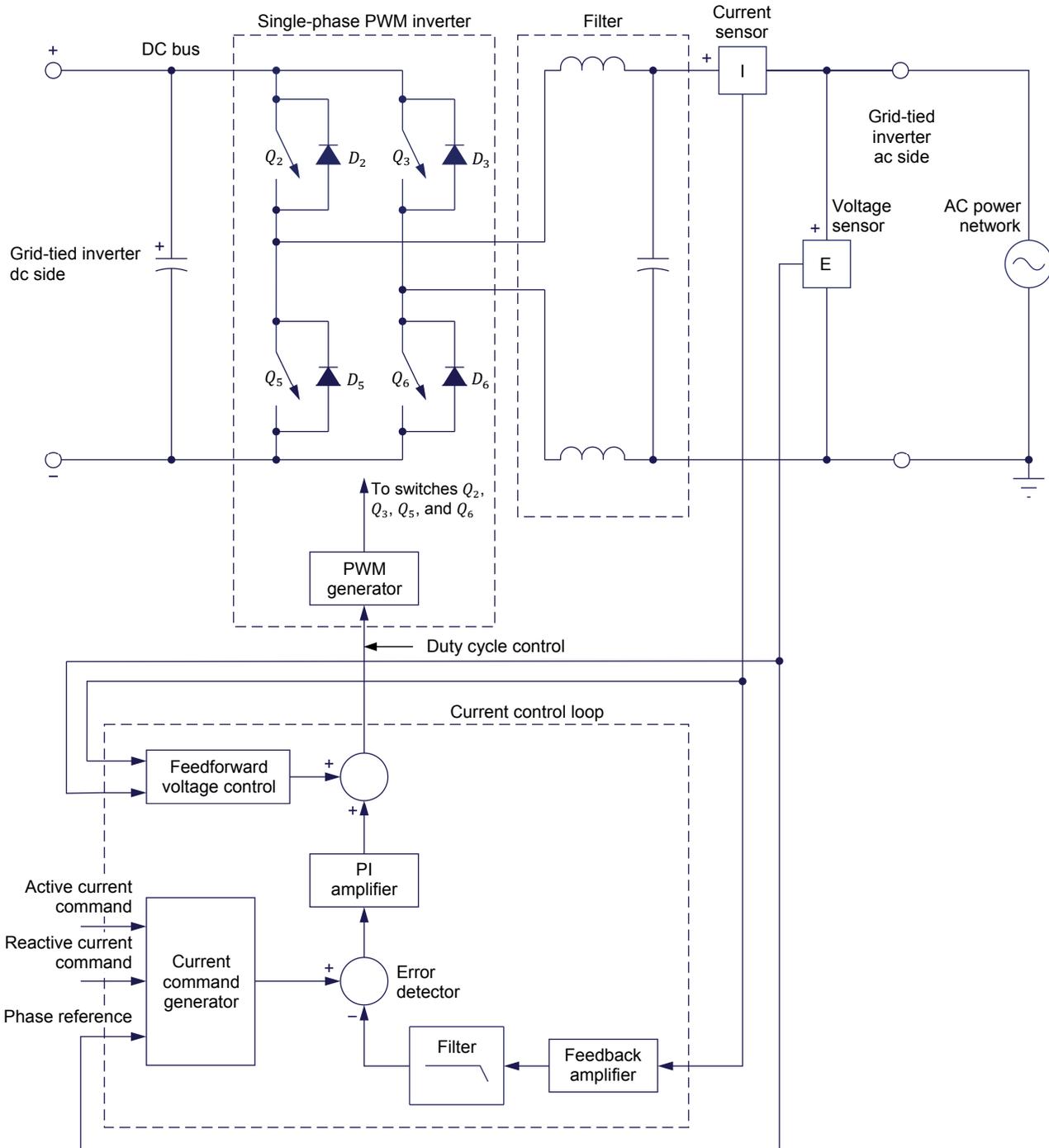


Figure 22. Block diagram of a single-phase grid-tied inverter showing the feedforward voltage control circuit used in the current control loop.

DC bus voltage versus the local ac power network voltage

The voltage required at the dc side of a single-phase grid-tied inverter (i.e., the dc bus voltage) is directly proportional to the ac power network voltage. For instance, the dc bus voltage required is about 200 V when the rms value of the ac power network voltage is 120 V, and about 350-400 V when the rms value of the ac power network voltage is either 220 V or 240 V.

A dc-to-dc converter is often added to the dc side of the PWM inverter in a single-phase grid-tied inverter to adjust the value of the incoming dc voltage to the dc bus voltage value which the PWM inverter requires to produce sine-wave voltage at the ac power network voltage value. Furthermore, a voltage control loop is often used in conjunction with the dc-to-dc converter to make the dc bus voltage independent of fluctuations in the incoming dc voltage. Figure 23 shows an example of a single-phase grid-tied inverter that includes a dc-to-dc converter and voltage control loop. In this particular example, the dc-to-dc converter is a buck-boost chopper. It is also the high-voltage side of the buck-boost chopper that is connected to the dc side of the PWM inverter in this example, because the incoming dc voltage is lower than the required dc bus voltage. Conversely, if the incoming dc voltage were higher than the required dc bus voltage, the low-voltage side of the buck-boost chopper would be connected to the dc side of the PWM inverter. The use of the buck-boost chopper topology for the dc-to-dc converter allows power flow in both directions.

Whenever the incoming voltage of the buck-boost chopper changes, the dc bus voltage (i.e., the voltage at the high-voltage side of the buck-boost chopper) also changes and becomes different from the dc bus voltage command. Consequently, a voltage error is produced in the voltage control loop and the loop automatically adjusts the duty cycle of the buck-boost chopper in order to correct the voltage error. For instance, when the dc bus voltage (i.e., the voltage at the high-voltage side of the buck-boost chopper) is less than the dc bus voltage command, the output signal of the error detector in the voltage control loop is positive, therefore increasing the duty cycle of the buck-boost chopper (i.e., the duty cycle of switch Q_4 increases and that of switch Q_1 decreases). This increases the dc bus voltage until the error is corrected. At this point, the error detector signal is zero and the PI amplifier produces a fixed signal that sets the duty cycle of the buck-boost chopper to the exact value required to maintain equilibrium.

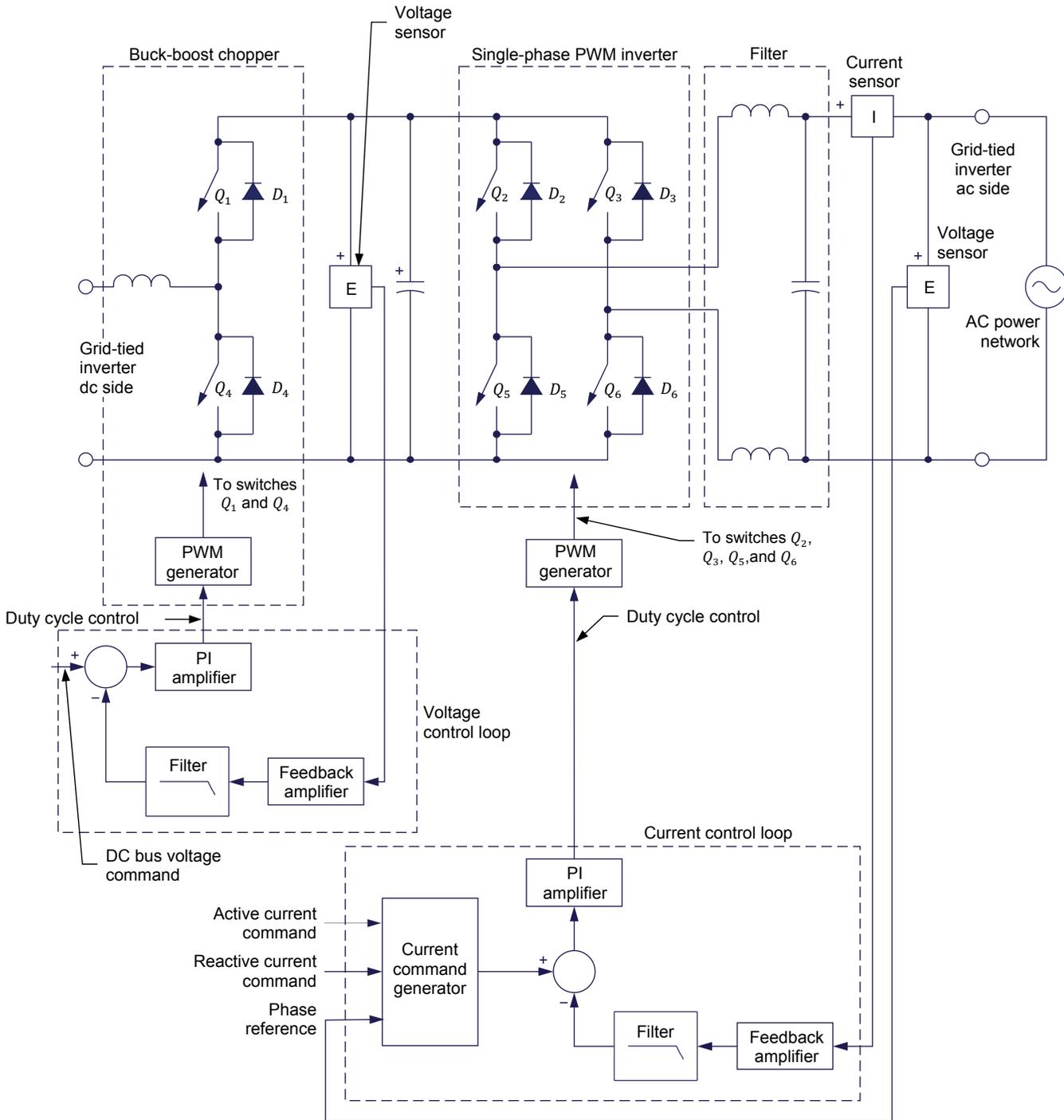


Figure 23. Example of a single-phase grid-tied inverter that includes a dc-to-dc converter and voltage control loop.

