

Photovoltaic Systems

FESTO

FESTO

Electricity and New Energy

LabVolt Series

Student Manual

230 V - 50 Hz



Student Manual

Photovoltaic Systems

Germany
Festo Didactic SE
Rechbergstr. 3
73770 Denkendorf
Tel.: +49 711 3467-0
Fax: +49 711 347-54-88500
did@festo.com

United States
Festo Didactic Inc.
607 Industrial Way West
Eatontown, NJ 07724
Tel.: +1 732 938-2000
Toll Free: +1-800-522-8658
Fax: +1 732 774-8573
services.didactic@festo.com

Canada
Festo Didactic Ltée/Ltd
675, rue du Carbone
Québec (Québec) G2N 2K7
Tel.: +1 418 849-1000
Toll Free: +1-800-522-8658
Fax: +1 418 849-1666
services.didactic@festo.com

www.festo-didactic.com

Festo Didactic
en
54337-0C



30543370C0000

Electricity and New Energy

Photovoltaic Systems

Student Manual

54337-0C

Order no.: 54337-0C

First Edition

Revision level: 10/2017

By the staff of Festo Didactic

© Festo Didactic Ltée/Ltd, Quebec, Canada 2017

Internet: www.festo-didactic.com

e-mail: did@de.festo.com

Printed in Canada

All rights reserved

ISBN 978-2-89747-955-8 (Printed version)

ISBN 978-2-89747-957-2 (CD-ROM)

Legal Deposit – Bibliothèque et Archives nationales du Québec, 2017

Legal Deposit – Library and Archives Canada, 2017

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. Consult the relevant user documentation.
	Caution, lifting hazard
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation
	Consult the relevant user documentation.
	Direct current
	Alternating current

Safety and Common Symbols

Symbol	Description
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal
	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
Introduction Photovoltaic Systems	1
DISCUSSION OF FUNDAMENTALS	1
Stand-alone and grid-tied photovoltaic (PV) systems	1
Protection and disconnection components in PV systems	4
Exercise 1 Stand-Alone PV Systems for DC Loads	7
DISCUSSION	7
Introduction to stand-alone PV systems for dc loads	7
PV panel	8
Battery	9
Charge controller	12
Physical representation of a stand-alone PV system for dc loads	12
Operation of a stand-alone PV system for dc loads	13
Selection of the PV panel, charge controller, and battery for a specific stand-alone PV system	15
On-off charge controllers	16
Battery charging control method	16
Battery overdischarge protection	18
Topology	21
Power switching device technology	22
Pulse-width modulation (PWM) charge controllers	22
Battery charging control method	22
Battery overdischarge protection	25
Topology	25
Power switching device technology	25
Applications of stand-alone PV systems for dc loads	25
Electric power provision in small buildings	26
Battery charging in recreational vehicles	26
Refrigeration in developing countries	27
Lighting of public spaces	27
Road signaling	28
Effect of using energy-efficient electric equipment on the size and cost of stand-alone PV systems for dc loads	29

Table of Contents

PROCEDURE.....	30
Setup and connections	31
Emulated PV panel settings.....	32
Main components of a stand-alone PV system for dc loads	32
Setting up a stand-alone PV system for dc loads.....	34
Stand-alone PV system operation	37
PV panel producing no electricity.....	37
PV panel producing electricity at a rate below the power demand of the dc loads	38
PV panel producing electricity at a rate equal to the power demand of the dc loads	38
PV panel producing electricity at a rate exceeding the power demand of the dc loads.....	39
Battery charging.....	40
Comparing the energy consumption of two different types of dc lamps.....	42
Battery overdischarge protection	43
 Exercise 2 Use of an MPPT Charge Controller in Stand-Alone PV Systems.....	49
DISCUSSION	49
Introduction	49
MPPT charge controllers	49
Topology.....	50
Battery charging control method	53
Battery overdischarge protection	54
Power switching device technology	54
Operating point of the PV panel in stand-alone PV systems using an on-off or PWM charge controller	54
Operating point of the PV panel in stand-alone PV systems using an MPPT charge controller	56
Comparison of the on-off, PWM, and MPPT charge controllers	57
PROCEDURE.....	58
Setup and connections	58
Partial discharge of the battery pack	59
Emulated PV panel settings.....	61
Setting up a stand-alone PV system for dc loads.....	62
Operating point of the PV panel in a stand-alone PV system using a PWM charge controller	63
Operating point of the PV panel in a stand-alone PV system using an MPPT charge controller	67

Table of Contents

Exercise 3	Stand-Alone PV Systems for AC Loads.....	73
	DISCUSSION.....	73
	Introduction to stand-alone PV systems for ac loads	73
	Physical representation of a stand-alone PV system for ac loads.....	75
	Selection of the PV panel, charge controller, battery, and stand-alone inverter for a specific stand-alone PV system ...	76
	Applications of stand-alone PV systems for ac loads.....	79
	Electric power provision in homes	79
	Electric power provision in small buildings	80
	Effect of using energy-efficient electric equipment on the size and cost of stand-alone PV systems for ac loads	80
	PROCEDURE.....	82
	Setup and connections	82
	Emulated PV panel settings.....	83
	Main components of a stand-alone PV system for ac loads	83
	Setting up a stand-alone PV system for ac loads.....	86
	Operation of the stand-alone inverter	88
	Comparing the energy consumption of different types of ac lamps.....	89
	Battery overdischarge protection function of the stand- alone inverter	91
Exercise 4	Grid-Tied PV Systems.....	95
	DISCUSSION.....	95
	Introduction to grid-tied PV systems.....	95
	PV panel.....	96
	Grid-tied inverter.....	96
	Energy meter.....	97
	Operation of a grid-tied PV system.....	97
	PV panel/grid-tied inverter arrangements.....	99
	Central inverter.....	99
	String inverters	101
	Micro-inverters.....	103
	Physical representation of a grid-tied PV system.....	104
	Selection of the PV panel, grid-tied inverter, and energy meter for a specific grid-tied PV system	106
	Energy metering in grid-tied PV systems	108
	Net metering.....	108
	Gross metering.....	110
	Monitoring and setting the operation of micro-inverters	110
	Effect of using energy-efficient electric equipment on grid-tied PV systems.....	112

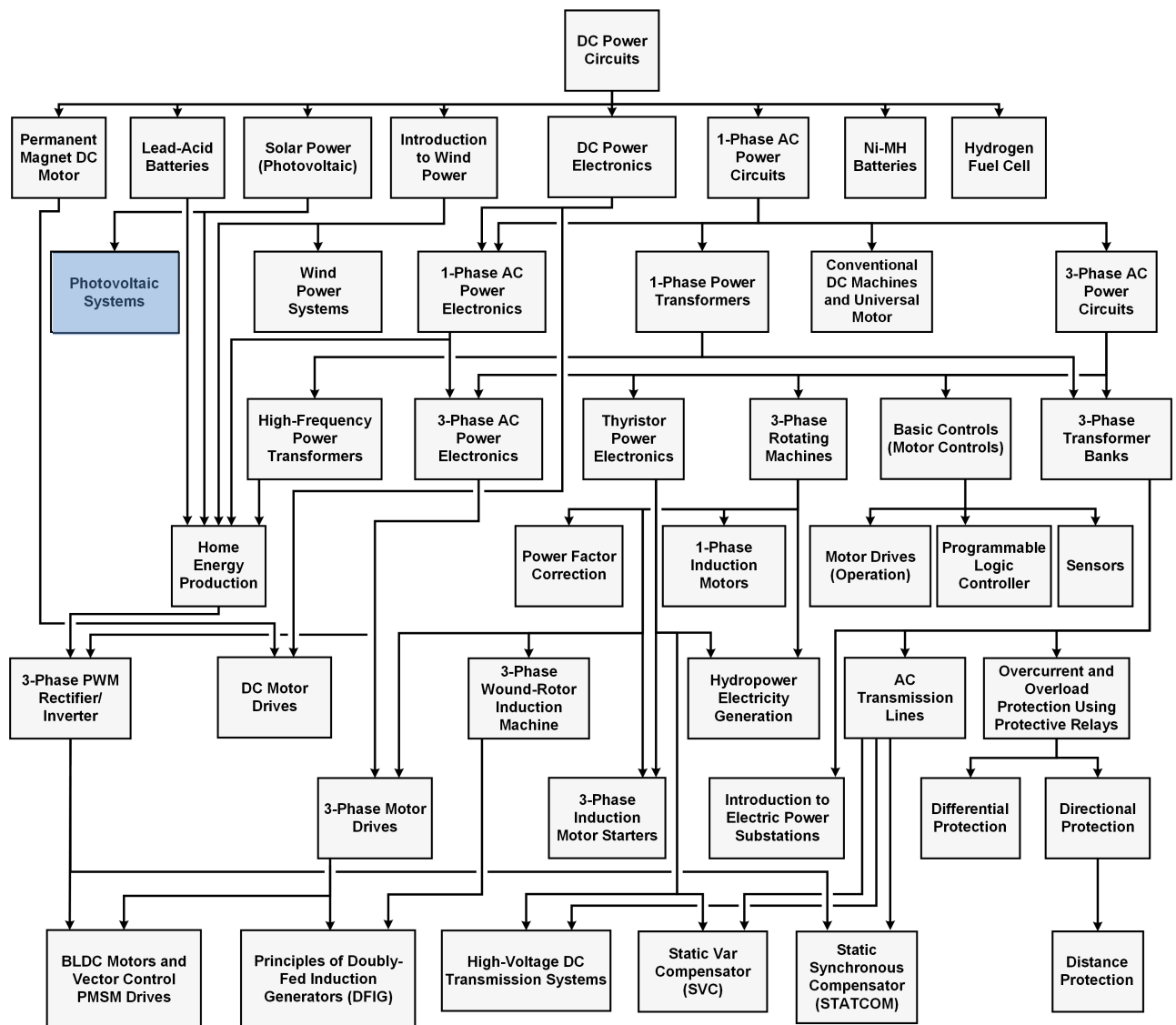
Table of Contents

PROCEDURE.....	112
Setup and connections	112
Emulated PV panel settings.....	114
Main components of a grid-tied PV system	114
Setting up a grid-tied PV system using gross metering.....	116
Operation of the grid-tied PV system using gross metering	118
Automatic disconnection of the grid-tied inverter during a power outage	121
Setting up a grid-tied PV system using net metering/self- consumption.....	122
Operation of the grid-tied PV system using net metering/self-consumption.....	124
Appendix A Equipment Utilization Chart	129
Appendix B Glossary of New Terms	131
Appendix C Safe Handling of PV Panels	133
Appendix D Preparation of the 48V Lead-Acid Battery Pack.....	135
Charging procedure	135
Sulfation test	136
Battery maintenance.....	138
Appendix E Setting up the Communications Gateway	139
Index of New Terms	143
Acronyms	145
Bibliography.....	147

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

Climate changes observed throughout the world in recent years have led to an ever-growing demand for renewable sources of energy to counteract these changes and to help minimize their negative effects on our lives. Solar power is by far Earth's most available source of renewable energy, easily capable of providing many times the total current energy demand.

The present manual discusses photovoltaic (PV) systems, i.e., systems that convert sunlight into electric power that can be used to power electrical equipment or feed the local ac power network. The manual covers the major aspects of both stand-alone PV systems and grid-tied PV systems, paying special attention to the integration of the major components used in these systems. Several applications of PV systems are presented throughout the manual. Finally, the manual demonstrates the impact of using energy-efficient equipment on the size and cost of the PV system required in any specific application.



Home equipped with a photovoltaic (PV) system converting sunlight into electricity.

Safety considerations

Safety symbols that may be used in this manual and on the equipment are listed in the Safety and Common 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. Before performing manipulations with the equipment, you should read all sections in the Safety Instructions and Commissioning manual of the Electric Power Technology Training Equipment regarding safety.

About This Manual

Prerequisite

As a prerequisite to this course, you should have read the manuals titled *DC Power Circuits* and *Solar Power (Photovoltaic)*.

Systems of units

Units are expressed using the International System of Units (SI) followed by units expressed in the U.S. customary system of units (between parentheses).

Photovoltaic Systems

MANUAL OBJECTIVE

When you have completed this manual, you will be familiar with the configuration and operation of both stand-alone and grid-tied photovoltaic (PV) systems. You will know typical applications of each of these two types of PV systems. You will understand the role and operation of each of the main components (PV panel, charge controller, battery, stand-alone inverter, grid-tied inverter, etc.) used in stand-alone and grid-tied PV systems. You will be able to check the electrical specifications of these components to make sure that they can work together without causing problems.

DISCUSSION OUTLINE

The Discussion of Fundamentals covers the following :

- Stand-alone and grid-tied photovoltaic (PV) systems
- Protection and disconnection components in PV systems

DISCUSSION OF FUNDAMENTALS

Stand-alone and grid-tied photovoltaic (PV) systems

A **photovoltaic (PV) system** uses a PV panel and power control/conversion devices to convert sunlight into electricity that can be used to power electric equipment (loads). There are two main types of PV systems: stand-alone and grid-tied.

A **stand-alone PV system** is not connected to the local ac power network, as is shown in Figure 1. Consequently, the electricity produced is used to supply power to local electric loads connected to the system. Since the system is not connected to the local ac power network, it includes a battery to store electricity produced by the PV panel that is not used immediately by the loads. The energy stored in the battery can then be used to power the loads when the PV panel produces no electricity (at night) or little electricity (during cloudy periods occurring during daytime). Depending on the application, the loads connected to a stand-alone PV system can be either dc powered or ac powered.

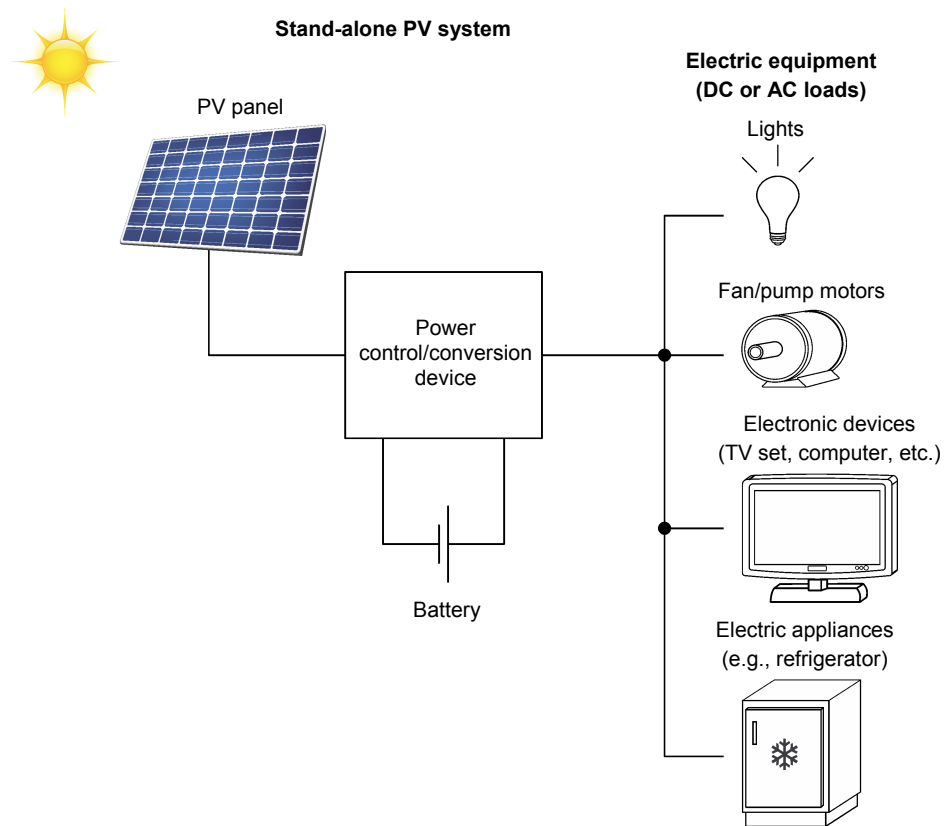


Figure 1. Simplified diagram of a stand-alone PV system.

The local ac power network is commonly referred to as the grid, hence the name grid-tied PV system.

On the other hand, a **grid-tied PV system** is connected to the local ac power network, as is shown in Figure 2. The electricity produced can be used to supply power to local electric loads connected to the system and/or to feed the local ac power network. No battery is required because electricity from the local ac power network is available (as long as there is no power outage) to power the local loads when the PV panel produces no or little electricity. An energy meter (commonly referred to as an electricity meter) is required to measure the amount of energy which the grid-tied PV system exchanges with the local ac power network. The loads are generally ac powered in most grid-tied PV systems.