Another solution to match the incoming dc voltage with the ac voltage that needs to be produced (i.e., sine-wave voltage at the ac power network voltage value) consists in connecting the ac side of the PWM inverter to the network using either a step-down or step-up power transformer having the proper turns ratio as shown in Figure 24. This solution has the advantage of providing electrical insulation between the dc side and ac side of the single-phase grid-tied inverter.

Such insulation is required in certain applications as per the local regulations. Furthermore, using this circuit topology allows power flow in both directions such as when a buck-boost chopper is used at the dc side of the PWM inverter.

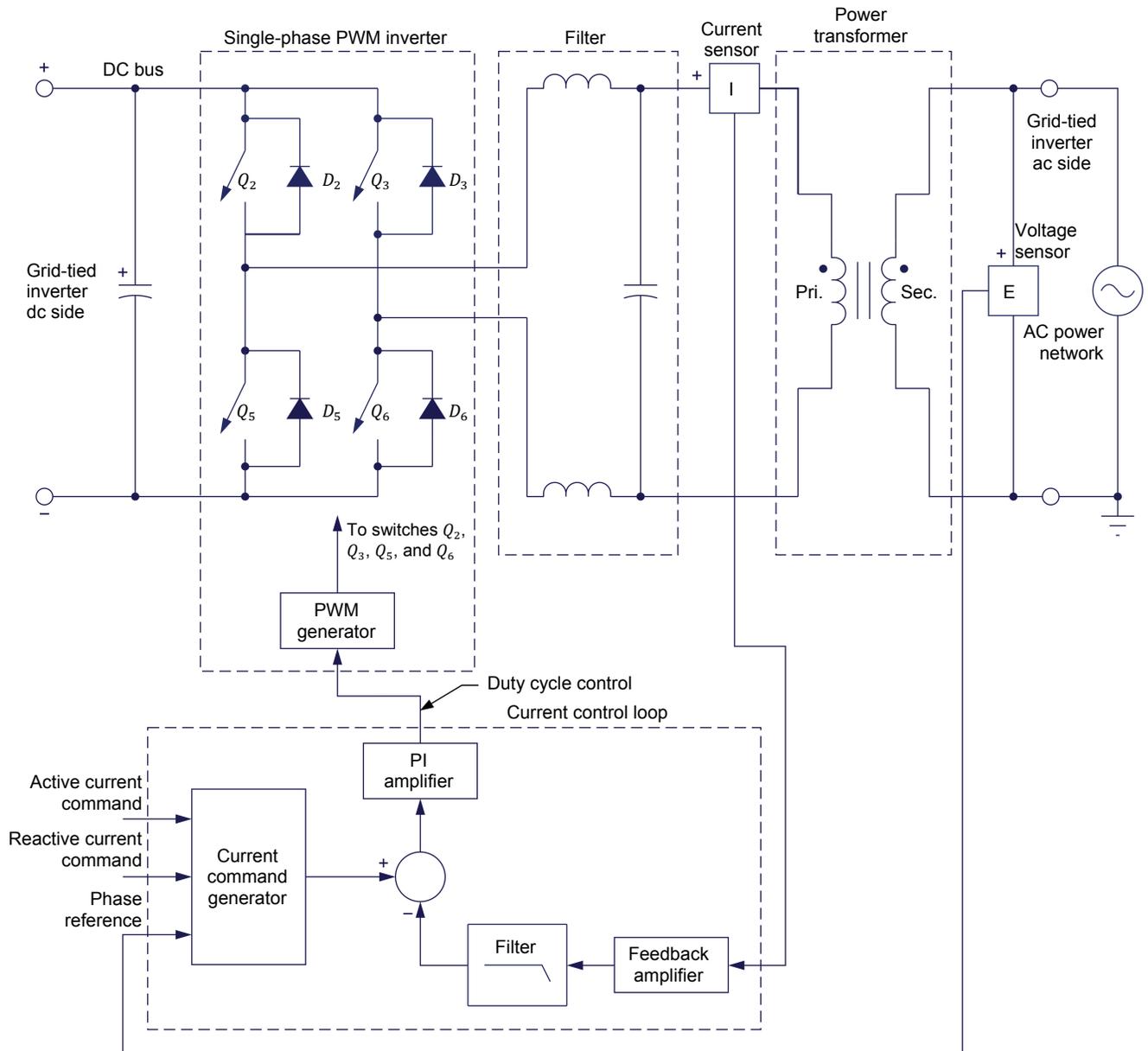


Figure 24. Example of a single-phase grid-tied inverter using a power transformer with the proper turns ratio to match the incoming dc voltage with the ac voltage that needs to be produced.

Note that the current sensor of the current control loop in the diagram of Figure 24 is connected to the primary of the power transformer instead of being connected to the secondary (network side). This helps improve the stability of the current control loop by notably removing all non linearities that would otherwise be introduced by having the power transformer in the loop.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Active current command and active power flow control
- Reactive current command and reactive power flow control
- Active and reactive power flow control

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 the exercise.

Install the equipment in the [Workstation](#).



Before beginning this exercise, measure the open-circuit voltage across the [Lead-Acid Battery Pack, Model 8802](#), using a multimeter. If the open-circuit voltage is lower than 51.2 V, ask your instructor for assistance as the [Lead-Acid Battery Pack](#) is probably not fully charged. Appendix E of this manual indicates how to prepare (fully charge) the [Lead-Acid Battery Pack](#) before each laboratory period.

2. Connect the [Power Input](#) of the [Data Acquisition and Control Interface \(DACI\)](#) to a 24 V ac power supply.

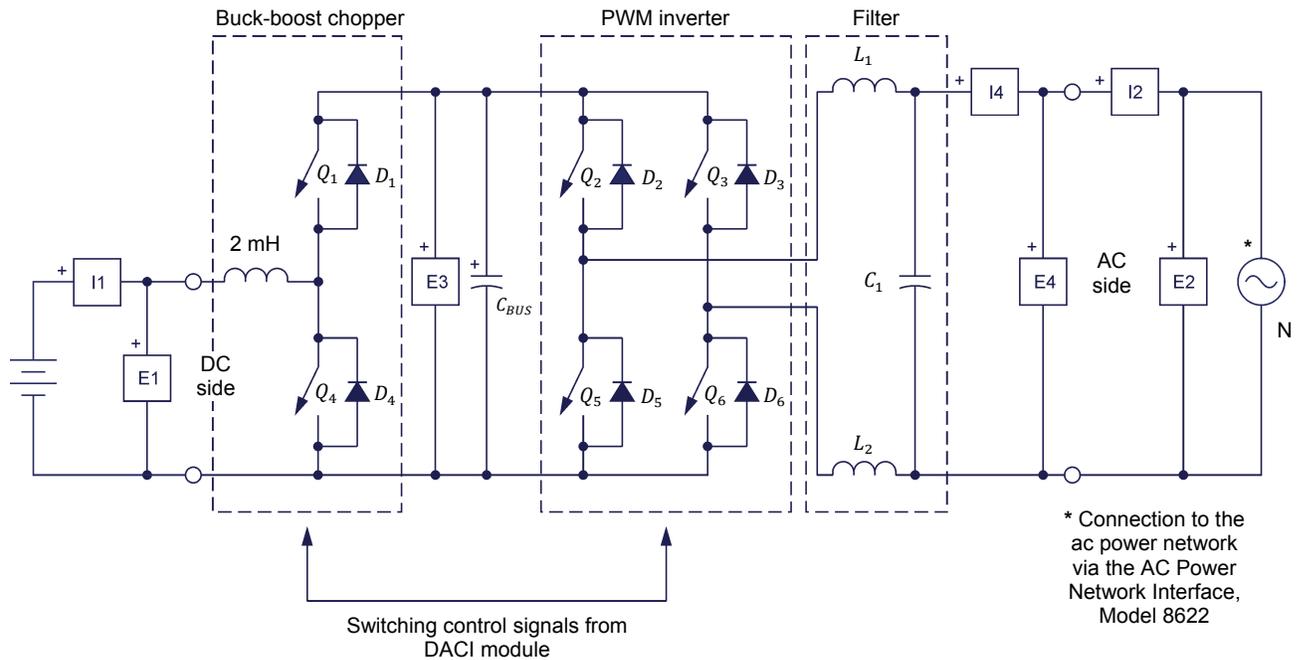
Connect the [Low Power Input](#) of the [Chopper/Inverter](#) to the [Power Input](#) of the [Data Acquisition and Control Interface](#). Turn the 24 V ac power supply on.

3. Connect the USB port of the [Data Acquisition and Control Interface](#) to a USB port of the host computer.
4. 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 [Home Energy Production 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.