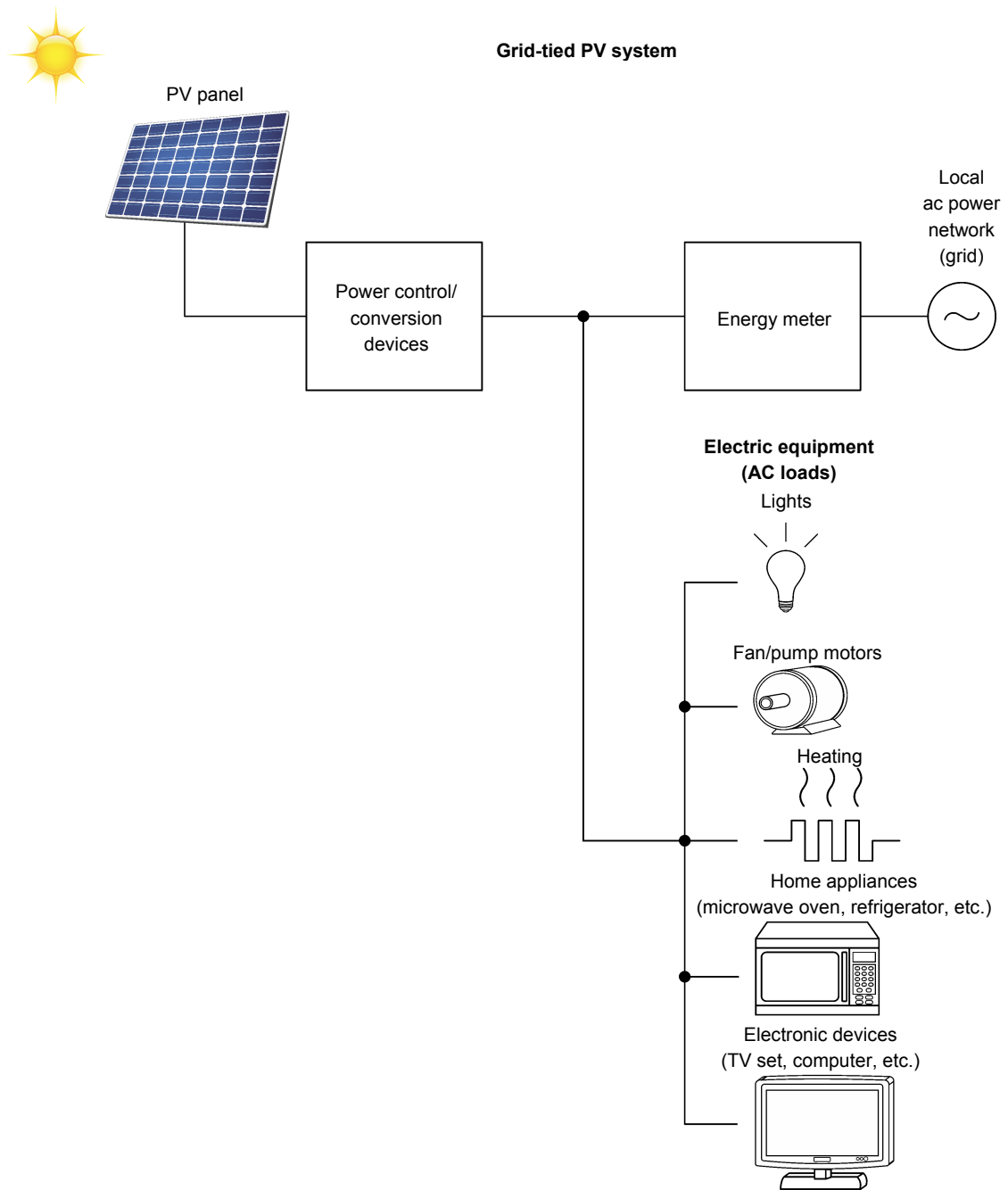


Figure 2. Simplified diagram of a grid-tied PV system.

The configuration and operation of both the stand-alone and grid-tied PV systems are studied in this manual. Typical applications are presented for each of these two types of PV system. Finally, the operation of each of the main components used in these two types of PV systems is discussed.

Protection and disconnection components in PV systems

Grid-tied PV systems are studied in Exercise 4 of this manual.

Figure 3 shows the diagram of a grid-tied PV system. The diagram includes the essential components of the system, i.e., a PV panel array, PV panel array bypass and blocking diodes, a grid-tied inverter, and an energy meter. The diagram also includes various ancillary components such as PV panel string fuses, a PV panel array lightning surge arrester, a fused disconnect switch on the dc power side of the system, and circuit breakers on the ac power side of the system.

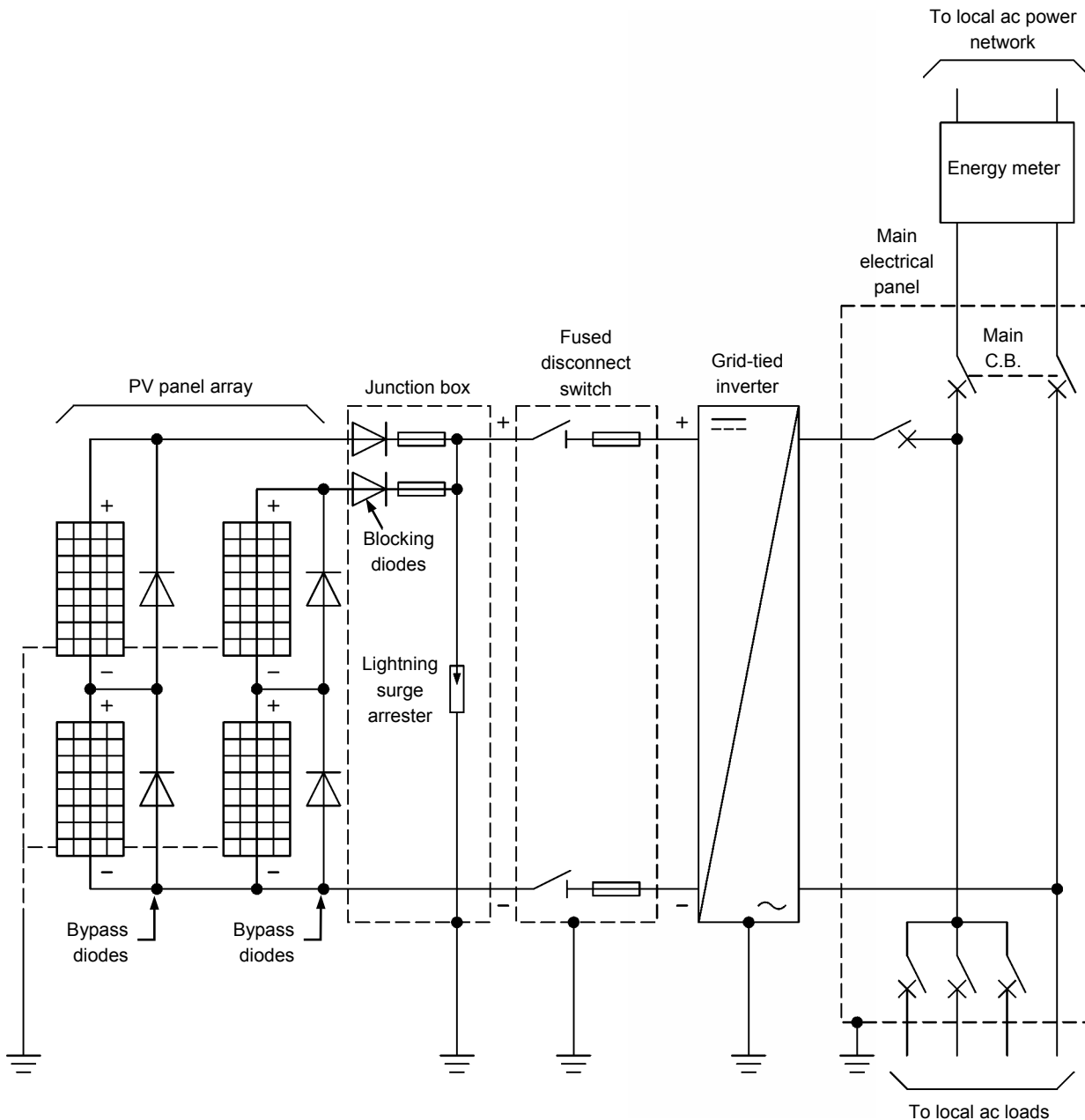


Figure 3. Diagram of a grid-tied PV system including various protection and disconnection components.

The various ancillary components mentioned above are not directly involved in the production of electricity by the grid-tied PV system. The role of these components is mainly to protect the system as well as to de-energize the major parts of the system when required. The various fuses and circuit breakers prevent overcurrent from causing damage to the system. Similarly, the PV panel array lightning surge arrester prevents overvoltage due to lightning from causing damage to the system. On the other hand, the fused disconnect switch allows the PV panel array to be completely isolated from system. This provides a means of de-energizing the dc power side of the grid-tied inverter when the PV panel array is producing electricity. Similarly, opening the main circuit breaker provides a means of de-energizing the ac power side of the system. Together, the fused disconnect switch and the main circuit breaker allow the grid-tied inverter and local ac loads to be de-energized when required, e.g., during system maintenance or an emergency situation like fire.

Most of the protection and disconnection components shown in the diagram of Figure 3 are often mandatory. In any case, all directives in the local electrical code which apply to PV systems must be respected when installing a PV system. Consequently, a sound knowledge of the local electrical code requirements is required to install any PV system properly, no matter if the PV system is a stand-alone PV system or a grid-tied PV system.

The remainder of this manual uses numerous diagrams to show the configuration of various types of PV systems as well as to explain the operation of these PV systems. In most cases, the diagrams have been simplified, i.e., the PV panel array bypass and blocking diodes as well as most of the protection and disconnection components discussed above have been omitted for the sake of clarity.

Stand-Alone PV Systems for DC Loads

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the configuration and operation of stand-alone PV systems for dc loads. You will be able to verify that the PV panel, charge controller, and battery selected for a specific stand-alone PV system can work together without causing problems. You will understand how battery charging control and battery overdischarge protection work in on-off charge controllers. You will also understand how battery charging control and battery overdischarge protection work in PWM charge controllers. You will know several common applications of stand-alone PV systems for dc loads. Finally, you will understand that using energy-efficient electric equipment is a means of reducing the size and cost of the stand-alone PV system for dc loads required in any application.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to stand-alone PV systems for dc loads
PV panel. Battery. Charge controller.
- Physical representation of a stand-alone PV system for dc loads
- Operation of a stand-alone PV system for dc loads
- Selection of the PV panel, charge controller, and battery for a specific stand-alone PV system
- On-off charge controllers
Battery charging control method. Battery overdischarge protection. Topology. Power switching device technology.
- Pulse-width modulation (PWM) charge controllers
Battery charging control method. Battery overdischarge protection. Topology. Power switching device technology.
- Applications of stand-alone PV systems for dc loads
Electric power provision in small buildings. Battery charging in recreational vehicles. Refrigeration in developing countries. Lighting of public spaces. Road signaling.
- Effect of using energy-efficient electric equipment on the size and cost of stand-alone PV systems for dc loads

DISCUSSION

Introduction to stand-alone PV systems for dc loads

Figure 4 shows a simplified diagram of a stand-alone PV system for dc loads. The system consists of a PV panel, a battery, and a charge controller.



Several elements, such as the PV panel blocking and bypass diodes, PV panel lightning surge arrester, PV panel fused disconnect switch, and load circuit-breaker panel, have been omitted in the simplified diagram of Figure 4 for the sake of clarity.

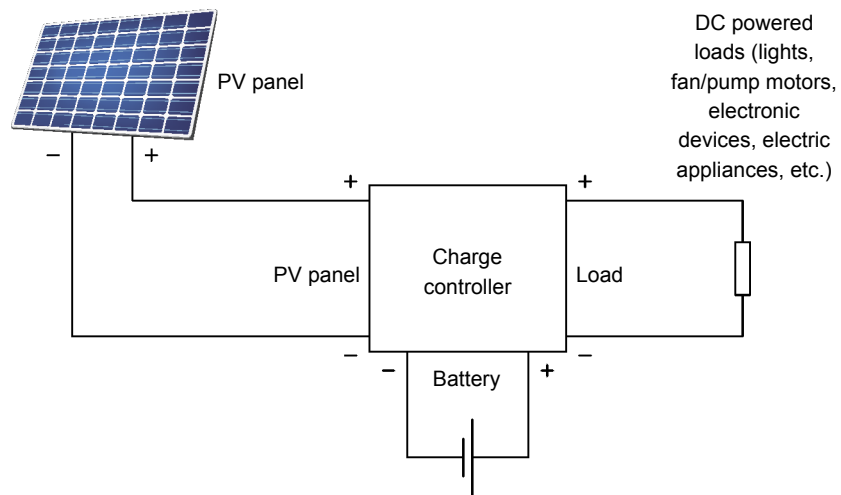


Figure 4. Simplified diagram of a stand-alone PV system for dc loads.

For each of the elements in the stand-alone PV system above, the remainder of this section states the function of the element, describes what the element consist of, and briefly explains how the element operates.

PV panel

The PV panel converts sunlight into electricity which takes the form of direct-current (dc) power. It can consist of a single panel or an array of panels connected in series, in parallel, or in series-parallel, as shown in Figure 5.



Bypass and/or blocking diodes have been omitted in Figure 5 for the sake of clarity.

The solar irradiation is also commonly referred to as the solar irradiance.

A single PV panel is often sufficient in applications where the **daily energy demand** is low (e.g., a roadside information panel). On the other hand, an array of PV panels is generally used in applications where the daily energy demand is larger (e.g., energy provision for a home). Determining the size (power) of the PV panel required in a specific stand-alone PV system mainly depends on the daily energy demand (kWh/day) and the average value of the daily solar irradiation (kWh/m² - day) at the location the PV system is installed. It also depends on other parameters of lesser importance and is a fairly complex process which is beyond the scope of this manual.

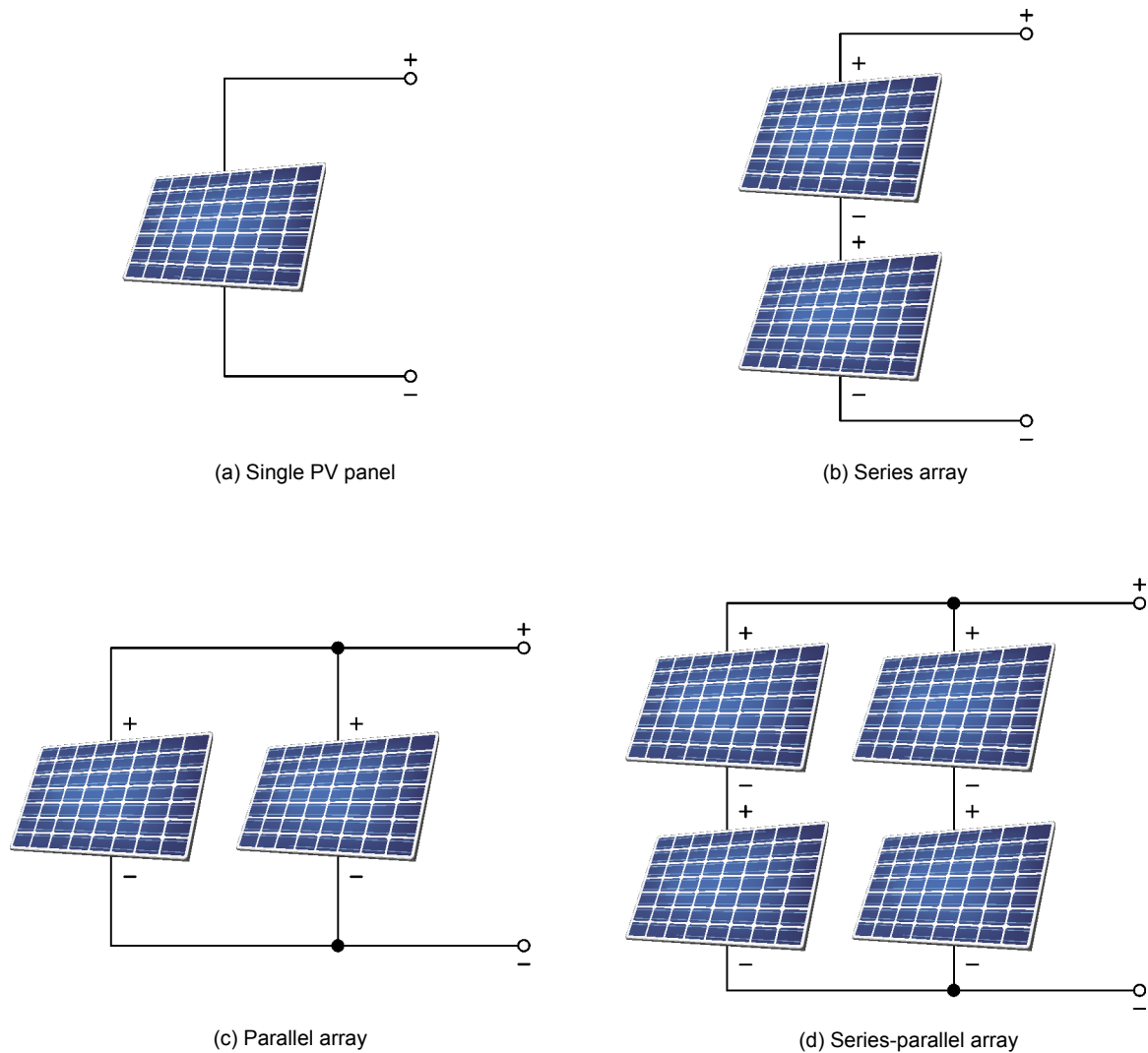


Figure 5. The PV panel can consist of a single panel or an array of panels connected in series, in parallel, or in series-parallel.

Battery

An array of batteries is commonly referred to as a battery bank.

The battery stores electricity produced by the PV panel. It consists of a single battery in low-power applications, or an array of batteries connected in series, in parallel, or in series-parallel in applications requiring more power. Deep-cycle lead-acid batteries are generally used in stand-alone PV systems because they can be discharged repeatedly to a large percentage (generally up to 80%) of their rated capacity without harm, although such repetitive deep discharges will likely shorten the battery life. Deep-cycle lead-acid batteries are also commonly used in stand-alone PV systems because they are cost effective.

The nominal voltage of the battery or battery bank in a stand-alone PV system is generally 12 V, 24 V, or 48 V. The battery voltage sets the voltage at which the PV system operates, and thus is commonly referred to as the system voltage. Figure 6 shows typical arrangements of battery banks resulting in system voltages of 12 V, 24 V, and 48 V.

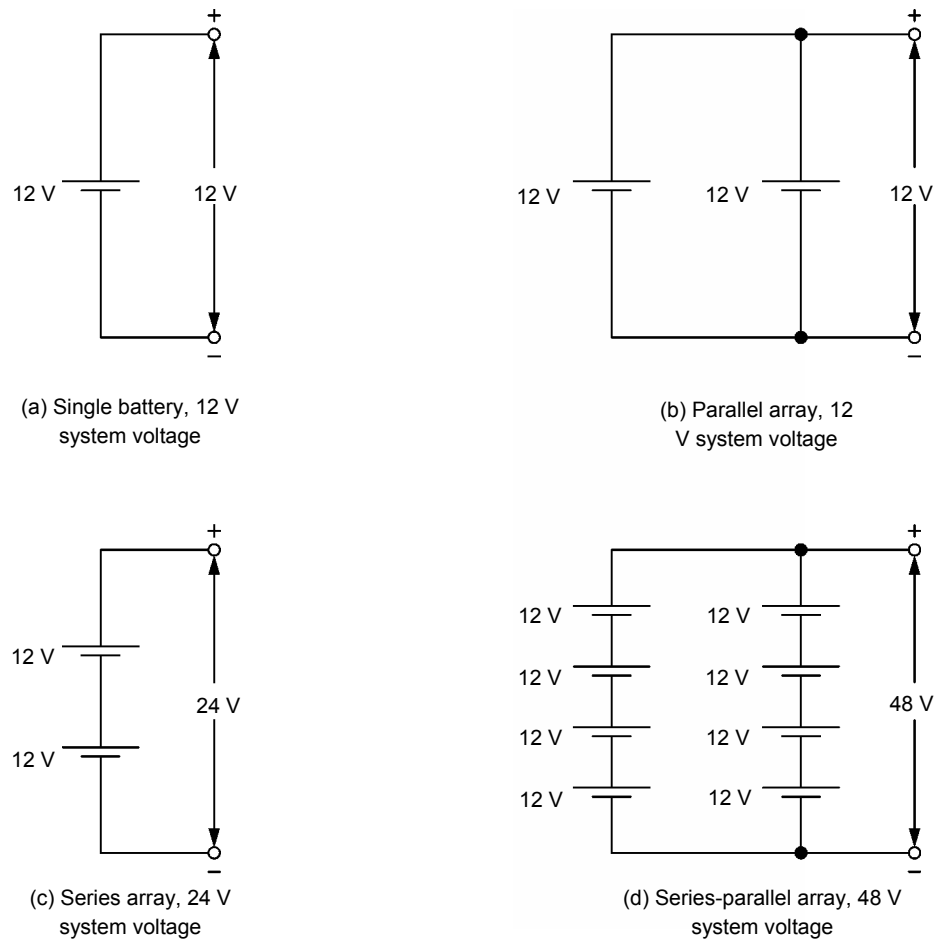


Figure 6. Typical arrangements of battery banks resulting in system voltages of 12 V, 24 V, and 48 V.

Connecting batteries in series increases the system voltage. Connecting batteries in parallel increases the system capacity (Ah), i.e., the amount of electricity that the stand-alone PV system can store. The larger the storage capacity, the longer the PV system can continue to supply power to the loads when the PV panel produces no or little electricity. The parameters listed below are the key factors used to determine the capacity (Ah) of the battery or battery bank required in a specific stand-alone PV system.

- Daily energy demand (kWh/day) of the loads.
- Average value of the daily solar irradiation (kWh/m² - day) at the location the PV system is installed.
- Desired system autonomy, i.e., the period (generally a given number of days) during which the stand-alone PV system should be able to supply power to the loads without the PV panel producing electricity.

Determining the capacity (Ah) of the battery required in a stand-alone PV system also depends on other parameters of lesser importance and is a fairly complex process which is beyond the scope of this manual.

Figure 7 shows an ideal battery and its current-voltage (I-U) characteristic curve. The I-U curve is a vertical line showing that the voltage U across an ideal battery remains constant no matter the value of the current I flowing through the battery. In other words, an ideal battery acts like an ideal voltage source. The curve also reveals that the value of the voltage U is equal to the battery voltage U_{Batt} , i.e., the battery voltage when no current flows through the battery (in other words, the open-circuit voltage). Notice that the value of voltage U_{Batt} increases slowly when

the battery is charging, thereby causing the I-U curve to slide toward the right. Inversely, the value of voltage $U_{\text{Batt.}}$ decreases slowly when the battery is discharging, thereby causing the I-U curve to slide toward the left.



In the following figures, current I is considered to be of positive polarity when the battery is charging and of negative polarity when the battery is discharging.

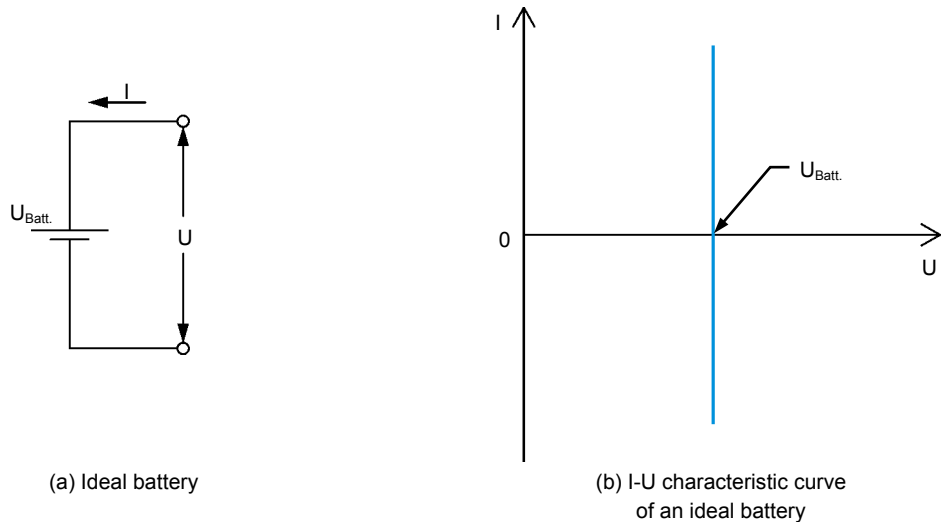


Figure 7. Ideal battery and its I-U characteristic curve.

Actual batteries, however, have internal resistance. Consequently, an actual battery is represented by an ideal battery connected in series with a resistor. Figure 8 shows the equivalent circuit of an actual battery and its current-voltage (I-U) characteristic curve. The I-U curve is a sloped line instead of a vertical line. This shows that the internal resistance causes the voltage U across an actual battery to vary with the value of the current I flowing through the battery.

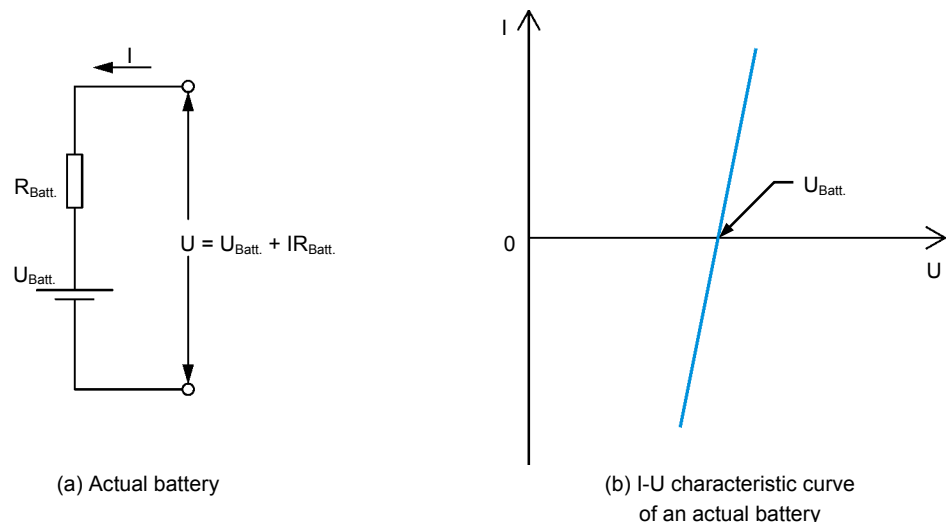


Figure 8. Equivalent circuit of an actual battery and resulting current-voltage (I-U) characteristic curve.

In fact, the voltage U across an actual battery is governed by the following equation, considering that current I is of positive polarity when the battery is charging.

$$U = U_{Batt.} + I \cdot R_{Batt.} \quad (1)$$

where $U_{Batt.}$ is the battery voltage when no current flows through the battery.

$R_{Batt.}$ is the resistance of the battery resistor.

This means that the voltage U across an actual battery is higher than the battery voltage $U_{Batt.}$ when the battery is charging and lower than the battery voltage $U_{Batt.}$ when the battery is discharging. Like an ideal battery, the value of voltage $U_{Batt.}$ increases slowly when the actual battery is charging, thereby causing the I-U curve to slide toward the right. Inversely, the value of voltage $U_{Batt.}$ decreases slowly when the actual battery is discharging, thereby causing the I-U curve to slide toward the left.

The I-U characteristic curve of actual batteries is useful to help understand the interaction between the PV panel, charge controller, and battery in a stand-alone PV system. This is studied later in this manual.

Charge controller

The **charge controller** is a power control device that controls battery charging, prevents battery overcharging, and prevents the battery from being discharged too deeply. It uses electronic circuitry and power switching devices such as contact relays and/or electronic power switches to achieve the functions mentioned above. The charge controller is the “intelligent” device around which a stand-alone PV system is built. It generally has three distinct sets of terminals: one for the PV panel, one for the battery, and one for the dc powered loads.

The following three types of charge controller are commonly available on the market: on-off, PWM, and MPPT. The battery charging control method, topology, and power switching device technology are the main factors that differentiate these three types of charge controller. Each one of these three types of charge controller is further discussed later in this manual.

Physical representation of a stand-alone PV system for dc loads

Figure 9 is an example of the physical representation of a stand-alone PV system for dc loads. In this example, the PV panel is installed on the roof of a building. The PV panel could also be installed on a support located close to the building. The charge controller and battery are generally located inside the building so they are protected from weather. The battery is located as close as possible to the charge controller in order to minimize the length of the interconnecting leads. Note that because the PV panel is installed outdoors, the leads connecting the PV panel to the charge controller are generally quite long (i.e., much longer than the leads connecting the battery to the charge controller).



Several elements, such as the PV panel blocking and bypass diodes, PV panel lightning surge arrester, PV panel fused disconnect switch, and load circuit-breaker panel, have been omitted in the simplified representation of Figure 9 for the sake of clarity.

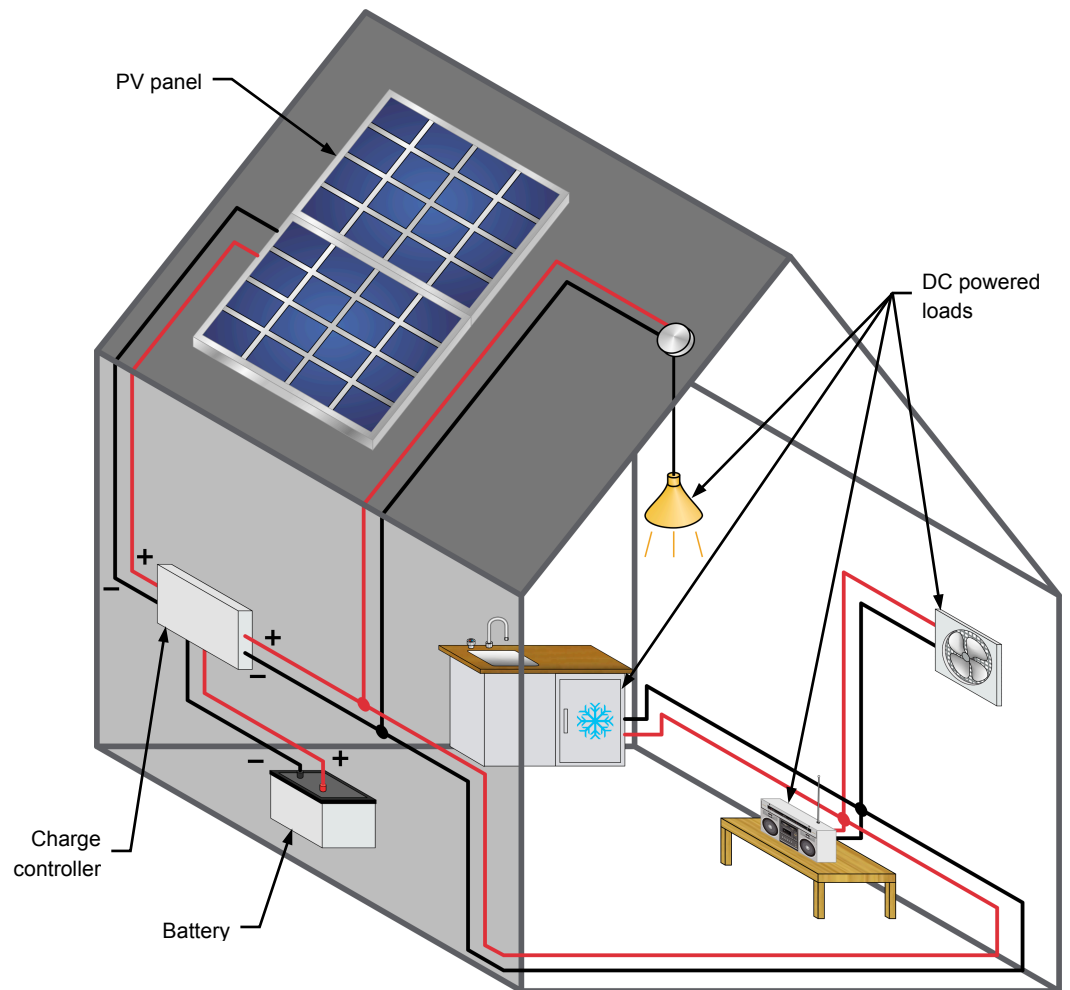


Figure 9. Simplified physical representation of a stand-alone PV system for dc loads.

Operation of a stand-alone PV system for dc loads

A stand-alone PV system for dc loads operates as follows. When sunlight strikes the PV panel, it produces electricity that is routed to the dc loads via the charge controller. Whenever the PV panel produces electricity at a rate exceeding the power demand of the dc loads, the charge controller uses the excess energy produced by the PV panel to charge the battery (when required), as shown in Figure 10. The charge controller automatically stops charging the battery or reduces the charge current to a very low value as soon as it detects that the battery is fully charged, thereby preventing battery overcharging.

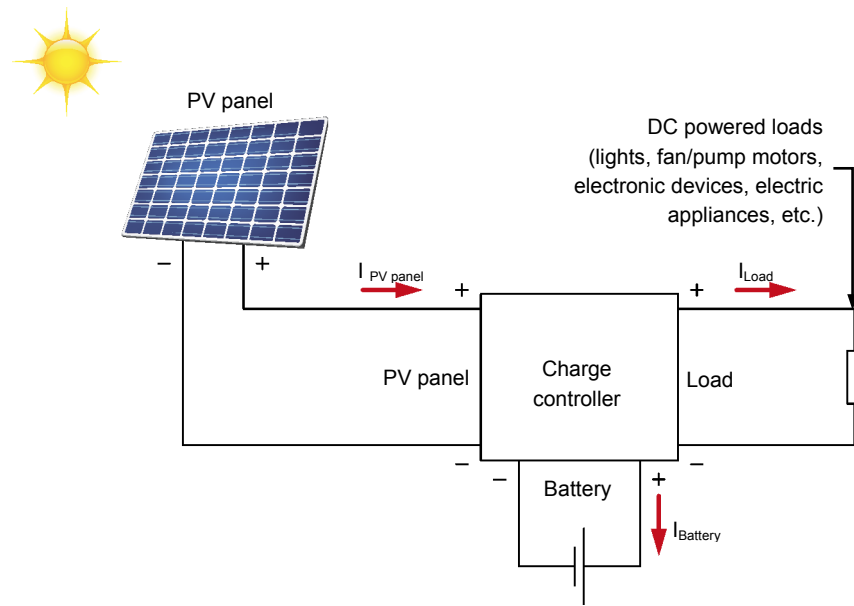


Figure 10. Daytime operation of a stand-alone PV system for dc loads when the PV panel produces electricity at a rate exceeding the power demand of the loads. This allows the battery to be charged when required.

When the PV panel produces no or little electricity, the charge controller continues to supply power to the dc loads using electricity drawn from the battery, as shown in Figure 11. The battery discharges slowly as it supplies power to the dc loads, thereby causing the battery voltage ($U_{\text{Batt.}}$) to decrease gradually. When the battery voltage decreases down to a certain value, the charge controller automatically disconnects the dc loads to prevent the battery from being discharged too deeply. Once the battery has recovered enough charge, the charge controller automatically reconnects the dc loads to the battery.

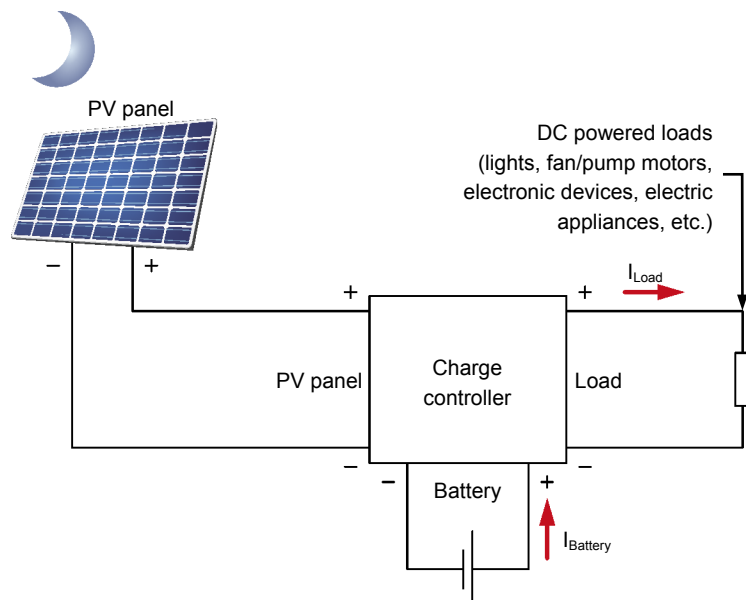


Figure 11. Nighttime operation of a stand-alone PV system for dc loads. The PV panel produces no electricity and all power supplied to the loads comes from the battery.

In brief, the charge controller is the centerpiece that manages power flow in any stand-alone PV system to ensure efficient and reliable operation. It is thus important to understand how the different types of charge controller available on

the market operate. Operation of the on-off and PWM charge controllers is studied later in this discussion. Operation of the MPPT charge controller is studied in the discussion of the next exercise in this manual.

Selection of the PV panel, charge controller, and battery for a specific stand-alone PV system

Table 1 presents the key specifications that must be considered when making sure that the PV panel, charge controller, and battery selected for a specific stand-alone PV system can work together without causing problems.

Table 1. Key specifications to be considered when making sure that the PV panel, charge controller, and battery selected for a specific stand-alone PV system can work together without problems.