5. Connect the *Digital Outputs* of the *Data Acquisition and Control Interface* to the *Switching Control Inputs* of the *Chopper/Inverter* using a DB9 connector cable. On the *Chopper/Inverter*, set the *Dumping* switch to the *O* (off) position.
6. Set up the circuit shown in Figure 25. Use the *Lead-Acid Battery Pack* as the voltage source. Use the inductor in the *AC Power Network Interface* to implement the boost chopper inductor. Use the *Filtering Inductors/Capacitors* to implement the PWM inverter output filter; the inductance and capacitance values to be used for L_1 , L_2 , and C_1 depend on your local ac power network (see table in the diagram).

Use the *AC Power Network Interface* to connect the ac side of the PWM inverter to the local ac power network. To do so, temporarily set the *AC Power Inlet* switch to *O* (off), connect the *AC Power Inlet* to an ac power outlet using the line cord supplied, connect the *AC Power Inlet* terminals to the ac side of the PWM inverter via the filter and current inputs *I2* and *I4* as shown in Figure 25, and set the *AC Power Inlet* switch to *I* (on).



Local ac power network		L_1, L_2 (mH)	C_1 (μ F)
Voltage (V)	Frequency (Hz)		
120	60	2	5.0
220	50	8	1.5
240	50	8	1.5
220	60	8	1.5

Figure 25. Single-phase grid-tied inverter.

Active current command and active power flow control

In this part of the exercise, you will vary the active current command. For each current command setting, you will measure the voltage, current, and power at the dc side of the single-phase grid-tied inverter, the voltage, current, active power, reactive power, THD of the current waveform, and power factor at the ac side of the single-phase grid-tied inverter, as well as the phase shift between the current I_{AC} and the ac power network voltage E_{AC} . You will observe the voltage, current, and power waveforms at the ac side of the single-phase grid-tied inverter. You will also observe the phasors of the voltage and current at the ac side of the single-phase grid-tied inverter. Finally, you will determine in which direction active power flows.

7. In LVDAC-EMS, open the Home Energy Production Control window, then make the following settings:
 - Set the *Function* parameter to *Single-Phase Grid-Tied Inverter*.
 - Make sure that the *Active Current Command* and *Reactive Current Command* parameters are set to 0 A.
 - Do not modify the settings of the other parameters.

Do not start the *Single-Phase Grid-Tied* inverter for now.

8. In LVDAC-EMS, open the *Metering* window.

In the *Options* menu, select *Acquisition Settings* to open the corresponding dialog box. Set the *Sampling Window* to 8 cycles, then click *OK* to close the dialog box.

Set meters to measure the voltage, current, and power at the dc side of the single-phase grid-tied inverter. Also set meters to measure the voltage, current, active power, reactive power, and power factor at the ac side of the single-phase grid-tied inverter.

9. In LVDAC-EMS, open the *Oscilloscope* window and make the settings required to observe the voltage, current, and power waveforms at the ac side of the single-phase grid-tied inverter.
10. In LVDAC-EMS, open the *Phasor Analyzer* window and make the settings required to observe the voltage and current phasors at the ac side of the single-phase grid-tied inverter. Select input *E2* as the reference phasor.
11. In LVDAC-EMS, open the *Harmonic Analyzer* window and make the settings required to observe the harmonic content of the current waveform (input *I2*) at the ac side of the single-phase grid-tied inverter.

12. Observe that voltage is present at the ac side of the single-phase grid-tied inverter as displayed on the **Oscilloscope** screen. Explain why voltage is present at the ac side of the single-phase grid-tied inverter even if it is not in operation.

Voltage is present because the ac power network applies (i.e., imposes) voltage to the ac side of the single-phase grid-tied inverter.

13. Start the *Single-Phase Grid-Tied Inverter*.

Is the current observed at the ac side of the single-phase grid-tied inverter virtually equal to zero? Explain why.

Yes. The current observed at the ac side of the single-phase grid-tied inverter should be virtually equal to zero because both the active and reactive current commands of the inverter are set to 0 A.

Positive active-current command

The current commands in the *Single-Phase Grid-Tied Inverter* function are expressed in rms values.

14. Gradually increase the *Active Current Command* of the *Single-Phase Grid-Tied Inverter* to the value given in Table 1 while observing the meters, the **Oscilloscope**, and the **Phasor Analyzer**.

Table 1. Active current command for various local ac power networks.

Local ac power network		Active current command (A)
Voltage (V)	Frequency (Hz)	
120	60	0.50
220	50	0.25
240	50	0.25
220	60	0.25

Does current flow at the ac side of the single-phase grid-tied inverter?

- Yes No

Yes

15. Set the *Active Current Command* of the *Single-Phase Grid-Tied Inverter* to the value given in Table 2.

Table 2. Active current command for various local ac power networks.

Local ac power network		Active current command (A)
Voltage (V)	Frequency (Hz)	
120	60	1.0
220	50	0.5
240	50	0.5
220	60	0.5

Compare the rms value of the current I_{ac} flowing at the ac side of the single-phase grid-tied inverter with the active current command. Is the rms value of current I_{ac} approximately equal to the active current command?

- Yes No

Yes

Is the current I_{ac} virtually in phase with the ac power network voltage E_{ac} ?

- Yes No

Yes

Explain why.

The active and reactive current commands of the single-phase grid-tied inverter are set to 1.0 A and 0 A, respectively. This is equivalent to a current command of $1.0 \text{ A} \angle 0^\circ$, which corresponds to a current I_{ac} of 1.0 A that is in phase with the ac power network voltage E_{ac} .

16. Measure and record the active and reactive current commands, the voltage, current, and power at the dc side of the single-phase grid-tied inverter, the voltage, current, active power, and reactive power at the ac side of the single-phase grid-tied inverter, as well as the phase shift between the current I_{ac} and the ac power network voltage E_{ac} using the [Data Table](#).

The results are presented in the following table.

Measured parameters of the single-phase grid-tied inverter.

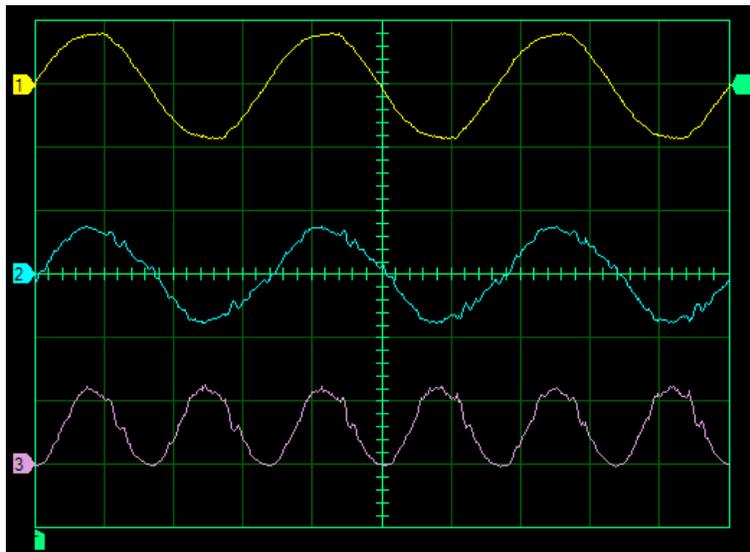
Current commands		Single-phase grid-tied inverter							
		DC side			AC side				
Active (A)	Reactive (A)	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Active Power (W)	Reactive Power (var)	Phase shift (°)
1.0	0.0	49.7	2.77	137.6	119.0	1.03	119.7	11.7	-4

Observe the waveform of the voltage, current, and power at the ac side of the grid-tied inverter displayed on the Oscilloscope. Also observe the phasors of the voltage and current at the ac side of the grid-tied inverter. Is active power exchanged between the single-phase grid-tied inverter and the ac power network? Explain why.

Yes. Active power is exchanged between the single-phase grid-tied inverter and the ac power network because the current I_{ac} is virtually in phase with the ac power network voltage E_{ac} .

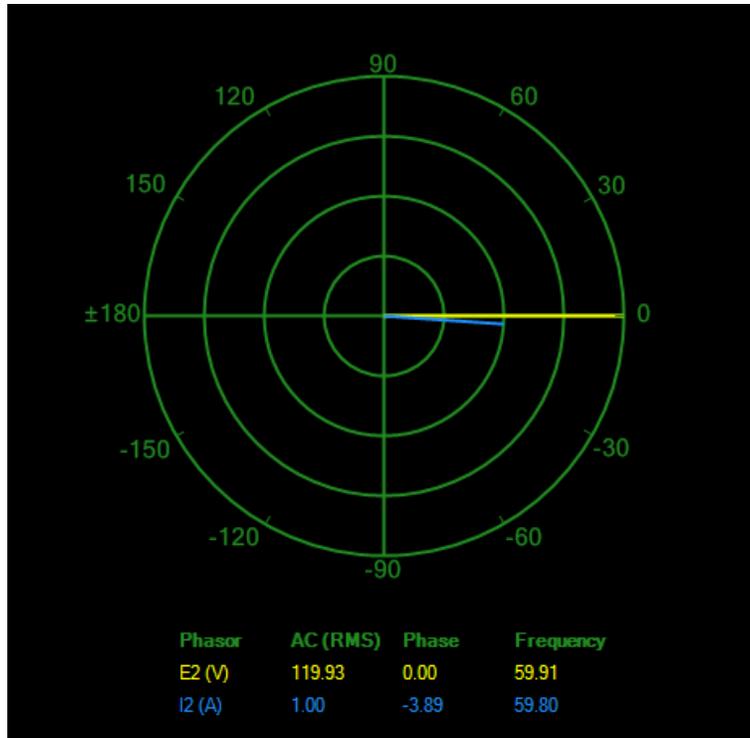
The resulting waveforms and phasors are shown below.