Component	Specified parameter	Description of parameter
PV panel	Short-circuit current (I_{sc})	Current that flows through the PV panel when its terminals are short-circuited, measured under standard test conditions (STC).
	Open-circuit voltage (U_{oc})	Voltage which the PV panel produces when its terminals are left open, measured under standard test conditions (STC).
Charge controller	Maximum PV panel input current	Maximum current that can flow through the PV panel input terminals of the charge controller without causing overheating of the unit (and eventual damage to the unit).
	Maximum PV panel input voltage	Maximum voltage that can be applied across the PV panel input terminals of the charge controller without causing damage to the unit.
	System (load) voltage	Nominal voltage across the battery terminals and load terminals of the charge controller.
	Maximum load current	Maximum load current that can flow through the charge controller without causing overheating of the unit (and eventual damage to the unit).
Battery	Nominal voltage	Nominal voltage across the battery terminals.



In most charge controllers, the maximum PV panel input current and the maximum load current have the same value.

The following steps must be performed when making sure that the PV panel, charge controller, and battery selected for a specific stand-alone PV system can work together without causing problems.

1. The maximum PV panel input current of the charge controller must be larger than the short-circuit current (I_{sc}) of the PV panel. This ensures that the charge controller can route all the current which the PV panel can produce without overheating. In other words, this ensures that damage to the charge controller due to overheating cannot occur.

2. The maximum PV panel input voltage of the charge controller must be higher than the open-circuit voltage (U_{oc}) of the PV panel. This ensures that the PV panel cannot cause overvoltage at the PV panel input terminals of the charge controller (and ensuing damage to the controller). Note that the open-circuit voltage of the PV panel is measured under standard test conditions (STC) which stipulate a PV panel temperature of 25°C. The open-circuit voltage of a PV panel, however, decreases slightly as its temperature increases and vice versa. Consequently, when a stand-alone PV system is subject to operation in cold climate, the value of the open-circuit voltage of the PV panel must be corrected (to take the effect of temperature into account) before checking if the maximum PV panel input voltage of the charge controller is sufficient. For instance, let's consider a stand-alone PV system in which the PV panel temperature can be as low as -10°C during normal operation. The PV panel in this system has an open-circuit voltage of 80 V (under STC) which varies at a rate of -0.4%/°C. This results in an open-circuit voltage of 91.2 V at a temperature of -10°C. This is significantly higher than the specified open-circuit voltage of 80 V. The maximum PV panel input voltage of the charge controller, therefore, must be higher than 91.2 V (not 80 V) to ensure the PV panel cannot cause overvoltage.
3. The nominal voltage of the battery must be the same as the system (load) voltage. Naturally, all dc loads connected to the stand-alone PV system must be designed to operate at this voltage.
4. The system (load) voltage and maximum load current of the charge controller determine the maximum power that the stand-alone PV system can supply to the dc loads. The power rating of any one of the dc loads connected to the system must not exceed the maximum power that the system can supply, otherwise overheating of the charge controller will occur.

On-off charge controllers

On-off charge controllers are the oldest type of charge controller. They are cheaper than the other types of charge controller but provide lower battery charging performance that may reduce battery life. This section briefly explains how on-off charge controllers operate. It also presents two topologies commonly used in on-off charge controllers and states the types of power switching devices that are commonly used in these controllers.

Battery charging control method

The battery is charged by the current provided by the PV panel with no control of the magnitude of this current. The value of the charge current is simply equal to the value of the current the PV panel produces at the solar irradiation value at which it is operating. The on-off charge controller simply stops battery charging when the battery voltage reaches a certain value, called the voltage regulation (VR) setpoint, at which the battery is considered to be fully charged. The charge controller resumes battery charging when the battery voltage decreases to a certain value, called the voltage regulation reconnect (VRR) setpoint. Battery charging control in an on-off charge controller is illustrated in Figure 12.

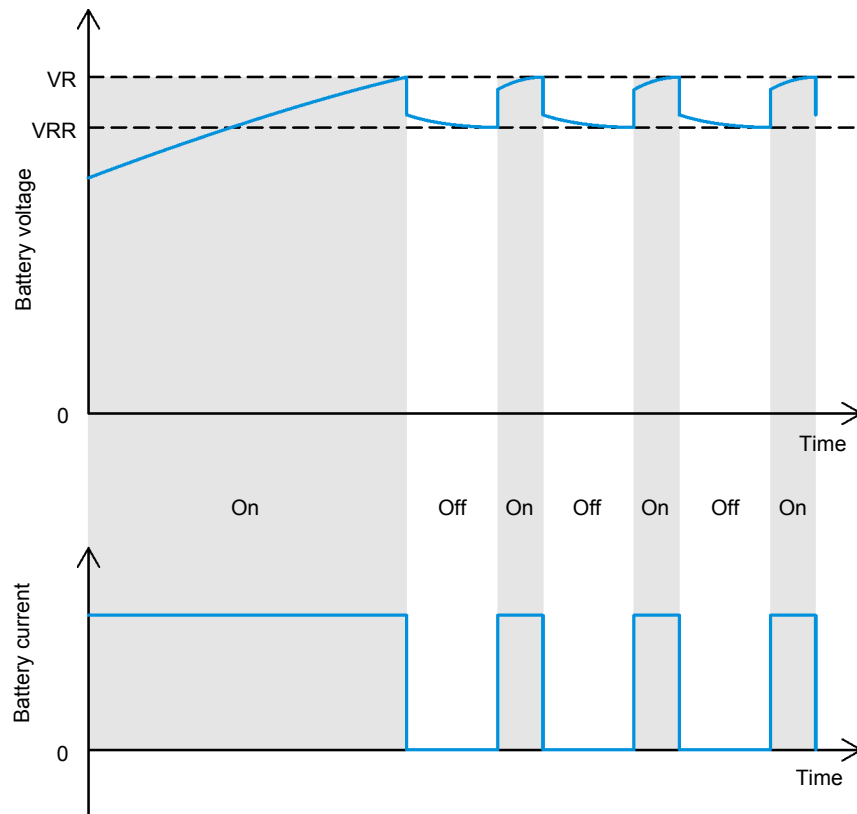


Figure 12. Battery charging control in an on-off controller.

Table 2 shows typical values of the VR and VRR setpoints that can be used in on-off charge controllers for various types of lead-acid batteries commonly available on the market. The values presented are for 12 V batteries. The values of the VR and VRR setpoints which the on-off charge controller uses to charge the battery whenever required are those given under the heading *Normal charge* in the table. Every 10 to 20 days, some on-off charge controllers perform an equalization charge of the battery. An equalization charge is simply a charging cycle that slightly overcharges the battery to equalize the state-of-charge of the battery cells. For this purpose, the values of the VR and VRR setpoints which the charge controller uses during an equalization charge (see heading *Equalization charge* in the table) are slightly higher than those used during a normal charge.



In on-off charge controllers that do not have the charge equalization feature, the values of the VR and VRR setpoints used during a normal charge may be increased slightly (generally by about 0.3 V to 0.6 V).

Table 2. Typical values of the VR and VRR setpoints that can be used in on-off charge controllers for various types of 12 V lead-acid batteries.

Type of lead-acid battery	Normal charge		Equalization charge	
	VR (V)	VRR (V)	VR (V)	VRR (V)
Flooded, vented	14.4	13.5	15.3	14.1
Flooded, sealed	14.4	13.5	15.0	13.8
AGM	14.1	13.2	14.4	13.5
GEL	14.1	13.2	14.7	13.5

The values of the VR and VRR setpoints used in a particular on-off charge controller are normally indicated in the documentation provided by the manufacturer.

Battery overdischarge protection

The on-off charge controller prevents overdischarge of the battery by disconnecting the load when the battery voltage decreases down to a certain value, called the low-voltage disconnect (LVD) setpoint. The controller automatically reconnects the loads when the battery voltage increases up to a certain value, called the low-voltage reconnect (LVR) setpoint. Battery overdischarge protection is illustrated in Figure 13.

The value of the LVD setpoint mainly depends on the maximum depth of discharge (DOD) recommended by the battery manufacturer. The value of the LVD setpoint is also influenced by the value of the discharge current that is expected. This is because the battery internal resistance makes the voltage across the battery decrease as the value of the discharge current increases. Table 3 shows approximate values of the LVD setpoint that can be used to implement battery overdischarge protection for different values of maximum DOD and discharge rate (i.e., discharge current expressed as a function of the battery capacity C). The values presented are for 12 V batteries. The higher the maximum DOD value that is acceptable, the lower the value of the LVD setpoint. Also, for any maximum DOD value, the higher the discharge rate expected, the lower the value of the LVD setpoint.

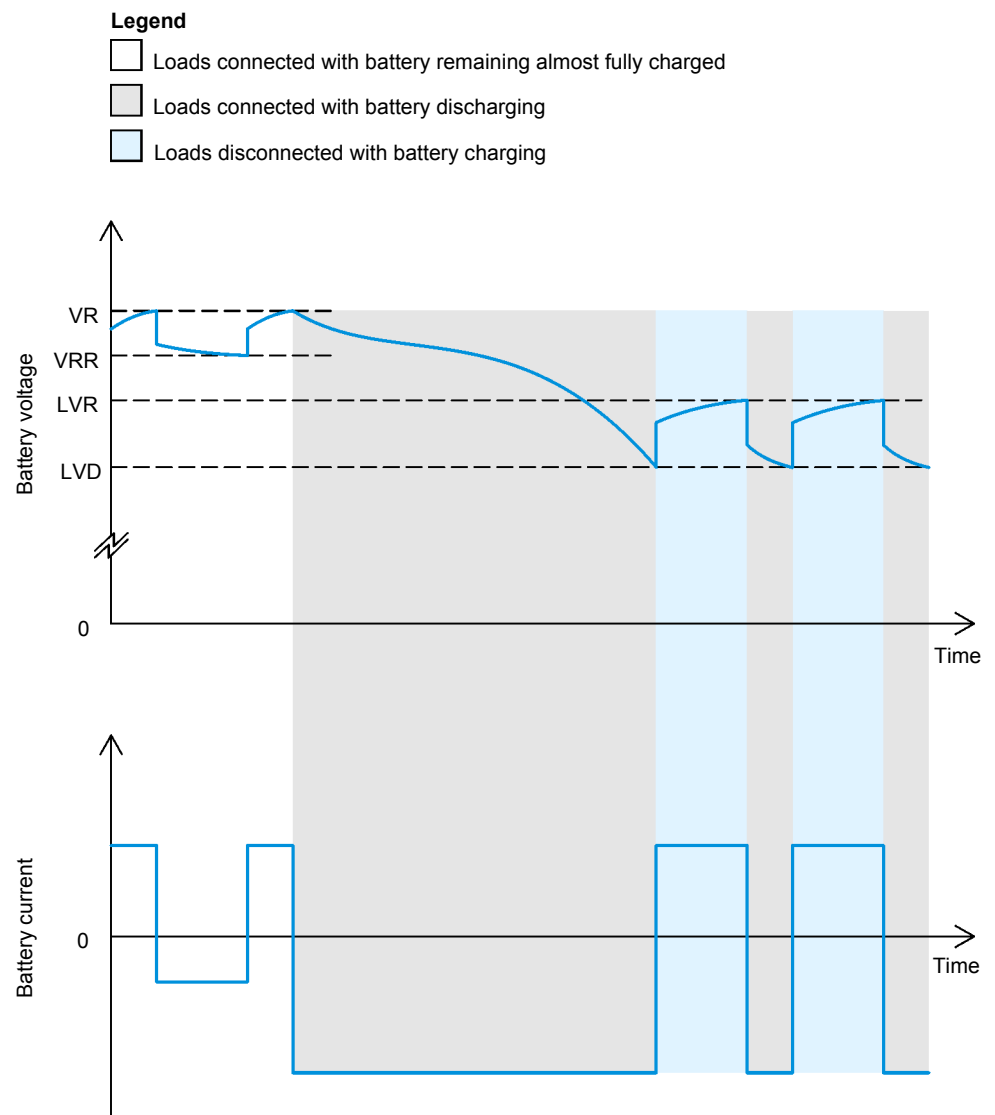


Figure 13. Battery overdischarge protection.

Table 3. Approximate values of the LVD setpoint that can be used to implement battery overdischarge protection for different values of maximum DOD and discharge rate (12 V batteries).

Maximum DOD	LVD setpoint			
(%)	@ C/200 (V)	@ C/60 (V)	@ C/20 (V)	@ C/10 (V)
20	12.8	12.7	12.5	12.4
30	12.7	12.6	12.4	12.3
40	12.5	12.5	12.3	12.2
50	12.4	12.3	12.2	12.1
60	12.2	12.1	12.0	11.9
70	12.0	11.9	11.9	11.8
80	11.8	11.8	11.7	11.5

The value of the LVR setpoint is mainly governed by the minimum state of charge (SOC) that the battery should recover before the load is reconnected. The value of the LVR setpoint is also influenced by the value of the charge current that is expected. This is because the battery internal resistance makes the voltage across the battery increase as the value of the charge current increases. Table 4 shows approximate values of the LVR setpoint that can be used to implement battery overdischarge protection for different values of minimum SOC and charge rate (i.e., charge current expressed as a function of the battery capacity C). The values presented are for 12 V batteries. The higher the minimum SOC value that is required before the loads are reconnected, the higher the value of the LVR setpoint. Also, for any minimum SOC value, the higher the charge rate expected, the higher the value of the LVR setpoint.

Table 4. Approximate values of the LVR setpoint that can be used to implement battery overdischarge protection for different values of minimum SOC and charge rate (12 V batteries).

Minimum SOC	LVR setpoint			
(%)	@ C/200 (V)	@ C/60 (V)	@ C/20 (V)	@ C/10 (V)
30	12.5	12.6	12.8	12.9
40	12.7	12.8	13.0	13.1
50	12.9	13.0	13.3	13.4
60	13.2	13.3	13.5	13.6
70	13.5	13.6	13.9	14.0
80	13.9	14.0	14.5	14.6

The values of the LVD and LVR setpoints used in a particular charge controller are normally indicated in the documentation provided by the manufacturer.

Topology

Stopping battery charging can be done by short-circuiting the PV panel. This is achieved by closing a power switching device connected in parallel with the PV panel, as shown in Figure 14. In this case, the charge controller is said to be of the shunt on-off type. Note that a blocking diode is required to prevent short-circuiting the battery when the PV panel is short-circuited by the power switching device. Battery overdischarge protection is achieved by opening a power switching device connected between the battery and the dc loads.

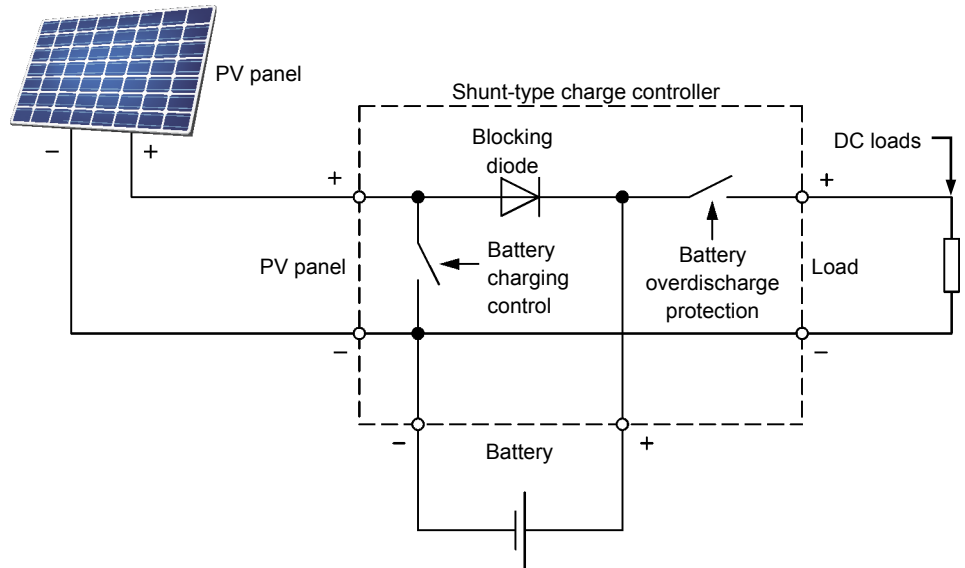


Figure 14. Topology of shunt-type charge controllers.

Stopping battery charging can also be done by disconnecting the PV panel from the battery. This is achieved by opening a power switching device connected between the PV panel and the battery, as shown in Figure 15. In this case, the charge controller is said to be of the series on-off type. A blocking diode may or may not be provided depending on the type of power switching device that is used in the charge controller. Battery overdischarge protection is achieved the same way as in a shunt-type charge controller, i.e., by opening a power switching device connected between the battery and the dc loads.

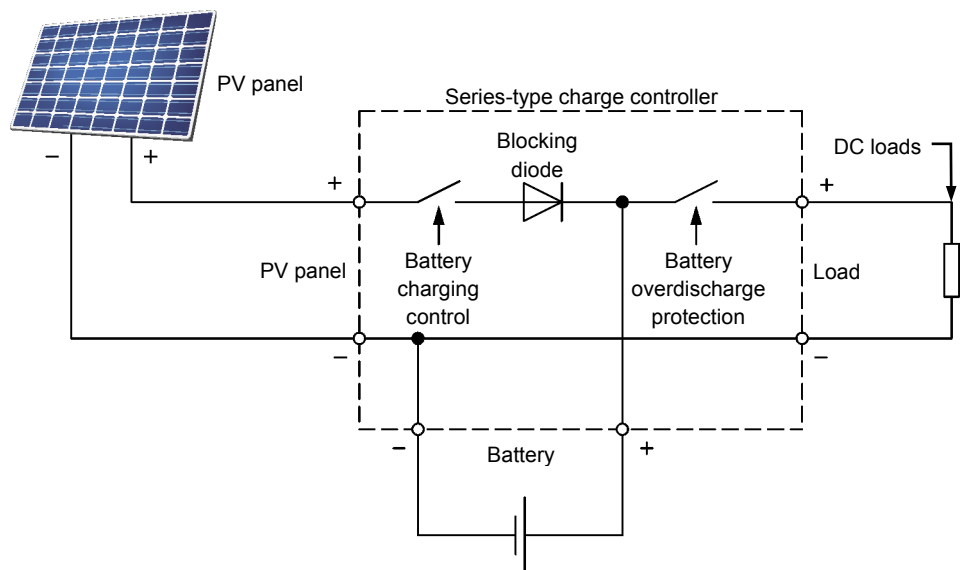


Figure 15. Topology of series-type charge controllers.