Oscilloscope settings
 Channel-1 Input E2
 Channel-1 Scale 200 V/div
 Channel-1 Coupling DC
 Channel-2 Input I-2
 Channel-2 Scale 2.0 A/div
 Channel-2 Coupling DC
 Channel-3 Input P-2
 Channel-3 Scale 200 W/div
 Channel-3 Coupling DC
 Time Base 0.5 ms/div
 Trigger Source Ch1
 Trigger Level 0 V
 Trigger Slope Rising



Voltage, current, and power waveforms at the ac side of the single-phase inverter obtained when the active current command is set to 1.0 A and the reactive current command is set to 0 A.

Phasor Analyzer settings
 Reference Phasor E2
 Voltage Scale 20 V/div
 Current Scale 0.5 A/div



Voltage and current phasors at the ac side of the single-phase inverter obtained when the active current command is set to 1.0 A and the reactive current command is set to 0 A.

17. In which direction does active power flow? Explain why.

Active power flows from the single-phase grid-tied inverter to the ac power network because the polarity of the active power is positive. In other words, the grid-tied inverter draws power from the battery (this is confirmed by the positive polarity of the power measured at the dc side of the inverter) and converts it into ac power that is fed to the ac power network.

18. Is reactive power exchanged between the single-phase grid-tied inverter and the ac power network? Explain why.

Virtually no reactive power is exchanged between the single-phase grid-tied inverter and the ac power network because the current I_{ac} is almost in phase with the ac power network voltage E_{ac} . This, in turn, results from the fact that the active current command is positive (+1.0 A) and the reactive current command is zero, leading to a current command of 1.0 A $\angle 0^\circ$.

19. Measure the power factor Q and the total harmonic distortion THD of the current at the ac side of the inverter.

Power factor Q: _____

THD of the current at the ac side of the inverter: _____%

Power factor Q: 0.99

THD of the current at the ac side of the inverter: 10%

20. Is the power factor approximately equal to one? What does this confirm?

Yes. This confirms that only active power is transferred between the inverter and the grid. This also confirms that the current waveform at the ac side of the inverter contains few harmonics.

Negative active-current command

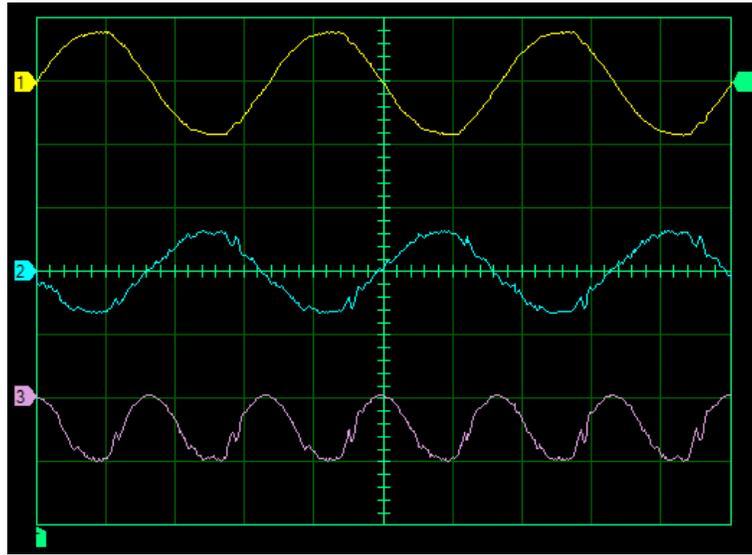
21. Let the system operate during about 15 minutes to slightly discharge the battery. Then, gradually decrease the *Active Current Command* of the *Single-Phase Grid-Tied Inverter* to the value given in Table 3 while observing the meters, the *Oscilloscope*, and the *Phasor Analyzer*.

Table 3. Active current command for various local ac power networks.

Local ac power network		Active current command (A)
Voltage (V)	Frequency (Hz)	
120	60	-1.0
220	50	-0.5
240	50	-0.5
220	60	-0.5

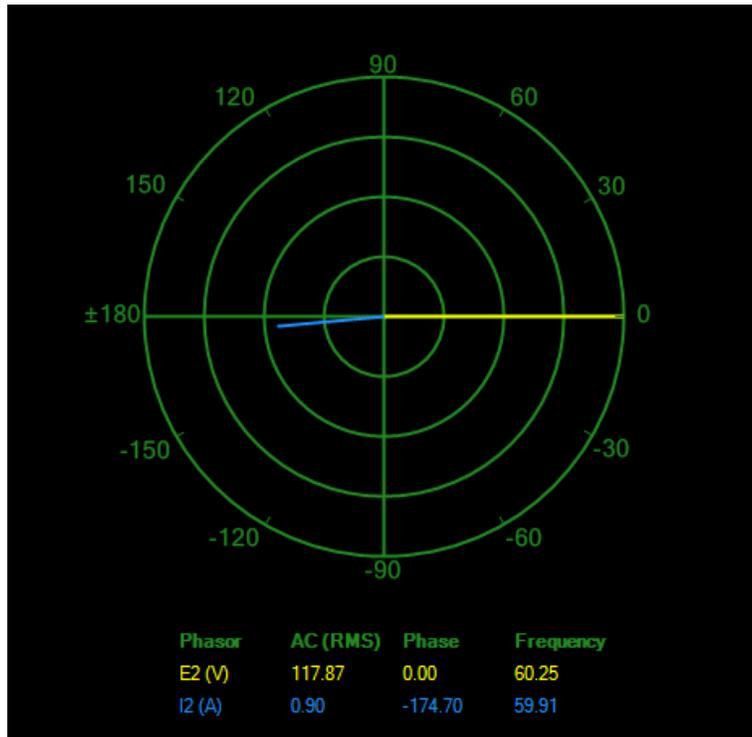
The resulting waveforms and phasors are shown below.

Oscilloscope settings
 Channel-1 Input E2
 Channel-1 Scale 200 V/div
 Channel-1 Coupling DC
 Channel-2 Input I-2
 Channel-2 Scale 2.0 A/div
 Channel-2 Coupling DC
 Channel-3 Input P-2
 Channel-3 Scale 200 W/div
 Channel-3 Coupling DC
 Time Base 0.5 ms/div
 Trigger Source Ch1
 Trigger Level 0 V
 Trigger Slope Rising



Voltage, current, and power waveforms at the ac side of the single-phase inverter obtained when the active current command is set to -1.0 A and the reactive current command is set to 0 A.

Phasor Analyzer settings
 Reference Phasor E2
 Voltage Scale 20 V/div
 Current Scale 0.5 A/div



Voltage and current phasors at the ac side of the single-phase inverter obtained when the active current command is set to -1.0 A and the reactive current command is set to 0 A.

Measure and record the active and reactive current commands, the voltage, current, and power at the dc side of the single-phase grid-tied inverter, the voltage, current, active power, and reactive power at the ac side of the single-phase grid-tied inverter, as well as the phase shift between the current I_{ac} and the ac power network voltage E_{ac} using the Data Table.

The results are presented in the following table.

Measured parameters of the single-phase grid-tied inverter.

Current commands		Single-phase grid-tied inverter							
		DC side			AC side				
Active (A)	Reactive (A)	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Active Power (W)	Reactive Power (var)	Phase shift (°)
-1.0	0.0	54.0	-1.66	-89.7	115.9	0.89	-102.0	10.0	-175

22. Describe how the rms value of the current I_{ac} flowing at the ac side of the single-phase grid-tied inverter, and the phase shift between the current I_{ac} and the ac power network voltage E_{ac} , change when the polarity of the active current command is reversed. Explain why.

The rms value of the current I_{ac} flowing at the ac side of the single-phase grid-tied inverter remains approximately 1.0 A when the active current command is either +1.0 A or -1.0 A. However, the current I_{ac} is phase shifted 180° with respect to the ac power network voltage E_{ac} (instead of being in phase with voltage E_{ac}) when the active current command is set to -1.0 A. When the active and reactive current commands of the single-phase grid-tied inverter are set to -1.0 A and 0 A, respectively, this is equivalent to a current command of 1.0 A $\angle 180^\circ$, which corresponds to a current I_{ac} of 1.0 A that is phase shifted 180° with respect to the ac power network voltage E_{ac} .

23. Observe that for a given value of the active current command, approximately the same amount of active power is exchanged between the single-phase grid-tied inverter and the ac power network no matter the polarity of the active current command. However, when the active current command is negative, the polarity of the active power is negative instead of being positive. What does the negative polarity of the active power indicate? Explain why.

The negative polarity of the active power indicates that active power flows from the ac power network to the single-phase grid-tied inverter. The grid-tied inverter thus operates as a rectifier, that is, it converts ac power from the network into dc power that charges the battery (this is confirmed by the negative polarity of the power measured at the dc side of the inverter). The active power is negative because the current I_{ac} is phase shifted $\sim 180^\circ$ with respect to the ac power network voltage E_{ac} .

Reactive current command and reactive power flow control

In this part of the exercise, you will vary the reactive current command. For each current command setting, you will measure the voltage, current, and power at the dc side of the single-phase grid-tied inverter, the voltage, current, active power, reactive power at the ac side of the single-phase grid-tied inverter, as well as the phase shift between the current I_{AC} and the ac power network voltage E_{AC} . You will observe the voltage, current, and power waveforms at the ac side of the single-phase grid-tied inverter. You will also observe the phasors of the voltage and current at the ac side of the single-phase grid-tied inverter. Finally, you will determine the direction in which power flows.

Positive reactive-current command

- 24. Set the **Active Current Command** to zero. The current I_{ac} should be approximately zero.
- 25. Gradually increase the **Reactive Current Command** of the **Single-Phase Grid-Tied Inverter** to the value given in Table 4 while observing the meters, the Oscilloscope, and the Phasor Analyzer.

Table 4. Reactive current command for various local ac power networks.

Local ac power network		Reactive current command (A)
Voltage (V)	Frequency (Hz)	
120	60	1.0
220	50	0.5
240	50	0.5
220	60	0.5

Measure and record the active and reactive current commands, the voltage, current, and power at the dc side of the single-phase grid-tied inverter, the voltage, current, active power, and reactive power at the ac side of the single-phase grid-tied inverter as well as the phase shift between the current I_{ac} and the ac power network voltage E_{ac} using the **Data Table**.

The results are presented in the following table.

Measured parameters of the single-phase grid-tied inverter.

Current commands		Single-phase grid-tied inverter							
		DC side			AC side				
Active (A)	Reactive (A)	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Active Power (W)	Reactive Power (var)	Phase shift (°)
0.0	1.0	51.9	0.40	20.5	117.7	0.87	9.6	-99.6	85

26. Observe that the rms value of the current I_{ac} flowing at the ac side of the single-phase grid-tied inverter is approximately equal to the reactive current command. Also observe that the current I_{ac} leads the ac power network voltage E_{ac} by about 90° . Explain why.

The active and reactive current commands of the single-phase grid-tied inverter are set to 0 A and 1.0 A, respectively. This is equivalent to a current command of $1.0 \text{ A} \angle 90^\circ$, which corresponds to a current of 1.0 A that leads the ac power network voltage by 90° .

27. How does the ac power network appear to the grid-tied inverter? Explain why.

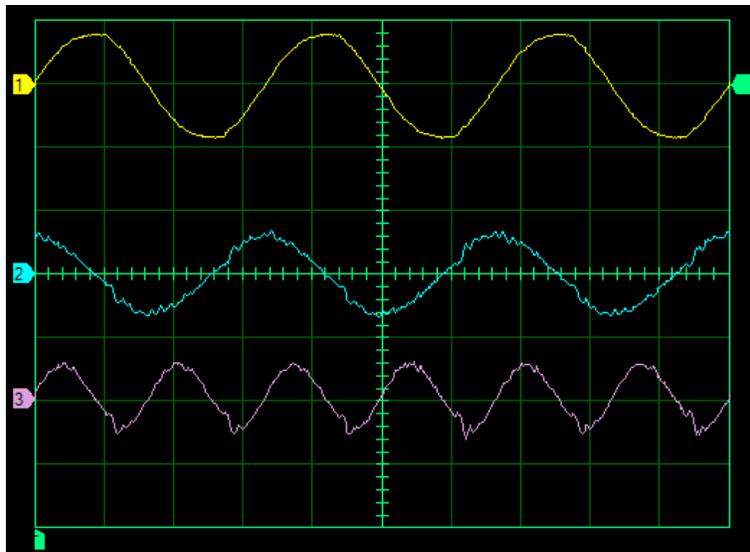
The ac power network appears to the single-phase grid-tied inverter as a capacitor because the current I_{ac} leads the ac power network voltage E_{ac} by about 90° .

28. Observe the waveforms of the voltage, current, and power at the ac side of the grid-tied inverter displayed on the Oscilloscope. Also observe the phasors of the voltage and current at the ac side of the grid-tied inverter. Is reactive power exchanged between the single-phase grid-tied inverter and the ac power network? Explain why.

Reactive power is exchanged between the single-phase grid-tied inverter and the ac power network because the current I_{ac} is phase shifted about 90° with respect to the ac power network voltage.

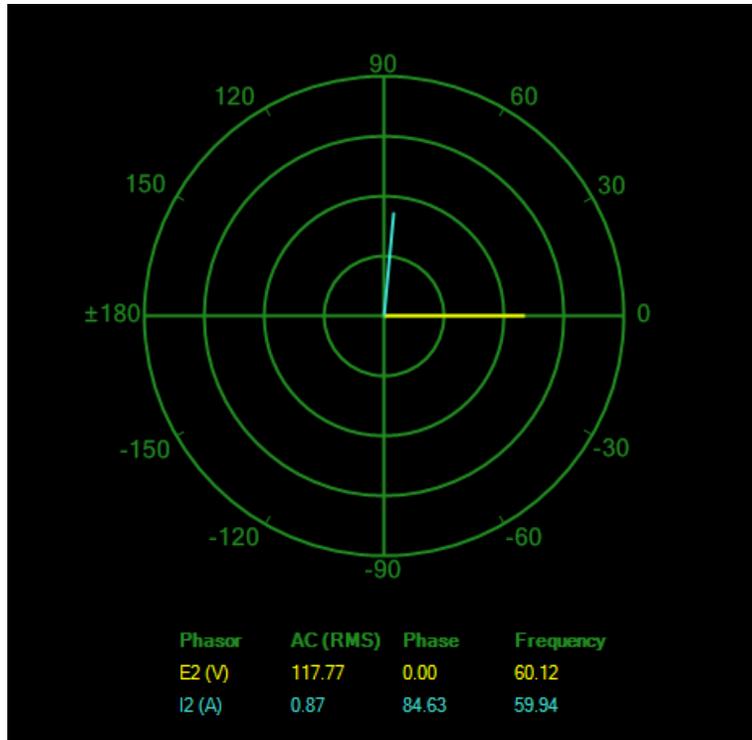
The resulting waveforms and phasors are shown below.

Oscilloscope settings
 Channel-1 Input E2
 Channel-1 Scale 200 V/div
 Channel-1 Coupling DC
 Channel-2 Input I-2
 Channel-2 Scale 2.0 A/div
 Channel-2 Coupling DC
 Channel-3 Input P-2
 Channel-3 Scale 200 W/div
 Channel-3 Coupling DC
 Time Base 0.5 ms/div
 Trigger Source Ch1
 Trigger Level 0 V
 Trigger Slope Rising



Voltage, current, and power waveforms at the ac side of the single-phase inverter obtained when the active current command is set to 0 A and the reactive current command is set to 1.0 A.

Phasor Analyzer settings
 Reference Phasor..... E2
 Voltage Scale.....50 V/div
 Current Scale.....0.5 A/div



Voltage and current phasors at the ac side of the single-phase inverter obtained when the active current command is set to 0 A and the reactive current command is set to 1.0 A.

29. In which direction does the reactive power flow? Explain why.

Reactive power flows from the ac power network to the single-phase grid-tied inverter. This is because the ac power network appears to the single-phase grid-tied inverter as a capacitor (i.e., a reactive element that supplies reactive power). The polarity of the reactive power is negative in this case.

30. Is active power exchanged between the single-phase grid-tied inverter and the ac power network? Explain why.

Virtually no active power is exchanged between the single-phase grid-tied inverter and the ac power network because the current I_{ac} leads the ac power network voltage E_{ac} by about 90° . This results from the fact that the reactive current command is positive (+1.0 A) and the active current command is zero, leading to a current command of $1.0 \text{ A} \angle 90^\circ$.

31. Although the single-phase grid-tied inverter exchanges a significant amount of reactive power with the ac power network, explain why the power measured at the dc side of the grid-tied inverter is virtually zero.

The power at the dc side of the grid-tied inverter is virtually zero even if the ac power network supplies a significant amount of reactive power to the inverter because reactive power does not actually flow from the network to the inverter. In fact, reactive power goes back and forth between the network and the grid-tied inverter. Consequently, the net amount of power exchanged is virtually zero, and thus, the power measured at the dc side of the inverter is virtually zero.

Negative reactive-current command

32. Gradually decrease the *Reactive Current Command* of the *Single-Phase Grid-Tied Inverter* to the value given in Table 5 while observing the meters, the *Oscilloscope*, and the *Phasor Analyzer*.

Table 5. Reactive current command for various local ac power networks.

Local ac power network		Reactive current command (A)
Voltage (V)	Frequency (Hz)	
120	60	-1.0
220	50	-0.5
240	50	-0.5
220	60	-0.5

Measure and record the active and reactive current commands, the voltage, current, and power at the dc side of the single-phase grid-tied inverter, the voltage, current, active power, and reactive power at the ac side of the single-phase grid-tied inverter, as well as the phase shift between the current I_{ac} and the ac power network voltage E_{ac} using the *Data Table*.

The results are presented in the following table.

Measured parameters of the single-phase grid-tied inverter.

Current commands		Single-phase grid-tied inverter							
		DC side			AC side				
Active (A)	Reactive (A)	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Active Power (W)	Reactive Power (var)	Phase shift (°)
0.0	-1.0	51.3	0.29	15.0	117.8	1.03	6.6	121.1	-87

- 33.** Observe that the rms value of the current I_{ac} flowing at the ac side of the single-phase grid-tied inverter is still approximately equal to the reactive current command. However, the current I_{ac} now lags the ac power network voltage E_{ac} by 90° . Explain why.