Power switching device technology

A contact relay, a **solid-state relay (SSR)**, or a power transistor of the **MOSFET** type is used in on-off charge controllers to implement battery charging. On the other hand, a contact relay or an SSR is used to implement battery overdischarge protection.

Pulse-width modulation (PWM) charge controllers

Design-wise, PWM charge controllers are newer than on-off charge controllers. This is particularly true of the battery charging control method used in PWM charge controllers. PWM charge controllers are more expensive than on-off charge controllers but provide better battery charging performance. This generally helps in maximizing battery life. This section briefly explains how PWM charge controllers operate. It also presents topologies commonly used in PWM charge controllers and states the types of power switching devices that are commonly used in these controllers.

Battery charging control method

The battery is charged by pulses of current provided by the PV panel. The PWM charge controller produces the pulses of current by momentarily stopping battery charging at a fast rate (e.g., 300 Hz). The PWM charge controller can adjust the width of the charge current pulses to change the average value of the charge current as required. This technique is referred to as **pulse-width modulation (PWM)**, hence the name PWM charge controller.

An example is shown in Figure 16. Large changes in the width of the charge current pulses are used in this example. This results in large step variations in the average value of the charge current that clearly demonstrate the effect which changing the width of the charge current pulses produces. Gradual variation of the average value of the charge current can be achieved by slightly varying the pulse width from one pulse of charge current to the next. Note that the amplitude A of the charge current pulses is equal to the value of the current produced by the PV panel. The value of this current depends on the size of the PV panel and the solar irradiation value at which the PV panel is operating. Consequently, the average value of the charge current can be adjusted to any value up to the amplitude A of the charge current pulses.

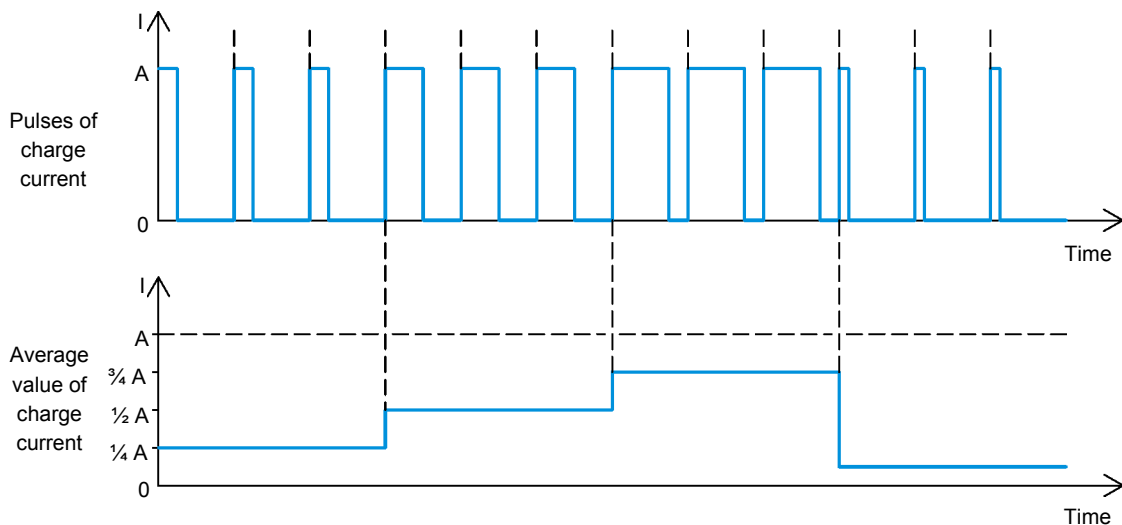


Figure 16. PWM charge controllers use pulse-width modulation (PWM) to adjust the average value of the charge current as required.

At the beginning of battery charging, maximum charge current is generally required. Consequently, charge current pulses of maximum width are required to make the average value of the charge current maximum (i.e., equal to the value of the current the PV panel is producing). In fact, most PWM charge controllers simply turn battery charging on (i.e., cease to momentarily stop battery charging to produce pulses of charge current) in order to make the average value of the charge current equal to the value of the current the PV panel is producing. This stage of battery charging is referred to as the bulk stage. The bulk stage of battery charging is in fact similar to battery charging using an on-off charge controller.

When the battery voltage reaches the voltage regulation (VR) setpoint, the PWM charge controller gradually decreases the average value of the charge current (by producing charge current pulses whose width decreases gradually) so that the battery voltage remains at the VR setpoint. This stage of battery charging is referred to as the absorption stage. The absorption stage allows the battery to be charged up to its nominal capacity C without affecting the battery life, something that most on-off charge controllers can hardly achieve.

When the average value of the charge current has decreased to a certain value, the PWM charge controller considers that the battery is fully charged, but continues battery charging using a lower voltage setpoint called the float voltage (V_{Float}). The PWM charge controller achieves this by adjusting the average value of the charge current (by adjusting the width of the charge current pulses) so that the battery voltage remains at the V_{Float} setpoint. This allows a charge current of low value to flow which maintains the full charge of the battery. This stage of battery charging is referred to as the float stage. The low charge current flowing during the float stage of battery charging is commonly referred to as the trickle current.

The three stages of this battery charging control method, which is commonly referred to as modified constant-voltage charging, are illustrated in Figure 17.

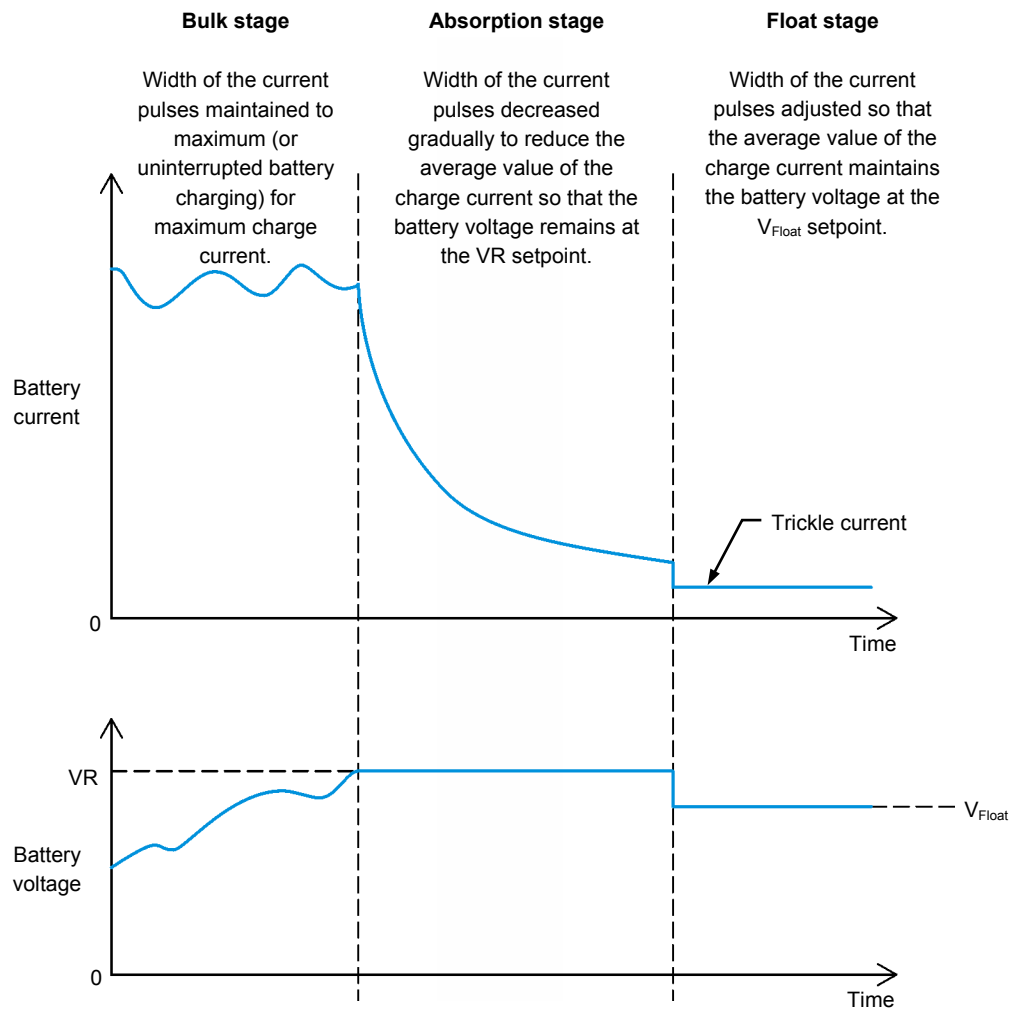


Figure 17. Modified constant-voltage charging used in PWM charge controllers.

Table 5 shows typical values of the VR and V_{Float} setpoints that can be used in PWM charge controllers for various types of lead-acid batteries commonly available on the market. The values presented are for 12 V batteries. The values of the VR and V_{Float} setpoints which the PWM charge controller uses to charge the battery whenever required are those given under the heading *Normal charge* in the table. Every 10 to 20 days, some PWM charge controllers perform an equalization charge of the battery. For this purpose, the value of the VR setpoint which the charge controller uses during an equalization charge (see heading *Equalization charge* in the table) is slightly higher than that used during a normal charge.

Table 5. Typical values of the VR and V_{Float} setpoints that can be used in PWM charge controllers for various types of 12 V lead-acid batteries.

Type of lead-acid battery	Normal charge		Equalization charge
	VR (V)	V_{Float} (V)	VR (V)
Flooded, vented	14.4	13.5	15.0
Flooded, sealed	14.7	13.8	15.0
AGM	14.1	13.5	14.4
GEL	14.4	13.5	14.7

In brief, battery charging in PWM charge controllers is better controlled than in on-off charge controllers. Consequently, PWM charge controllers are generally better than on-off charge controllers for optimizing battery capacity as well as for maximizing battery life.

Battery overdischarge protection

PWM charge controllers prevent overdischarge of the battery the same way as on-off charge controllers. Refer to section *On-off charge controllers* of this discussion for more detail.

Topology

PWM charge controllers use the same topologies as on-off charge controllers. When the shunt-type topology is used (see Figure 14 in the previous section), battery charging is momentarily stopped (to produce pulses of charge current) by closing a power switching device connected in parallel with the PV panel at a fast rate. In this case, the charge controller is said to be of the shunt PWM type. On the other hand, when the series-type topology is used (see Figure 15 in the previous section), battery charging is momentarily stopped by opening a power switching device connected between the PV panel and the battery at a fast rate. In this case, the charge controller is said to be of the series PWM type. In both topologies, battery overdischarge protection is achieved by opening a power switching device connected between the battery and the dc loads.

Power switching device technology

A solid-state relay (SSR) or a power transistor of the MOSFET type is used in PWM charge controllers to implement battery charging. On the other hand, a contact relay or an SSR is used to implement battery overdischarge protection.

Applications of stand-alone PV systems for dc loads

Stand-alone PV systems for dc loads are used in a variety of applications. This section describes some common applications of stand-alone PV systems for dc loads.

Electric power provision in small buildings

Stand-alone PV systems for dc loads are commonly used to provide dc power to low-power electric equipment in small buildings that are not connected to the grid (e.g., farm buildings, green houses, etc.) or that are in remote locations (e.g., hunting/fishing cabins, mountain refuges, etc.). The dc powered equipment in this type of application generally consist of low-power devices such as lighting fixtures, fan/pump motors, refrigerators, AM/FM radios, etc.



Figure 18. Small cabin powered by a stand-alone PV system.

Battery charging in recreational vehicles

Several low-power electrical devices (lighting fixtures, fan/pump motors, refrigerator, LP gas detector, etc.) in a recreational vehicle (RV) operate from dc power. A deep-cycle, lead-acid battery supplies dc power to these devices when the RV is not connected to an ac power outlet. A charge controller in the RV can use electricity produced by a PV panel to supply dc power to these devices and keep the battery charged. In this case, the dc power system in an RV operates exactly like a stand-alone PV system for dc loads. Note that when the RV is connected to an ac power outlet, the charge controller can draw power from the grid and convert it to dc power to supply the dc powered devices and keep the battery charged.



Figure 19. In recreational vehicles, PV panels can be used to supply electricity to dc powered devices and keep the battery charged.

Refrigeration in developing countries

In developing countries, keeping the vaccines and blood required to take care of the local population is challenging because electric power is not always available, or if available, may be subject to interruptions. DC powered refrigerators supplied by stand-alone PV systems are a very effective means of keeping vaccines and blood in these countries.

Lighting of public spaces

Some lighting systems for public spaces, such as streets, gardens, public transportation stops, etc., operate from dc power produced by stand-alone PV systems. In such systems, each light fixture is provided with its own stand-alone PV system. Solar-powered lighting systems do not require connection to the grid nor wires to route power from one light fixture to the next.



Figure 20. Solar-power street lighting system.

Road signaling

Similarly to lighting systems for public spaces, some road signaling devices, such as traffic lights, illuminated stop signs, roadside information panels, etc., operate from dc power produced by their own stand-alone PV system.



Figure 21. Solar-power traffic lights.

Effect of using energy-efficient electric equipment on the size and cost of stand-alone PV systems for dc loads

The daily energy demand (expressed in Wh/day or kWh/day) of each of the various loads that a stand-alone PV system has to supply must be considered to establish the total daily energy demand that is expected. The daily energy demand of a load is established by multiplying the power rating (expressed in W or kW) of the load by the time (expressed in hours) the load is expected to be used every day. The higher the total daily energy demand that is expected, the larger the size (in terms of either rated power or current capacity) of the PV panel, electronic devices (e.g., the charge controller), and battery required in the stand-alone PV system to ensure that the demand is met. This has a direct impact on the cost of the stand-alone PV system since the cost of each of these components increases with size. Consequently, reducing the total daily energy demand is highly desirable because it reduces the size, and thus the cost, of the stand-alone PV system required in any application.

Reduction in the total daily energy demand can be done by reducing the time of use of the loads. However, this alternative is limited, and sometimes it is simply not applicable. Reduction in the total daily energy demand can also be achieved by using electric equipment that is energy efficient, i.e., loads that require less power to perform the same task. For instance, using LED lamps instead of conventional incandescent lamps for lighting is a good means of reducing the total daily energy demand, and thus, the size of a stand-alone PV system for dc loads. This is because an LED lamp generally uses about 5 to 7 times less energy than a conventional incandescent lamp to produce an equivalent amount of light.

In conclusion, let's consider a cabin where two 60 W incandescent lamps are judged sufficient for lighting. Considering that the lamps are lit 4 hours a day, this results in a daily energy demand of 480 Wh. On the other hand, using LED lamps that are assumed to consume 5 times less energy than the incandescent lamps results in a daily energy demand of 96 Wh, a substantial reduction of 384 Wh in the total daily energy demand. Over a complete year, this represents a reduction in the total energy demand of about 140 kWh.



Figure 22. LED lamps use about 5 to 7 times less energy than conventional incandescent lamps to produce an equivalent amount of light.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Emulated PV panel settings
- Main components of a stand-alone PV system for dc loads
- Setting up a stand-alone PV system for dc loads
- Stand-alone PV system operation
 - PV panel producing no electricity. PV panel producing electricity at a rate below the power demand of the dc loads. PV panel producing electricity at a rate equal to the power demand of the dc loads. PV panel producing electricity at a rate exceeding the power demand of the dc loads.*
- Battery charging
- Comparing the energy consumption of two different types of dc lamps
- Battery overdischarge protection

PROCEDURE

WARNING



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

Setup and connections

In this section, you will set up and connect the equipment required to perform the exercise.

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

Install the equipment in the workstation. You will use this equipment later in this exercise to set up a stand-alone PV system for dc loads.



*Before continuing this exercise, measure the open-circuit voltage of the **48V Lead-Acid Battery Pack**. If the open-circuit voltage is lower than 51.2 V, ask your instructor for assistance as the **48V Lead-Acid Battery Pack** is probably not fully charged. Appendix D of this manual indicates how to fully charge the **48V Lead-Acid Battery Pack** before a lab period.*

Make the connections required to earth the equipment properly.



If necessary, check with the instructor to ensure that the connections you made provide proper earthing of the equipment.

2. Make sure that the main power switch of the **4 Quadrant Power Supply and Dynamometer Controller** is set to the **O** (off) position, then connect its **Power Input** to an ac power outlet that is properly protected.

Make sure that the main power switch of the **AC 24V Power Supply** is set to the **O** (off) position, then connect its **Power Input** to an ac power outlet that is properly protected.



If necessary, check with the instructor to ensure that the ac power outlets to which you connect the equipment are properly protected.

3. Connect the **Power Input** of the **Data Acquisition and Control Interface** to the **AC 24V Power Supply**.
4. Ask your instructor to turn on (i.e., to unlock) electric power at your workstation, if applicable.
5. Turn the **AC 24V Power Supply** on.
6. Turn the **4 Quadrant Power Supply and Dynamometer Controller** on, then set the **Operating Mode** switch to **Power Supply**.
7. Connect the USB port of the **Data Acquisition and Control Interface** to a USB port of the host computer.

Connect the USB port of the **4 Quadrant Power Supply and Dynamometer Controller** to a USB port of the host computer.

8. 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 **4 Quadrant Power Supply and Dynamometer Controller** are detected. Make sure that the **Basic Computer-Based Instrumentation** function for the **Data Acquisition and Control Interface** is available. Also make sure that the **Solar Panel Emulator** and **Lead-Acid Battery Charger** functions for the **4 Quadrant Power Supply and Dynamometer Controller** are available. Select the network voltage and frequency of your local ac power network, then click the **OK** button to close the **LVDAC-EMS Start Up** window.

Emulated PV panel settings

In this section, you will set the size of the emulated PV panel that will be used to implement a stand-alone PV system for dc loads.

9. 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 **4 Quadrant Power Supply and Dynamometer Controller** operate like a solar (PV) panel. The output terminals of the power supply are the terminals of the emulated PV panel.
 - Make sure that the **Solar Irradiance Control** parameter is set to **Slider**. This allows the solar irradiance to be controlled manually.
 - Set the **Solar Irradiance** parameter to 1000 W/m².
 - Set the **Number of PV modules in series** parameter to 8. Set the **Number of PV modules in parallel** parameter to 16. These two settings set the size of the emulated PV panel to 8 PV modules in series and 16 PV modules in parallel.
 - Make sure that the **Status** parameter is set to **Stopped**. This prevents the emulated PV panel from producing electricity even if the solar irradiation is currently set to 1000 W/m².