The active and reactive current commands of the single-phase grid-tied inverter are set to 0 A and -1.0 A, respectively. This is equivalent to a current command of $1.0 \text{ A} \angle -90^\circ$, which corresponds to a current of 1.0 A that lags the ac power network voltage by about 90° .

- 34.** How does the ac power network appear to the grid-tied inverter? Explain why.

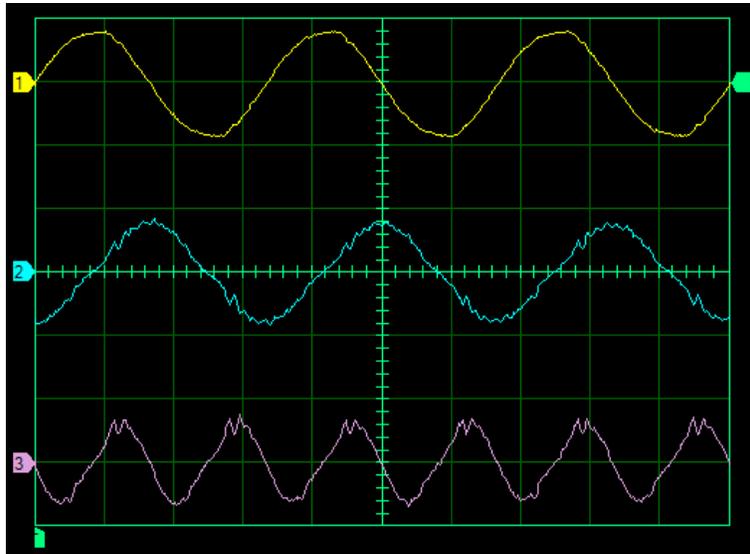
The ac power network appears to the single-phase grid-tied inverter as an inductor because the current I_{ac} now lags the ac power network voltage E_{ac} by about 90° .

35. Observe that for a given value of the reactive current command, approximately the same amount of reactive power is exchanged between the single-phase grid-tied inverter and the ac power network no matter the polarity of the reactive current command. However, when the reactive current command is negative, the polarity of the reactive power is positive instead of being negative. What does the positive polarity of the reactive power indicate? Explain why.

The positive polarity of the reactive power indicates that reactive power flows from the grid-tied inverter to the ac power network. The reactive power is positive because the current I_{ac} lags the ac power network voltage E_{ac} by about 90° , making the ac power network appear to the grid-tied inverter as an inductor (i.e., as a reactive element that absorbs reactive power).

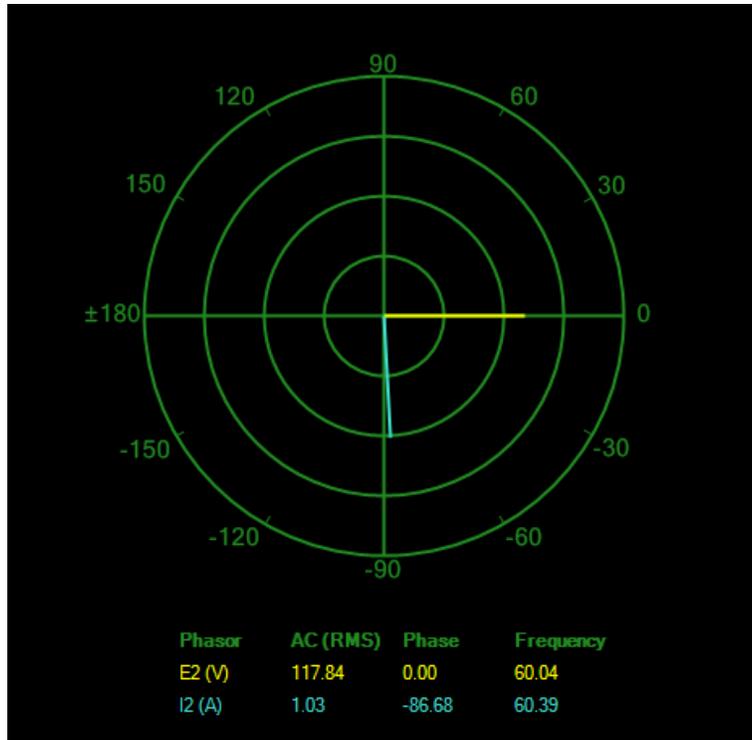
The resulting waveforms and phasors are shown below.

Oscilloscope settings
 Channel-1 Input.....E2
 Channel-1 Scale..... 200 V/div
 Channel-1 Coupling DC
 Channel-2 Input..... I-2
 Channel-2 Scale..... 2.0 A/div
 Channel-2 Coupling DC
 Channel-3 Input..... P-2
 Channel-3 Scale..... 200 W/div
 Channel-3 Coupling DC
 Time Base 0.5 ms/div
 Trigger Source Ch1
 Trigger Level 0 V
 Trigger Slope..... Rising



Voltage, current, and power waveforms at the ac side of the single-phase inverter obtained when the active current command is set to 0 A and the reactive current command is set to -1.0 A.

Phasor Analyzer settings
Reference Phasor..... E2
Voltage Scale..... 50 V/div
Current Scale..... 0.5 A/div



Voltage and current phasors at the ac side of the single-phase inverter obtained when the active current command is set to 0 A and the reactive current command is set to -1.0 A.

Active and reactive power flow control

In this part of the exercise, you will combine active and reactive current commands. For each combination, you will measure the voltage, current, and power at the dc side of the single-phase grid-tied inverter, the voltage, current, active power, reactive power at the ac side of the single-phase grid-tied inverter, as well as the phase shift between the current I_{AC} and the ac power network voltage E_{AC} . You will observe the voltage, current, and power waveforms at the ac side of the single-phase grid-tied inverter. You will also observe the phasors of the voltage and current at the ac side of the single-phase grid-tied inverter.

36. Set the active and reactive current commands to each combination of values shown in Table 6. For each combination (4) of current commands, measure and record the active and reactive current commands, the voltage, current, and power at the dc side of the single-phase grid-tied inverter, the voltage, current, active power, and reactive power at the ac side of the single-phase grid-tied inverter, as well as the phase shift between the current I_{ac} and the ac power network voltage E_{ac} using the [Data Table](#).

Table 6. Active and reactive current command combinations for various local ac power networks.

Local ac power network		Active and reactive current command combinations (A)							
Voltage (V)	Frequency (Hz)	1		2		3		4	
		Act.	React.	Act.	React.	Act.	React.	Act.	React.
120	60	+1.0	+1.0	-1.0	1.0	-1.0	-1.0	1.0	-1.0
220	50	+0.5	+0.5	-0.5	0.5	-0.5	-0.5	0.5	-0.5
240	50	+0.5	+0.5	-0.5	0.5	-0.5	-0.5	0.5	-0.5
220	60	+0.5	+0.5	-0.5	0.5	-0.5	-0.5	0.5	-0.5

The results are presented in the following table.

Measured parameters of the single-phase grid-tied inverter for the different active and reactive current commands indicated in Table 6.

Current commands		Single-phase grid-tied inverter							
		DC side			AC side				
Active (A)	Reactive (A)	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Active Power (W)	Reactive Power (var)	Phase shift (°)
1.0	1.0	49.9	2.91	145.4	119.1	1.35	123.0	-103.6	39
-1.0	1.0	51.9	-1.72	-89.2	116.6	1.26	-106.2	-104.1	135
-1.0	-1.0	53.0	-1.70	-89.9	116.8	1.40	-105.1	123.2	-131
1.0	-1.0	51.5	2.73	140.8	118.6	1.48	121.0	127.4	-46

37. Also, observe the voltage, current, and power waveforms at the ac side of the single-phase grid-tied inverter, as well as the voltage and current phasors at the ac side of the single-phase grid-tied inverter.

Do your observations confirm that by adjusting the active and reactive current commands, any combination of active and reactive power can be exchanged between the single-phase grid-tied inverter and the ac power network?

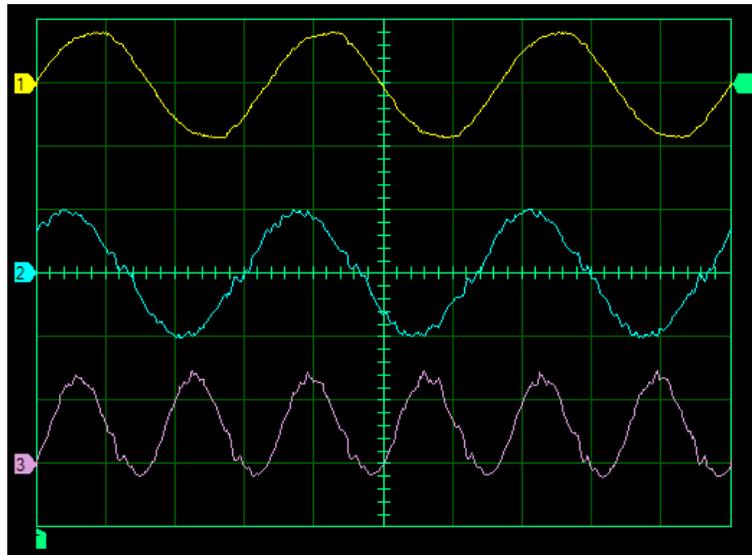
Yes No

Yes

The resulting waveforms and phasors are shown below.

Oscilloscope settings

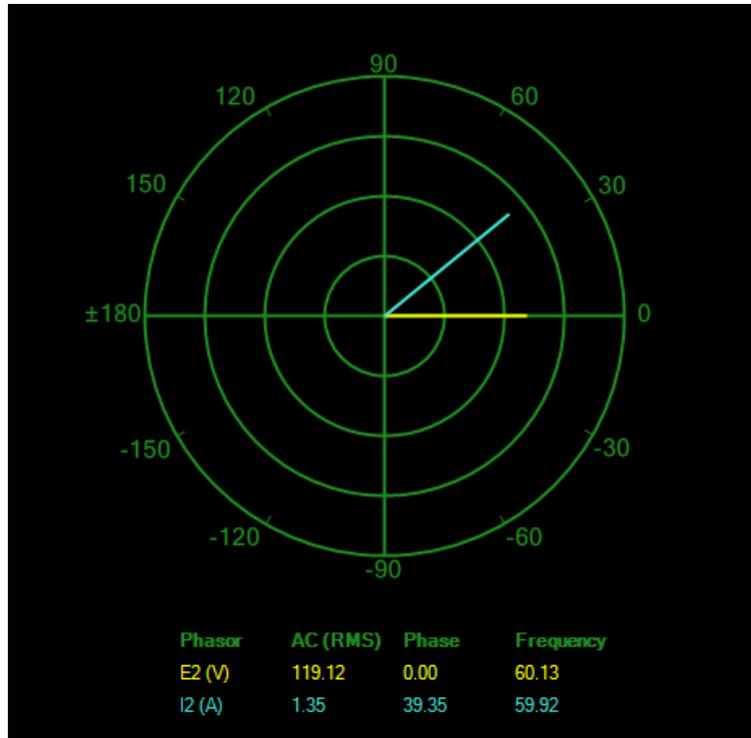
Channel-1 Input E2
Channel-1 Scale 200 V/div
Channel-1 Coupling DC
Channel-2 Input I-2
Channel-2 Scale 2.0 A/div
Channel-2 Coupling DC
Channel-3 Input P-2
Channel-3 Scale 200 W/div
Channel-3 Coupling DC
Time Base 0.5 ms/div
Trigger Source Ch1
Trigger Level 0 V
Trigger Slope Rising



Voltage, current, and power waveforms at the ac side of the single-phase inverter obtained when the active current command is set to 1.0 A and the reactive current command is set to 1.0 A.

Phasor Analyzer settings

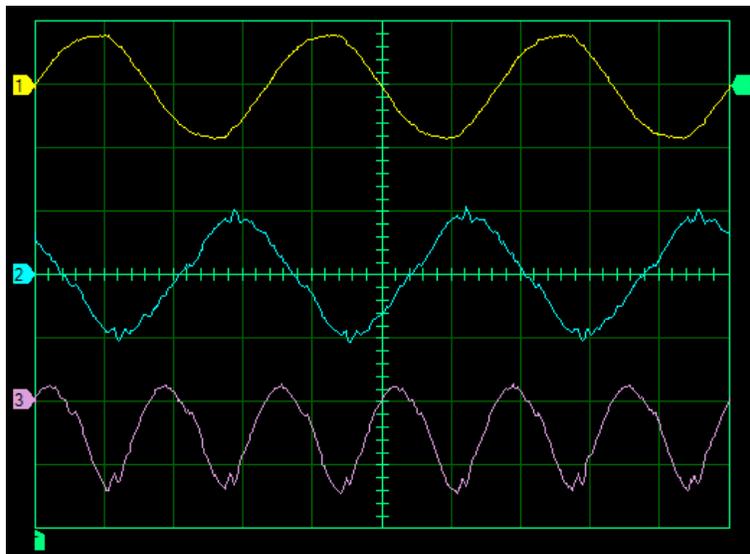
Reference Phasor E2
 Voltage Scale 50 V/div
 Current Scale 0.5 A/div



Voltage and current phasors at the ac side of the single-phase inverter obtained when the active current command is set to 1.0 A and the reactive current command is set to 1.0 A.

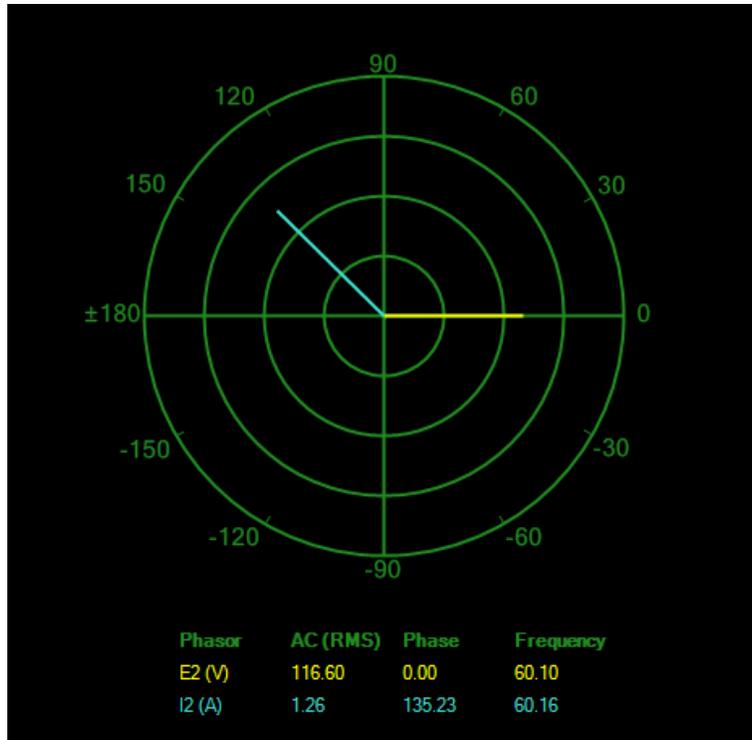
Oscilloscope settings

Channel-1 Input E2
 Channel-1 Scale 200 V/div
 Channel-1 Coupling DC
 Channel-2 Input I-2
 Channel-2 Scale 2.0 A/div
 Channel-2 Coupling DC
 Channel-3 Input P-2
 Channel-3 Scale 200 W/div
 Channel-3 Coupling DC
 Time Base 0.5 ms/div
 Trigger Source Ch1
 Trigger Level 0 V
 Trigger Slope Rising



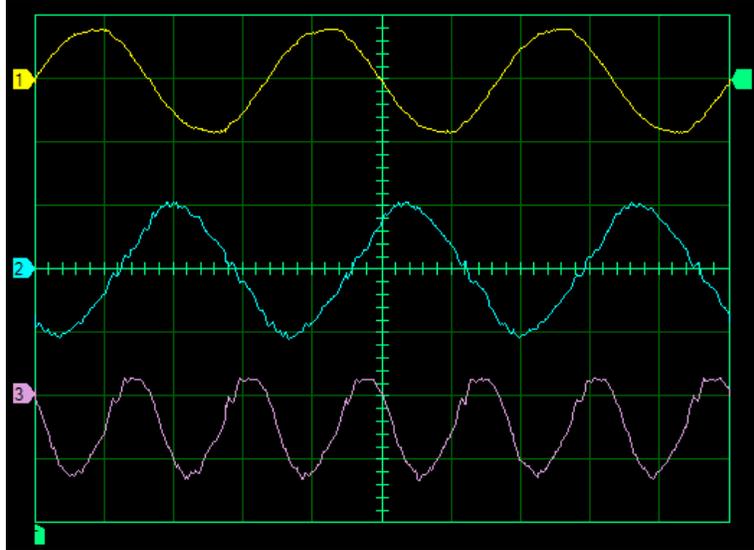
Voltage, current, and power waveforms at the ac side of the single-phase inverter obtained when the active current command is set to -1.0 A and the reactive current command is set to 1.0 A.

Phasor Analyzer settings
Reference Phasor..... E2
Voltage Scale.....50 V/div
Current Scale.....0.5 A/div



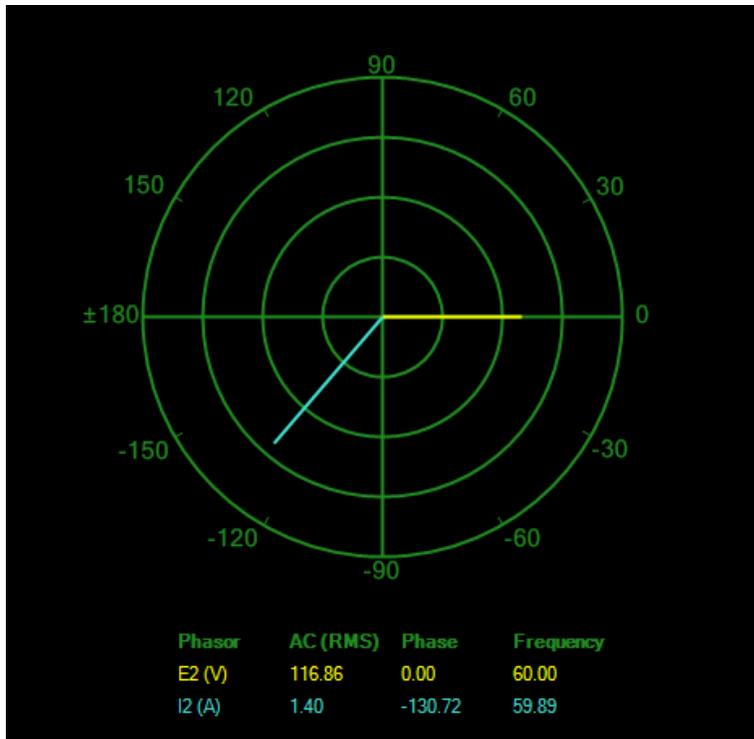
Voltage and current phasors at the ac side of the single-phase inverter obtained when the active current command is set to -1.0 A and the reactive current command is set to 1.0 A.