Main components of a stand-alone PV system for dc loads

*In this section, you will gather the key specifications of the emulated PV panel, **48V Lead-Acid Battery Pack**, **DC 48V PWM Charge Controller**, and **DC 48V Lamps** module. You will then use these specifications to verify that these pieces of equipment can work together without causing problems.*

10. Observe that the electrical specifications of each PV module in the emulated PV panel are indicated in the **Four-Quadrant Dynamometer/Power Supply** window.



In the remainder of this exercise, the emulated PV panel is also simply referred to as the PV panel.

According to the information provided in the [Four-Quadrant Dynamometer/Power Supply](#) window, what are the short-circuit current (I_{sc}) and open-circuit voltage (U_{oc}) of the emulated PV panel, at a solar irradiation of 1000 W/m²?

Short-circuit current (I_{sc}): _____ A

Open-circuit voltage (U_{oc}): _____ V

- 11.** In the [Four-Quadrant Dynamometer/Power Supply](#) window, enable continuous refresh of the meters and start the [Solar Panel Emulator](#). This makes the emulated PV panel produce electricity because the solar irradiation is currently set to 1000 W/m².

In the [Four-Quadrant Dynamometer/Power Supply](#) window, observe that the voltage which the emulated PV panel produces is equal to the open-circuit voltage (about 78 V). This is normal because the terminals of the emulated PV panel (i.e., the output terminals of the power supply in the [4 Quadrant Power Supply and Dynamometer Controller](#)) are currently open.

The voltage which certain PV panels produce when their terminals are left open can be high enough to cause severe electric shocks. Therefore, care must always be exercised when manipulating PV panels (more specifically the connection terminals of PV panels). Appendix C provides information on the safe handling of PV panels.

In the [Four-Quadrant Dynamometer/Power Supply](#) window, stop the [Solar Panel Emulator](#).

- 12.** Observe the [48V Lead-Acid Battery Pack](#). Notice that it consists of 4 sealed lead-acid batteries connected in series.



In the remainder of this exercise, the [48V Lead-Acid Battery Pack](#) is also referred to as the battery.

What are the battery voltage and battery capacity?

Battery voltage: _____ V

Battery capacity: _____ Ah

- 13.** Table 6 provides the main specifications of the [DC 48V PWM Charge Controller](#).

Table 6. Main specifications of the DC 48V PWM Charge Controller.

Parameter	Value
Maximum PV panel input current	7 A
Maximum PV panel input voltage	100 V
System voltage	48 V
Maximum load current	7 A

Based on the above specifications, can the **DC 48V PWM Charge Controller** be used with the emulated PV panel? Explain briefly.



Assume that the minimum operating temperature of the PV panel is 25°C.

Does the **DC 48V PWM Charge Controller** match the battery (system) voltage?

☐ Yes ☐ No

What is the maximum amount of power which the **DC 48V PWM Charge Controller** can deliver to loads?

14. Observe the **DC 48V Lamps** module. The voltage rating of the incandescent lamp and the LED lamp in the **DC 48V Lamps** module is 48 V. Are these lamps compatible with the battery (system) voltage?

☐ Yes ☐ No

Note the power rating of the incandescent lamp and the LED lamp in the **DC 48V Lamps** module. Can the **DC 48V PWM Charge Controller** supply dc power to these lamps without a problem? Explain briefly.

Setting up a stand-alone PV system for dc loads

*In this section, you will set up a stand-alone PV system for dc loads using the **Data Acquisition and Control Interface**, emulated PV panel, **48V Lead-Acid Battery Pack**, **DC 48V PWM Charge Controller**, and **DC 48V Lamps** module.*



*In the remainder of this exercise, the **DC 48V PWM Charge Controller** is also simply referred to as the PWM charge controller.*

15. Use the **Data Acquisition and Control Interface**, emulated PV panel, **48V Lead-Acid Battery Pack**, **DC 48V PWM Charge Controller**, and **DC 48V Lamps** module to set up the stand-alone PV system for dc loads shown in the diagram of Figure 23. In this system, the dc loads consist of the incandescent lamp and the LED lamp in the **DC 48V Lamps** module. The battery, the PV panel, and the dc loads should be connected to the PWM charge controller in the proper order. Proceed as follows to connect these components to the PWM charge controller.

- First, connect the **48V Lead-Acid Battery Pack** to the **Battery** terminals of the PWM charge controller via current input **I1** of the **Data Acquisition and Control Interface**. On the **48V Lead-Acid Battery Pack**, close the circuit breaker by setting its lever to the **I** (on) position. The PWM charge controller turns on and performs a short start-up routine as soon as the circuit breaker closes. Observe the middle LED (battery status LED) in the set of three LEDs on the PWM charge controller. This LED indicates the battery's state of charge (LED lit in green = full charge, LED lit in orange = middle charge, LED lit in red = low charge, LED blinking red = fully discharged). The battery status LED should be lit in green if the battery is fully charged, as requested at the beginning of the exercise.
- Then, connect the emulated PV panel to the **PV panel** terminals of the PWM charge controller.
- Finally, connect the dc loads (incandescent and LED lamps in the **DC 48V Lamps** module) to the **Load** terminals of the PWM charge controller via current input **I2** of the **Data Acquisition and Control Interface**. Before making the connections, make sure that the lamp switches on the **DC 48V Lamps** module are set to the **O** (off) position. This prevents load current from flowing, and arcing from occurring, when the lamps are connected to the PWM charge controller.

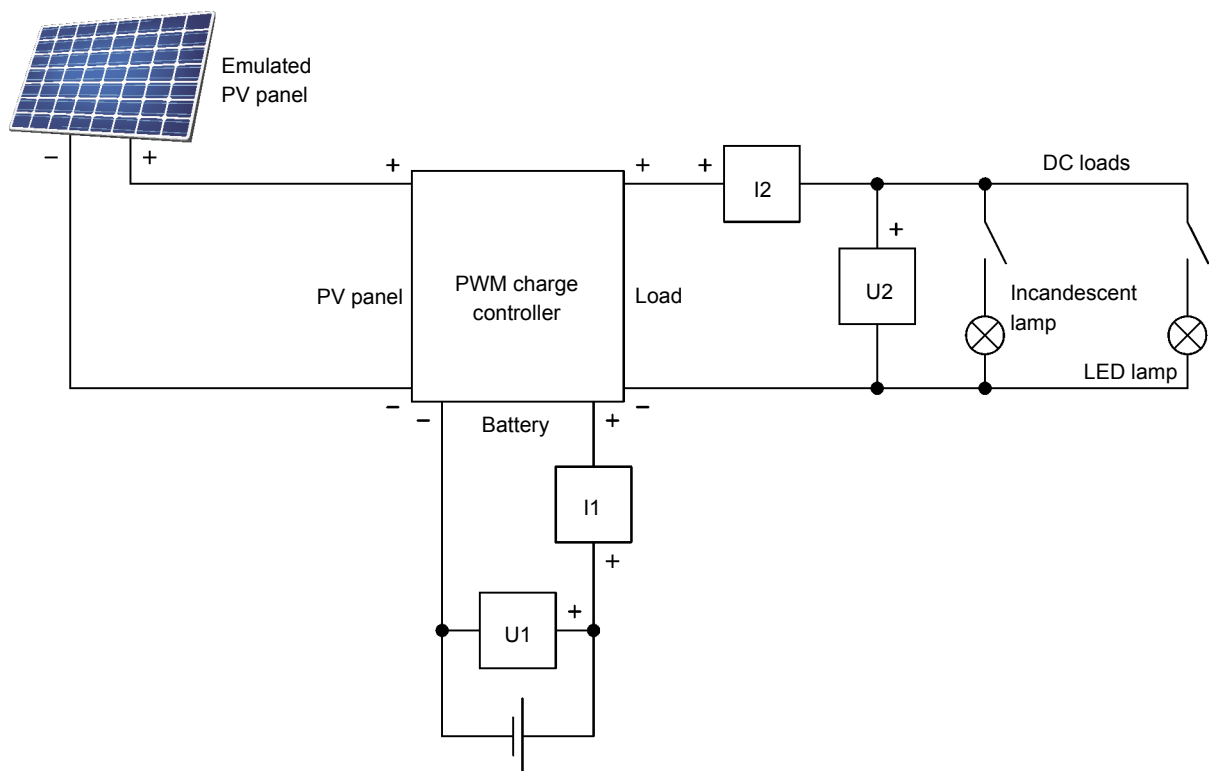


Figure 23. Stand-alone PV system for dc loads.

16. Several work modes are available in the PWM charge controller. The work mode determines the way in which the PWM charge controller manages the load. The selected work mode is indicated by a letter or a digit appearing for a few seconds in the **Work Mode** display of the PWM charge controller whenever the **ON/OFF/SET** button is depressed briefly. The work mode desired in this exercise is identified by the letter "C". In this work mode, the charge controller automatically disconnects the load when the battery voltage becomes too low, thereby preventing battery overdischarge.

On the PWM charge controller, depress the **ON/OFF/SET** button briefly using a pencil and observe the letter or the digit that appears in the **Work Mode** display. If the letter “C” appears in the **Work Mode** display, go to the next step of the procedure since the desired work mode is selected in the PWM charge controller. Otherwise, continue the present step of the procedure.

On the PWM charge controller, depress the **ON/OFF/SET** button using a pencil until the letter or the digit in the **Work Mode** display begins to blink. Then, repeatedly depress and release the **ON/OFF/SET** button until the letter “C” appears in the **Work Mode** display.



*The work mode of the PWM charge controller can only be changed when the letter or digit in the **Work Mode** display is blinking.*

17. Observe that the right-hand side LED (load status LED) in the set of three LEDs on the PWM charge controller is lit. This indicates that dc power is available at the **Load** terminals of the PWM charge controller.

On the **DC 48V Lamps** module, turn the incandescent lamp on. Observe that the incandescent lamp lights up, thereby confirming that dc power is available at the **Load** terminals of the PWM charge controller.

18. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **Solar Panel Emulator**.

Observe the left-hand side LED (charging stage LED) in the set of three LEDs on the PWM charge controller. This LED indicates the stage of battery charging the controller is in (LED off = no charge, LED blinking fast = bulk stage, LED lit continuously = absorption stage, LED blinking slowly = float stage). The charging stage LED should blink at a fast rate, thereby indicating that the controller is in the bulk stage of battery charging.

19. Observe that the voltmeter and ammeter in the **Four-Quadrant Dynamometer/Power Supply** window indicate the PV panel voltage and current. Notice that the polarity of the ammeter in the **Four-Quadrant Dynamometer/Power Supply** window is arranged so that the value of the measured current is positive when the PV panel produces electricity (i.e., when current exits through the positive terminal of the PV panel).

In **LVDAC-EMS**, open the **Metering** window and set voltmeters and ammeters to measure the dc voltage and current at the battery and loads.

The voltmeter and ammeter (PV panel voltage and current) in the **Four-Quadrant Dynamometer/Power Supply** window as well as the voltmeters and ammeters set in the **Metering** window will be used throughout the exercise to monitor the operation of the stand-alone PV system for dc loads.

With the polarity of the ammeter in the **Four-Quadrant Dynamometer/Power Supply** window and the polarity of the ammeters (current inputs **I1** and **I2** of the **Data Acquisition and Control Interface**) shown in the diagram above, the following equation relates the load current (I_{Load}) to the PV panel current (I_{PV}) and battery current ($I_{Batt.}$).

$$I_{Load} = I_{PV} + I_{Batt.}$$

Make sure that continuous refresh of the meters is enabled in the **Metering** window.

Stand-alone PV system operation

In this section, you will observe the operation of the stand-alone PV system for dc loads at various values of solar irradiance.

PV panel producing no electricity

- 20.** In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Solar Irradiance** parameter to 0 W/m². Observe that the charging stage LED on the PWM charge controller goes out to indicate that the battery is no longer charging.

Record the values of the dc voltage and current at the PV panel indicated in the **Four-Quadrant Dynamometer/Power Supply** window. Also record the values of the dc voltage and current at the battery and load indicated in the **Metering** window.

PV panel voltage: _____ V

PV panel current: _____ A

Battery voltage: _____ V

Battery current: _____ A

Load voltage: _____ V

Load current: _____ A

Do the values of dc current at the PV panel, battery, and load indicate that the battery provides all load current? Explain briefly.

What is the polarity of the battery current? What does this indicate?

Observe that the load voltage and the battery voltage have virtually the same value. Briefly explain why.



The load voltage is slightly less than the battery voltage because of the voltage drop (about 0.4 V) across the PWM charge controller and the connection leads.

Let the system operate for about 10 to 15 minutes in order to slightly discharge the battery. Ideally, the battery voltage should have decreased to about 49.7 V before continuing the exercise.

PV panel producing electricity at a rate below the power demand of the dc loads

21. In the **Four-Quadrant Dynamometer/Power Supply** window, slowly increase the value of the **Solar Irradiance** parameter to about 300 W/m² while observing the values of the various currents. Observe that the value of the battery current decreases as that of the PV panel current increases. Also observe that the value of the load current remains virtually the same.

On the PWM charge controller, observe that the charging stage LED blinks at a fast rate, thereby indicating that the controller is in the bulk stage of battery charging.



The PWM charge controller enters the bulk stage of battery charging when it detects that the PV panel produces electricity. However, battery charging does not actually begin because the solar irradiation is too low.

In the **Four-Quadrant Dynamometer/Power Supply** window, adjust the **Solar Irradiance** parameter so that the values of the PV panel current and battery current are approximately equal.

Record the values of the dc voltage and current at the PV panel indicated in the **Four-Quadrant Dynamometer/Power Supply** window. Also record the values of the dc voltage and current at the battery and load indicated in the **Metering** window.

PV panel voltage: _____ V

PV panel current: _____ A

Battery voltage: _____ V

Battery current: _____ A

Load voltage: _____ V

Load current: _____ A

Do the values of dc current at the PV panel, battery, and load indicate that the PV panel and the battery each provide half of the load current? Explain briefly.

PV panel producing electricity at a rate equal to the power demand of the dc loads

22. In the **Four-Quadrant Dynamometer/Power Supply** window, increase the value of the **Solar Irradiance** parameter until the value of the battery current indicated in the **Metering** window is approximately zero.

Record the values of the dc voltage and current at the PV panel indicated in the **Four-Quadrant Dynamometer/Power Supply** window. Also record the values of the dc voltage and current at the battery and load indicated in the **Metering** window.

PV panel voltage: _____ V

PV panel current: _____ A

Battery voltage: _____ V

Battery current: _____ A

Load voltage: _____ V

Load current: _____ A

Do the values of dc current at the PV panel, battery, and load indicate that the PV panel provides all load current? Explain briefly.

PV panel producing electricity at a rate exceeding the power demand of the dc loads

- 23.** In the **Four-Quadrant Dynamometer/Power Supply** window, increase the value of the **Solar Irradiance** parameter so that the polarity of the battery current indicated in the **Metering** window becomes negative. What does this indicate?

In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Solar Irradiance** parameter to 1000 W/m².

Record the values of the dc voltage and current at the PV panel indicated in the **Four-Quadrant Dynamometer/Power Supply** window. Also record the values of the dc voltage and current at the battery and load indicated in the **Metering** window.

PV panel voltage: _____ V

PV panel current: _____ A

Battery voltage: _____ V

Battery current: _____ A

Load voltage: _____ V

Load current: _____ A

Do the values of the dc current at the PV panel, battery, and load indicate that the PV panel supplies all load current as well as the current charging the battery? Explain briefly.

24. Compare the various values of the battery voltage and load voltage recorded so far. Do the battery voltage and load voltage vary slightly depending on whether the battery is charging or discharging?

☐ Yes ☐ No

Battery charging

In this section, you will observe the operation of the PWM charge controller when the battery is charging. The nominal values of the voltage regulation (VR) and float voltage (V_{Float}) setpoints in the PWM charge controller are 56.8 V and 55.2 V, respectively.



Completion of this part of the procedure is considered optional because it takes some time (generally between 15 and 45 minutes depending on the actual state of charge of the battery). You should skip this part of the procedure if less than 1 hour remains in the lab session.

25. On the **DC 48V Lamps** module, turn the incandescent lamp off. This causes the battery current to increase to about 1.5 A because all the current produced by the PV panel now charges the battery.

On the PWM charge controller, observe the charging stage LED. It should continue to blink at a fast rate, thereby indicating that the controller is still in the bulk stage of battery charging.

In the **Metering** window, observe the battery voltage. It should increase slowly as the battery is charging.

26. In the **Four-Quadrant Dynamometer/Power Supply** window, slowly decrease the value of the **Solar Irradiance** parameter while making sure that you maintain enough solar irradiation to keep the battery charging, then set the value back to 1000 W/m². While doing this, observe that the value of the battery charging current decreases when the solar irradiation decreases and vice versa. Briefly explain why.

27. Observe the charging stage LED on the PWM charge controller as well as the battery voltage indicated in the **Metering** window. The charging stage LED continues to blink at a fast rate as long as the PWM charge controller is in the bulk phase of battery charging. Also, the battery voltage continues to increase slowly throughout the bulk phase of battery charging.

Observe that after a certain time, the charging stage LED on the PWM charge controller stops blinking and lights up continuously. This indicates that the PWM charge controller is in the absorption stage of battery charging.



The duration of the bulk phase of battery charging depends on the actual state of charge of the battery. The lower the state of charge of the battery, the longer the duration of the bulk phase of battery charging.

28. In the **Metering** window, observe the battery voltage for 2 or 3 minutes. Does it continue to increase slowly as the battery is charging? Briefly explain why.

29. Record the values of the battery voltage and load voltage indicated in the **Metering** window.

Battery voltage: _____ V

Load voltage: _____ V

Does the measured battery voltage confirm that the PWM charge controller is in the absorption stage of battery charging? Explain briefly.

30. Observe the battery charging current indicated in the **Metering** window for 3 to 4 minutes. Does the value of the battery charging current decrease gradually as the battery is charging?