Oscilloscope settings
 Channel-1 Input E2
 Channel-1 Scale 200 V/div
 Channel-1 Coupling DC
 Channel-2 Input I-2
 Channel-2 Scale 2.0 A/div
 Channel-2 Coupling DC
 Channel-3 Input P-2
 Channel-3 Scale 200 W/div
 Channel-3 Coupling DC
 Time Base 0.5 ms/div
 Trigger Source Ch1
 Trigger Level 0 V
 Trigger Slope Rising



Voltage, current, and power waveforms at the ac side of the single-phase inverter obtained when the active current command is set to -1.0 A and the reactive current command is set to -1.0 A.

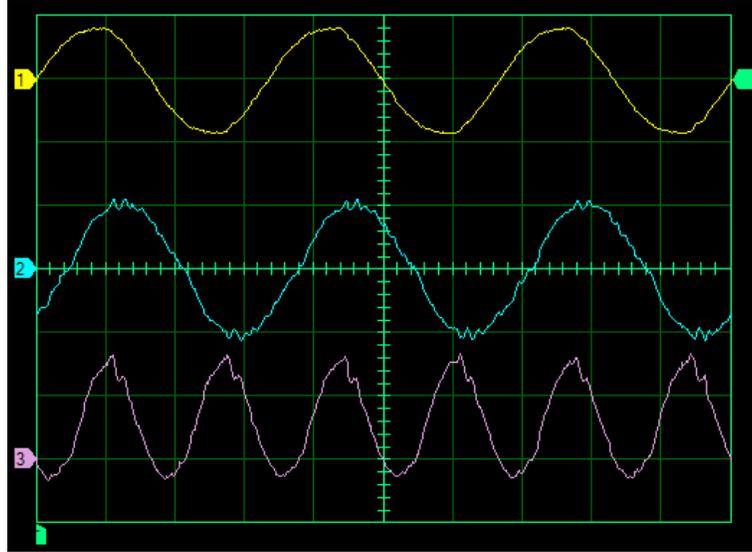
Phasor Analyzer settings
 Reference Phasor E2
 Voltage Scale 50 V/div
 Current Scale 0.5 A/div



Voltage and current phasors at the ac side of the single-phase inverter obtained when the active current command is set to -1.0 A and the reactive current command is set to -1.0 A.

Oscilloscope settings

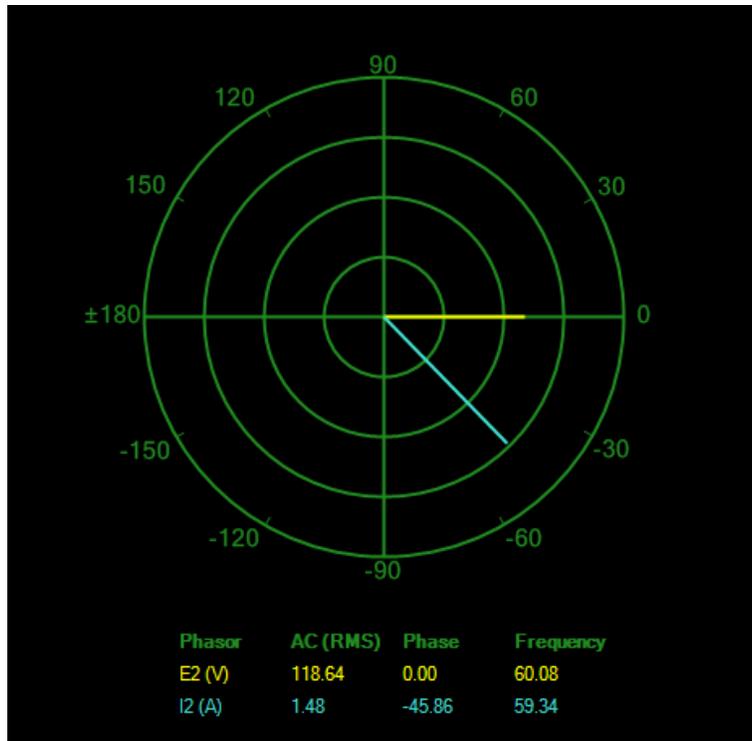
Channel-1 Input E2
 Channel-1 Scale 200 V/div
 Channel-1 Coupling DC
 Channel-2 Input I-2
 Channel-2 Scale 2.0 A/div
 Channel-2 Coupling DC
 Channel-3 Input P-2
 Channel-3 Scale 200 W/div
 Channel-3 Coupling DC
 Time Base 0.5 ms/div
 Trigger Source Ch1
 Trigger Level 0 V
 Trigger Slope Rising



Voltage, current, and power waveforms at the ac side of the single-phase inverter obtained when the active current command is set to 1.0 A and the reactive current command is set to -1.0 A.

Phasor Analyzer settings

Reference Phasor E2
 Voltage Scale 50 V/div
 Current Scale 0.5 A/div



Voltage and current phasors at the ac side of the single-phase inverter obtained when the active current command is set to 1.0 A and the reactive current command is set to -1.0 A.

38. Close LVDAC-EMS, then turn off all equipment. Remove all leads and cables.

CONCLUSION

You learned that when the output of a single-phase PWM inverter is connected to the local ac power network, the PWM inverter no longer has any control on the amplitude, frequency, and phase of the sine-wave voltage at its output since the values of these parameters are imposed by the local ac power network. However, the PWM inverter can exercise control over the amplitude and phase of the current which flows between its output and the local ac power network by using a current control loop.

You saw that it is common practice to express the current command in a single-phase grid-tied inverter using rectangular coordinates. This is because the x-axis component of the current command determines the value of a current that is either in phase or phase shifted 180° with respect to the network voltage. The value of the current determined by the x-axis component of the current command thus sets the amount of active power that is exchanged between the inverter and the ac power network. Consequently, the x-axis component of the current command is generally referred to as the active current command. Similarly, the y-axis component of the current command determines the value of a current that either leads or lags the network voltage by 90° . The value of the current determined by the y-axis component of the current command thus sets the amount of reactive power that is exchanged between the inverter and the ac power network. Consequently, the y-axis component of the current command is generally referred to as the reactive current command.

You learned that a dc-to-dc converter is often added to the dc side of the PWM inverter in a single-phase grid-tied inverter to adjust the value of the incoming dc voltage to the dc bus voltage value which the PWM inverter requires to produce sine-wave voltage at the ac power network voltage value. You also learned that another solution to match the incoming dc voltage with the ac voltage that needs to be produced consists in connecting the ac side of the PWM inverter to the network using either a step-down or step-up power transformer having the proper turns ratio. This solution has the advantage of providing electrical insulation between the dc side and ac side of the single-phase grid-tied inverter.

REVIEW QUESTIONS

1. Explain why the PWM inverter in a single-phase grid-tied inverter no longer has any control on the amplitude, frequency, and phase of the sine-wave voltage at its output.

The PWM inverter in a single-phase grid-tied inverter no longer has any control on the amplitude, frequency, and phase of the sine-wave voltage at its output since the values of these parameters are imposed by the local ac power network which acts as a voltage source.

2. What are the x-axis and y-axis components of the current command in a single-phase grid-tied inverter generally referred to as?

The x-axis and y-axis components of the current command in a single-phase grid-tied inverter are respectively referred to as the active current command and reactive current command.

3. Describe the exchange of power between the single-phase grid-tied inverter shown in Figure 12 and the ac power network when the active current command is negative and the reactive current command is zero. In this condition, does the grid-tied inverter work as an inverter or as a rectifier? Explain why.

When the active current command of the single-phase grid-tied inverter is negative and the reactive current command is zero, active power is received from the ac power network but no reactive power is exchanged. When active power is received from the ac power network, power is converted from ac to dc, and the grid-tied inverter, in fact, works as a rectifier.

4. Explain why a dc-to-dc converter is often used at the dc side of a single-phase grid-tied inverter.

A dc-to-dc converter (e.g., a buck-boost chopper) is often used at the dc side of a single-phase grid-tied inverter to match the incoming dc voltage with the dc bus voltage value that the PWM inverter requires to produce sine-wave voltage at the ac power network voltage value.

5. Describe the exchange of power between the single-phase grid-tied inverter shown in Figure 12 and the ac power network when the active current command is positive and the reactive current command is negative. In this condition, does the grid-tied inverter work as an inverter or as a rectifier? Explain why.

When the active current command of the single-phase grid-tied inverter is positive and the reactive current command is negative, active power is supplied to the ac power network and reactive power is also exchanged. When active power is supplied to the ac power network, power is converted from dc to ac, and the grid-tied inverter, in fact, works as an inverter.

Bibliography

HAU, Erich, Wind Turbines, Fundamentals, Technologies, Application, Economics, 2nd edition, Springer Berlin Heidelberg, New York, 2006, ISBN 13-978-3-540-24240-6.

MASTERS, Gilbert M., Renewable and Efficient Electric Power Systems, New Jersey: John Wiley & Sons, Inc., 2004, ISBN 0-471-28060-7.