*Current spikes in the battery charging current may exceed the maximum current (4 A) of current input I1 of the **Data Acquisition and Control Interface**. This causes clipping of the battery current measured by the **Data Acquisition and Control Interface**. The display of the battery current meter in the **Metering** windows turns to yellow when clipping occurs.*

☐ Yes ☐ No

31. In the **Four-Quadrant Dynamometer/Power Supply** window, slowly decrease the value of the **Solar Irradiance** parameter to 900 W/m², then set the value back to 1000 W/m². While doing this, observe that the value of the battery charging current remains virtually fixed. Briefly explain why.



If the value of the battery charging current varies when the solar irradiance is varied, let the system operate a few minutes and redo the manipulation above.

32. In the **Four-Quadrant Dynamometer/Power Supply** window, stop the **Solar Panel Emulator**. Observe that the charging stage LED on the PWM charge controller goes out to indicate that the battery is no longer charging.



Waiting for the PWM charge controller to enter the float stage of battery charging generally takes too much time. This is why battery charging is stopped at the absorption stage.

Comparing the energy consumption of two different types of dc lamps

In this section, you will compare the energy consumption of two dc lamps of different types (incandescent and LED) which produce approximately the same amount of light.

33. On the **DC 48V Lamps** module, turn the incandescent lamp on.

In the **Metering** window, set a meter to measure power at the dc loads.

Record the incandescent lamp voltage, current, and power indicated in the **Metering** window.

Incandescent lamp voltage: _____ V

Incandescent lamp current: _____ A

Incandescent lamp power: _____ W

Use the lamp power you just measured to calculate the daily energy demand of the incandescent lamp. Base your calculation on 4 hours of use per day.

34. Notice the amount of light which the incandescent lamp produces. On the **DC 48V Lamps** module, turn the incandescent lamp off, then turn the LED lamp on. Do the two lamps produce approximately the same amount of light?

☐ Yes ☐ No

Record the LED lamp voltage, current, and power indicated in the **Metering** window.

LED lamp voltage: _____ V

LED lamp current: _____ A

LED lamp power: _____ W

Use the lamp power you just measured to calculate the daily energy demand of the LED lamp. Base your calculation on 4 hours of use per day.

On the **DC 48V Lamps** module, turn the LED lamp off.

- 35.** Compare the daily energy demand of the LED lamp with that of the incandescent lamp.

Does this confirm that the LED lamp is more efficient than the incandescent lamp at converting electricity into light? Explain briefly.

Battery overdischarge protection

In this section, you will observe the operation of the battery overdischarge protection implemented in the PWM charge controller.

- 36.** Disconnect the emulated PV panel from the PV system.

On the **48V Lead-Acid Battery Pack**, open the circuit breaker by setting its lever to the **O** (off) position.

- 37.** In the **Four-Quadrant Dynamometer/Power Supply** window, make the following settings:

Set the **Function** parameter to **DC Voltage Source**. This function makes the power supply in the **4 Quadrant Power Supply and Dynamometer Controller** operate like a variable-voltage dc source. The output terminals of the power supply are the terminals of the dc source.

Make sure that the **Voltage Control** parameter is set to **Knob**. This allows the dc source voltage to be controlled manually.

Set the **Voltage** parameter to 51.2 V. This sets the dc source voltage to 51.2 V. This corresponds to the nominal open-circuit voltage of a 48 V lead-acid battery pack that is fully charged.

Make sure that the **Status** parameter is set to **Stopped**. This ensures that the dc source is disabled (i.e., it produces no voltage).

38. Replace the battery in the PV system by the variable-voltage dc source implemented using the **4 Quadrant Power Supply and Dynamometer Controller**. The equipment should be connected as shown in Figure 24.

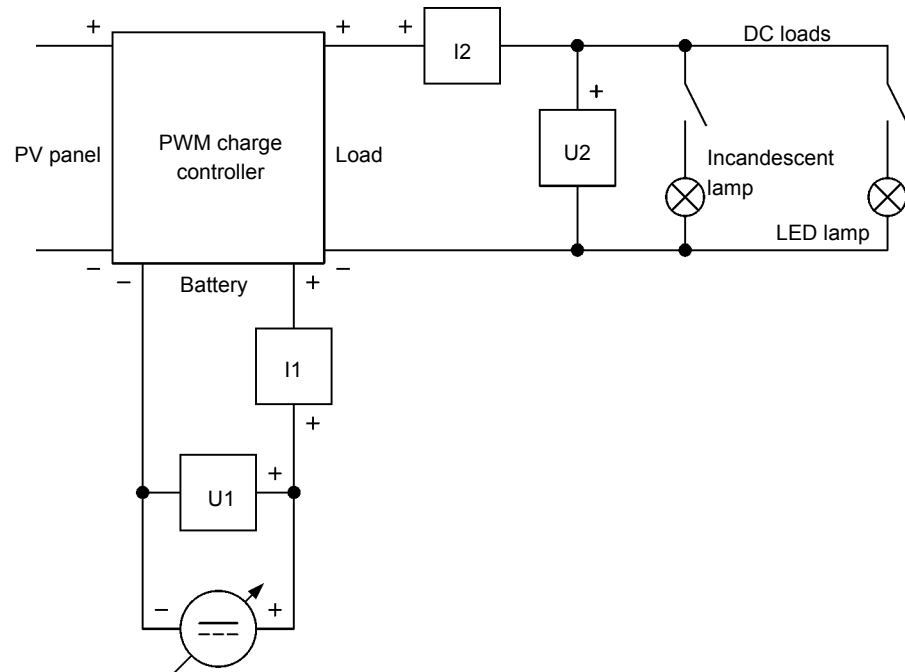


Figure 24. Circuit used to observe the operation of the battery discharge protection implemented in the PWM charge controller.

Varying the dc source voltage in the circuit above varies the voltage applied across the **Battery** terminals of the PWM charge controller. This allows the battery state of charge perceived by the PWM charge controller to be changed rapidly.

39. In the **Four-Quadrant Dynamometer/Power Supply** window, start the dc source. The PWM charge controller should turn on as soon as the dc source is started. Also, the battery status LED on the PWM charge controller should light up in green because the dc source voltage is currently set to the value (51.2 V) of the nominal open-circuit voltage of a 48 V lead-acid battery pack that is fully charged.

On the **DC 48V Lamps** module, turn the incandescent lamp on.

40. In the **Four-Quadrant Dynamometer/Power Supply** window, slowly decrease the dc source voltage to 43 V while observing the PWM charge controller. This decreases the voltage across the **Battery** terminals of the PWM charge controller, thereby emulating a battery whose state of charge becomes very low. In fact, the voltage across the **Battery** terminals is now below the low-voltage disconnect (LVD) setpoint (about 45 V) of the PWM charge controller.

Describe what happens.

Does the PWM charge controller achieve proper battery overdischarge protection?

☐ Yes ☐ No

- 41.** In the [Four-Quadrant Dynamometer/Power Supply](#) window, slowly increase the dc source voltage to 53 V while observing the PWM charge controller. This increases the voltage across the [Battery](#) terminals of the PWM charge controller, thereby emulating a battery which is charging. In fact, the voltage across the [Battery](#) terminals now exceeds the low-voltage reconnect (LVR) setpoint (about 52 V) of the PWM charge controller.

Describe what happens.

- 42.** In the [Four-Quadrant Dynamometer/Power Supply](#) window, stop the dc source.

Close [LVDAC-EMS](#).

- 43.** Turn the [4 Quadrant Power Supply and Dynamometer Controller](#) off.

Turn the [AC 24V Power Supply](#) off.

Turn electric power off at your workstation, if applicable. Remove all circuit connections, finishing with the equipment earthing connections. Return all equipment to its storage location.

CONCLUSION

In this exercise, you became familiar with the configuration and operation of stand-alone PV systems for dc loads. You learned how to use the specifications of the PV panel, charge controller, and battery selected for a specific stand-alone PV system to verify that they can work together without causing problems. You saw how the charge controller performs battery charging control and battery overdischarge protection. You also saw that choosing energy-efficient electric equipment (e.g., using LED lamps instead of incandescent lamps) is a means of reducing the size and cost of the stand-alone PV system for dc loads required in any application. You discovered several common applications of stand-alone PV systems for dc loads.

REVIEW QUESTIONS

1. What are the main functions of the charge controller in a stand-alone PV system?

2. The short-circuit current (I_{SC}) and open-circuit voltage (U_{OC}) of the PV panel in a stand-alone PV system are 7 A and 40 V, respectively. Voltage U_{OC} varies by $-0.4\%/^{\circ}\text{C}$. The maximum PV panel input current and maximum PV panel input voltage of the charge controller considered for the system are 10 A and 45 V. Assuming a minimum PV panel temperature of -15°C during normal system operation, can the charge controller work with the PV panel without problems? Explain briefly.

3. Name three common applications of stand-alone PV systems for dc loads.

4. The battery bank in a stand-alone PV system consists of four battery strings connected in parallel, each battery string consisting of two batteries connected in series. The voltage and capacity of each battery are 12 V and 80 Ah, respectively. What are the system voltage and the system capacity (i.e., the capacity of the battery bank)?

5. What is the effect of using energy-efficient electric equipment on the size and cost of a stand-alone PV system for dc loads? Explain briefly.

Use of an MPPT Charge Controller in Stand-Alone PV Systems

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the benefits of using an MPPT charge controller instead of an on-off or PWM charge controller in stand-alone PV systems for dc loads. You will be familiar with the topology, operation, and unique features of the MPPT charge controller. You will understand why a PV panel matching the battery (system) voltage as closely as possible is required in stand-alone PV systems using an on-off or PWM charge controller, to enable operation close to the maximum power point (MPP). You will understand why using an MPPT charge controller in stand-alone PV systems allows operation at the MPP (whenever required), even if the PV panel voltage at the MPP does not match the battery (system) voltage. Finally, you will be able to compare the on-off, PWM, and MPPT charge controllers in terms of performance and cost.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction
- MPPT charge controllers
Topology. Battery charging control method. Battery overdischarge protection. Power switching device technology.
- Operating point of the PV panel in stand-alone PV systems using an on-off or PWM charge controller
- Operating point of the PV panel in stand-alone PV systems using an MPPT charge controller
- Comparison of the on-off, PWM, and MPPT charge controllers

DISCUSSION

Introduction

In the previous exercise, you studied the operation of stand-alone PV systems for dc loads implemented with an on-off charge controller or a PWM charge controller. The goal of the present exercise is to demonstrate the benefits of using an **MPP tracking (MPPT)** charge controller instead of an on-off or PWM charge controller in stand-alone PV systems for dc loads. First, the exercise describes what an MPPT charge controller is and explains how it operates. Then, the exercise demonstrates that in stand-alone PV systems using an on-off or PWM charge controller, the battery voltage dictates the voltage at which the PV panel operates, and ultimately, the amount of power which the PV panel produces. The exercise continues by demonstrating that in stand-alone PV systems using an MPPT charge controller, the charge controller has full control over the voltage at which the PV panel operates, and ultimately, the amount of power which the PV panel produces. Finally, the exercise concludes with a brief comparison of the on-off, PWM, and MPPT charge controllers in terms of performance and cost.

MPPT charge controllers

Design-wise, MPPT charge controllers are newer than the on-off and PWM charge controllers studied in the previous exercise. MPPT charge controllers use the same battery charging control method (modified constant-

voltage charging) as in PWM charge controllers. However, MPPT charge controllers have some unique features that are briefly described below.

- An MPPT charge controller enables efficient operation with a PV panel producing voltages significantly higher than the battery (system) voltage. Any excess in the PV panel voltage is automatically converted into additional current to supply the dc loads and charge the battery. This provides flexibility when selecting the PV panel for a specific PV system. Also, operation of the PV panel at a voltage higher than the battery voltage allows reduction of the power losses in the leads interconnecting the PV panel and the charge controller or of the size (and thus, the cost) of these leads.
- An MPPT charge controller can make the PV panel operate at the **maximum power point (MPP)**, i.e., at the voltage at which the PV panel produces the maximum amount of power. This feature is used to ensure that the maximum current possible charges the battery when required (i.e., during the bulk phase of battery charging).

These unique features, however, make MPPT charge controllers significantly more expensive than on-off and PWM charge controllers. The remainder of this section presents the basic topology of MPPT charge controllers. It also explains how MPPT charge controllers operate and states the types of power switching devices that are commonly used in these controllers.

Topology

Figure 25 shows the basic topology of MPPT charge controllers. Battery overdischarge protection is achieved by opening a power switching device connected between the battery and the dc loads, as in the on-off and PWM charge controllers. On the other hand, battery charging control is achieved using a **buck chopper**.

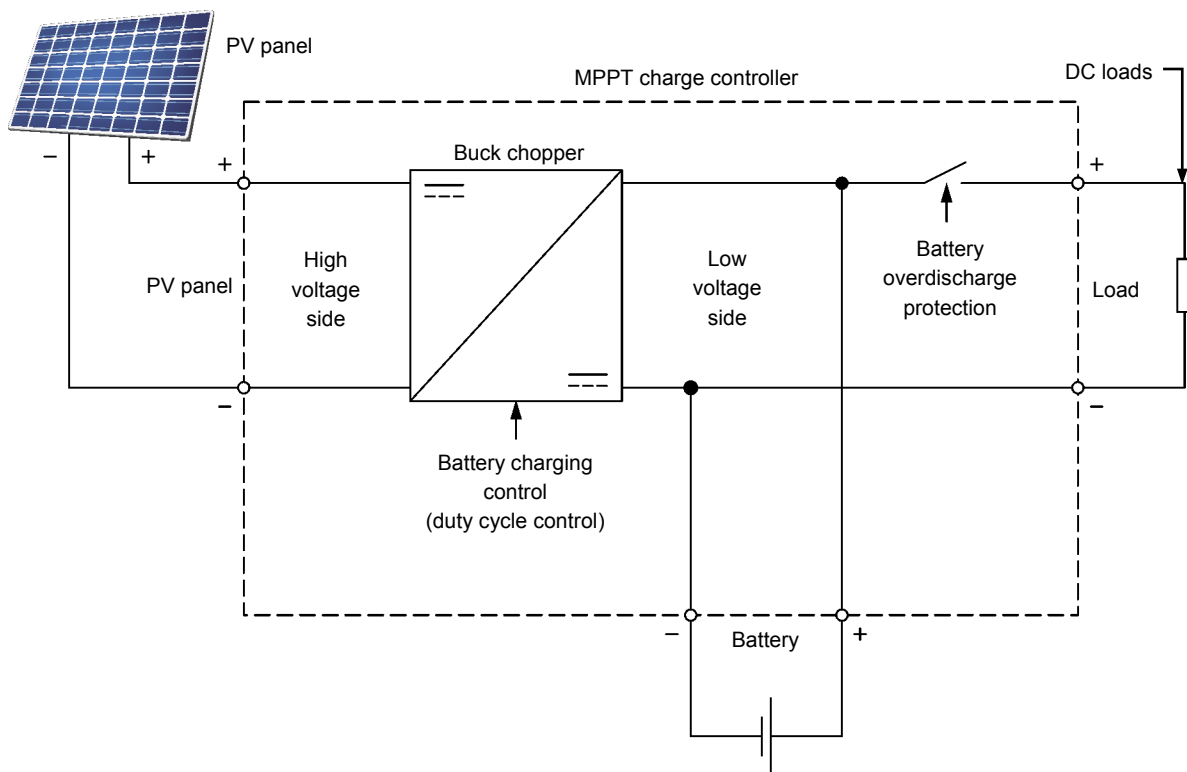


Figure 25. Basic topology of MPPT charge controllers.

A buck chopper is a power electronic circuit that converts a dc voltage into a dc voltage of lower value. Voltage conversion is achieved by turning an electronic power switching device on and off at a high frequency (e.g., 20 kHz). The values of the dc voltages on both sides of the buck chopper are related to each other via the equation below.

$$U_{out} = U_{in} \times \alpha \quad (2)$$

where U_{in} is the dc (average) voltage at the input (high-voltage side) of the buck chopper.
 U_{out} is the dc (average) voltage at the output (low-voltage side) of the buck chopper.
 α is the duty cycle, i.e., the ratio of the time the electronic power switching device in the buck chopper is on to the duration of each on-off cycle.

Figure 26 is an example of the values of the dc voltages on both sides of a buck chopper for two values of duty cycle. The figure also shows the values of the dc currents on both sides of the buck chopper. Note that the value of the dc current at the output (low-voltage side) of the buck chopper is always higher than the value of the dc current at its input (high-voltage side) because the value of power is virtually the same on both sides of the buck chopper.



Power losses in buck choppers are generally very low. This results in a very good power efficiency, generally around 95%. Consequently, it is reasonable to assume that the value of power is virtually the same on both sides of a buck chopper.

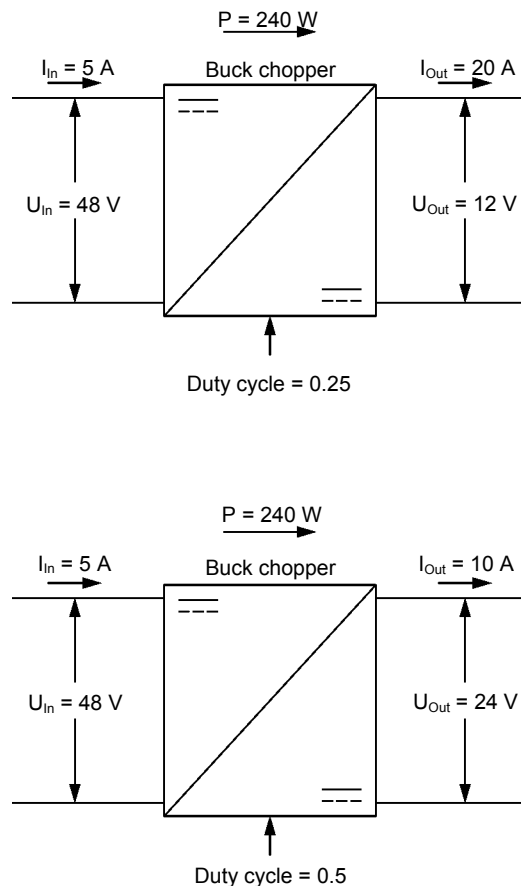
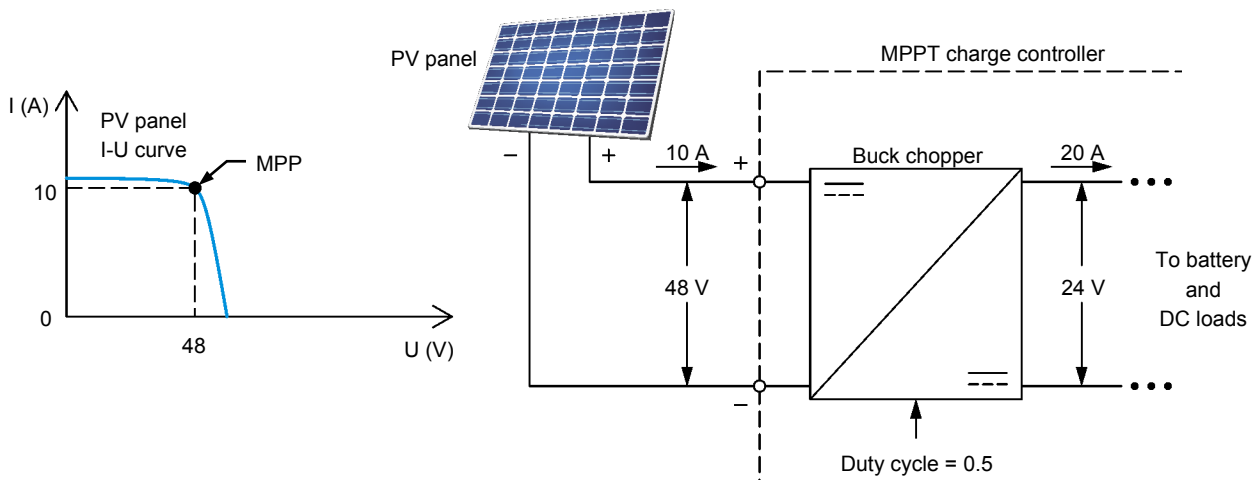
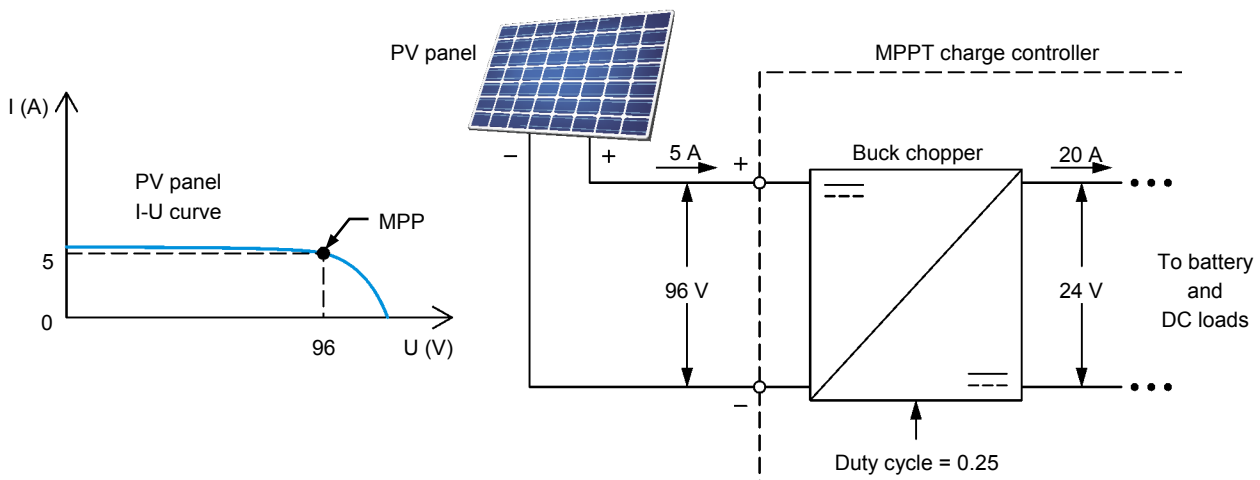


Figure 26. Values of the dc voltages and currents on both sides of a buck chopper for two values of duty cycle.

In MPPT charge controllers, the buck chopper lowers the PV panel voltage to the value of the battery (system) voltage. The MPPT charge controller automatically adjusts the duty cycle of the buck chopper according to the values of the PV panel voltage and battery voltage. This means that the voltage produced by the PV panel, when operating in the MPP area, does not need to match the battery voltage. This provides flexibility in the selection of the PV panel for a specific PV system. Figure 27 shows two PV systems operating at a battery voltage of 24 V and using PV panels producing 480 W at the MPP. The PV panel in one system produces 48 V at the MPP while the PV panel in the other system produces 96 V at the MPP. In both cases, the excess in PV panel voltage is automatically converted into additional current to supply the dc loads and charge the battery. Notice that increasing the PV panel voltage lowers the value of the current flowing between the PV panel and the buck chopper in the MPPT charge controller. Consequently, this decreases the power losses in the leads interconnecting the PV panel and the charge controller.



(a) 480 W PV system with 48 V PV panel



(b) 480 W PV system with 96 V PV panel

Figure 27. The buck chopper in MPPT charge controllers lowers the PV panel voltage to the value of the battery (system) voltage.

Battery charging control method

MPPT charge controllers use the same battery charging control method (modified constant-voltage charging) as in PWM charge controllers. However, the method is implemented in a different fashion using a buck chopper and MPP tracking.

During the bulk stage of battery charging, the MPPT charge controller uses MPP tracking to adjust the duty cycle of the buck chopper so that the voltage produced by the PV panel remains at the value required for MPP operation, no matter what the solar irradiation value is. This ensures that the maximum current possible charges the battery throughout the bulk phase of battery charging, thereby charging the battery as rapidly as possible.

When the battery voltage reaches the voltage regulation (VR) setpoint, the MPPT charge controller passes to the absorption stage of battery charging. During this stage, MPP tracking is no longer used and the MPPT charge controller continually adjusts the duty cycle of the buck chopper to maintain the battery voltage at the VR setpoint. This causes the average value of the charge current to decrease gradually.

When the average value of the charge current has decreased to a certain value, the MPPT charge controller considers that the battery is fully charged and passes to the float stage of battery charging. During this stage, the charge controller continues battery charging using a lower voltage setpoint (V_{Float} setpoint). The MPPT charge controller achieves this by adjusting the duty cycle of the buck chopper to maintain the battery voltage at the V_{Float} setpoint. This results in a low charge current (trickle current) which maintains the battery fully charged.

The three stages of this battery charging control method are illustrated in Figure 28.

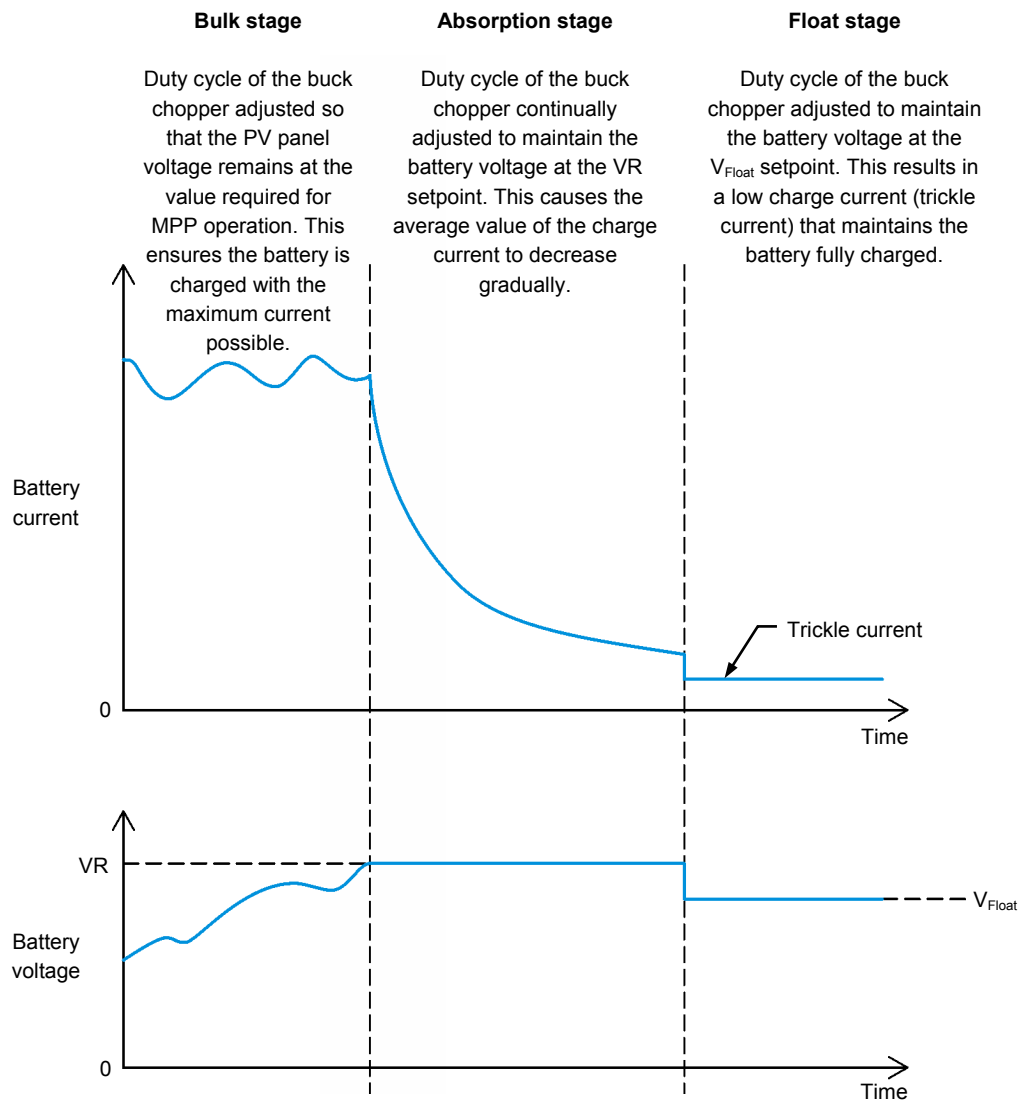


Figure 28. Modified constant voltage charging used in MPPT charge controllers.

Battery overdischarge protection

MPPT charge controllers prevent overdischarge of the battery the same way as on-off charge controllers. Refer to the section *On-off charge controllers* in the discussion of the previous exercise for more detail.

Power switching device technology

A power transistor of the MOSFET type is used in MPPT charge controllers to implement the buck chopper required for battery charging. On the other hand, a contact relay or an SSR is used to implement battery overdischarge protection.

Operating point of the PV panel in stand-alone PV systems using an on-off or PWM charge controller

In a PV system using an on-off or PWM charge controller, the battery voltage dictates the voltage at which the PV panel operates, and ultimately, the amount of power which the PV panel produces. This is illustrated in Figure 29, which shows the I-U curve of the battery superimposed onto the I-U curve and power

curve of the PV panel for a given value of solar irradiation. The operating point of the PV system is at the intersection of the I-U curves of the battery and the PV panel. In most cases, the operating point is off the MPP. When the PV panel is well matched with the battery, i.e., when the PV panel voltage at the MPP is slightly (about 25-30%) higher than the battery (system) voltage, the amount of power produced by the PV panel is generally 85% or more of the power at the MPP. In the example given in Figure 29, the battery (system) voltage is 12 V, the PV panel voltage at the MPP is 15.0 V, and the battery voltage when charging is 13.0 V. This sets the amount of power produced by the PV panel to 125 W (9.6 A @ 13.0 V). This is close to the power at the MPP which is 135 W (9.0 A @ 15.0 V), and thus, results in an efficient use of the PV panel.

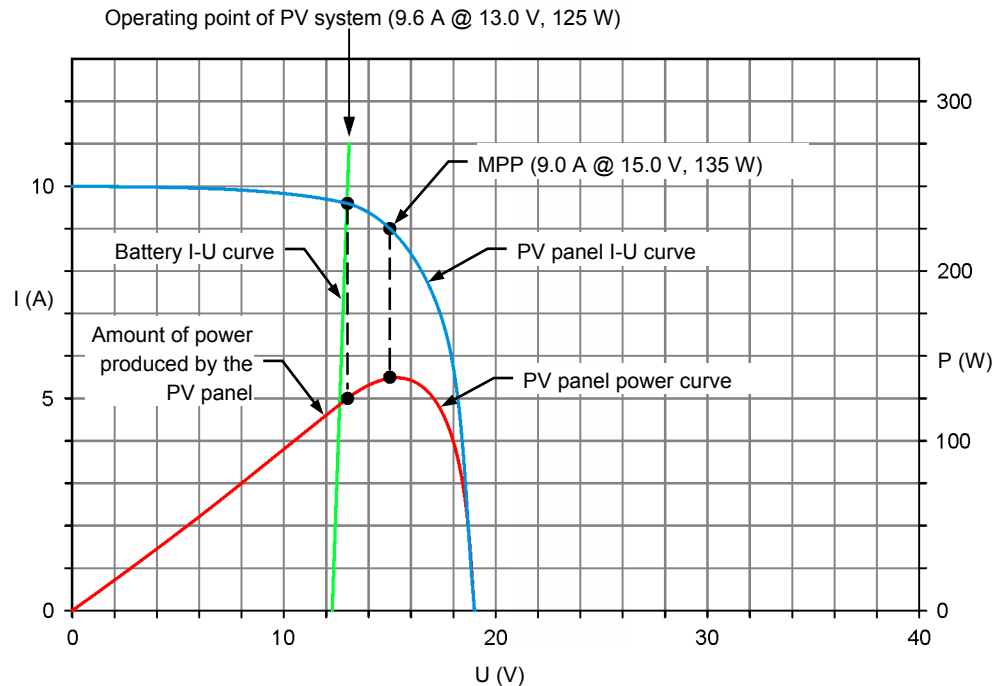


Figure 29. PV system using an on-off or PWM charge controller in which the PV panel voltage at the MPP is well matched with the battery (system) voltage.

On the other hand, when the PV panel is not well matched with the battery, i.e., when the PV panel voltage at the MPP is significantly higher than the battery (system) voltage, the amount of power produced by the PV panel is much lower than the power at the MPP. In the example given in Figure 30, the PV panel voltage at the MPP is 30.0 V instead of 15.0 V and the battery voltage while charging is still 13.0 V. This sets the amount of power produced by the PV panel to 130 W (10.0 A @ 13.0 V). This is well below the power at the MPP which is 270 W (9.0 A @ 30.0 V), and thus, results in a highly inefficient use of the PV panel.

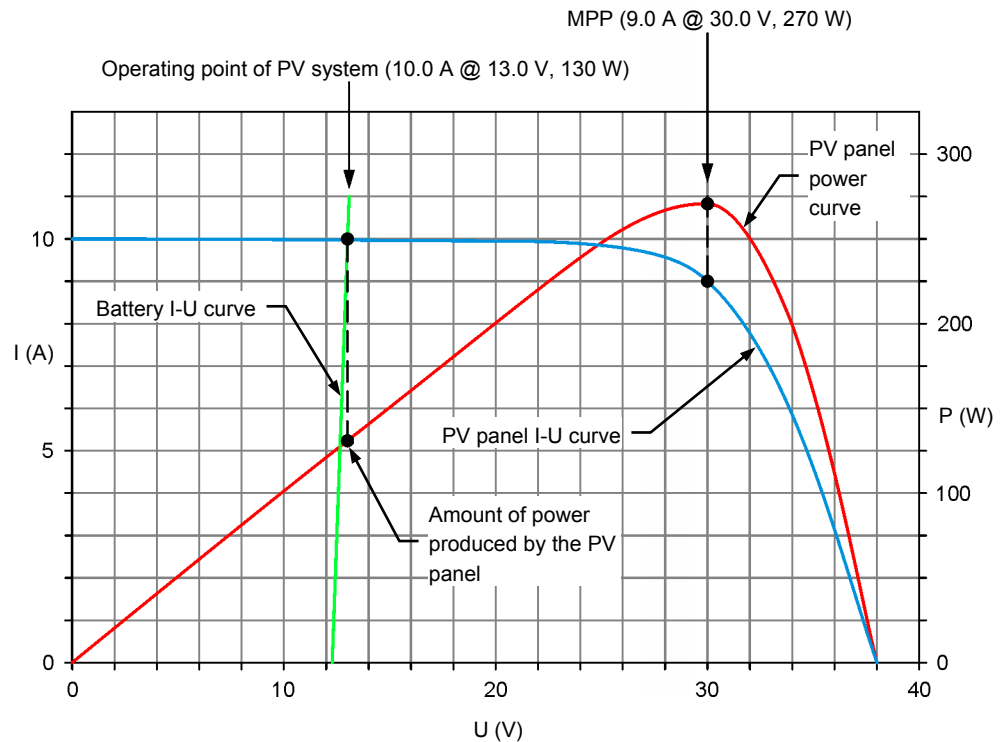


Figure 30. PV system using an on-off or PWM charge controller in which the PV panel voltage at the MPP is significantly higher than the battery (system) voltage.

Operating point of the PV panel in stand-alone PV systems using an MPPT charge controller

The two examples presented in the previous section of this discussion clearly demonstrate that in PV systems using an on-off or PWM charge controller, a PV panel matching the battery (system) voltage as closely as possible is required to optimize the amount of power produced. In PV systems using an MPPT charge controller, however, a PV panel matching the battery (system) voltage is not required. This is because the buck chopper in an MPPT charge controller makes the voltage at which the PV panel operates independent of the battery (system) voltage. This allows the PV panel to operate at the MPP when required (i.e., during the bulk phase of battery charging), even if the voltage the PV panel produces at the MPP is significantly higher than the battery (system) voltage. In fact, the buck chopper in an MPPT charge controller adapts the I-U curve of the PV panel so that it matches the battery voltage, as shown in Figure 31. In this example, the PV panel voltage at the MPP (30.0 V) and the battery (system) voltage (12 V) are the same as in the second example presented in the previous section. However, the PV panel produces 270 W (9.0 A @ 30.0 V at the PV panel and 20.0 A @ 13.5 V at the battery) instead of only about 130 W (10.0 A @ 13.0 V) because the MPPT charge controller allows operation at the MPP during the bulk phase of battery charging. Note that in this example, it is assumed that no power is lost in the buck chopper.

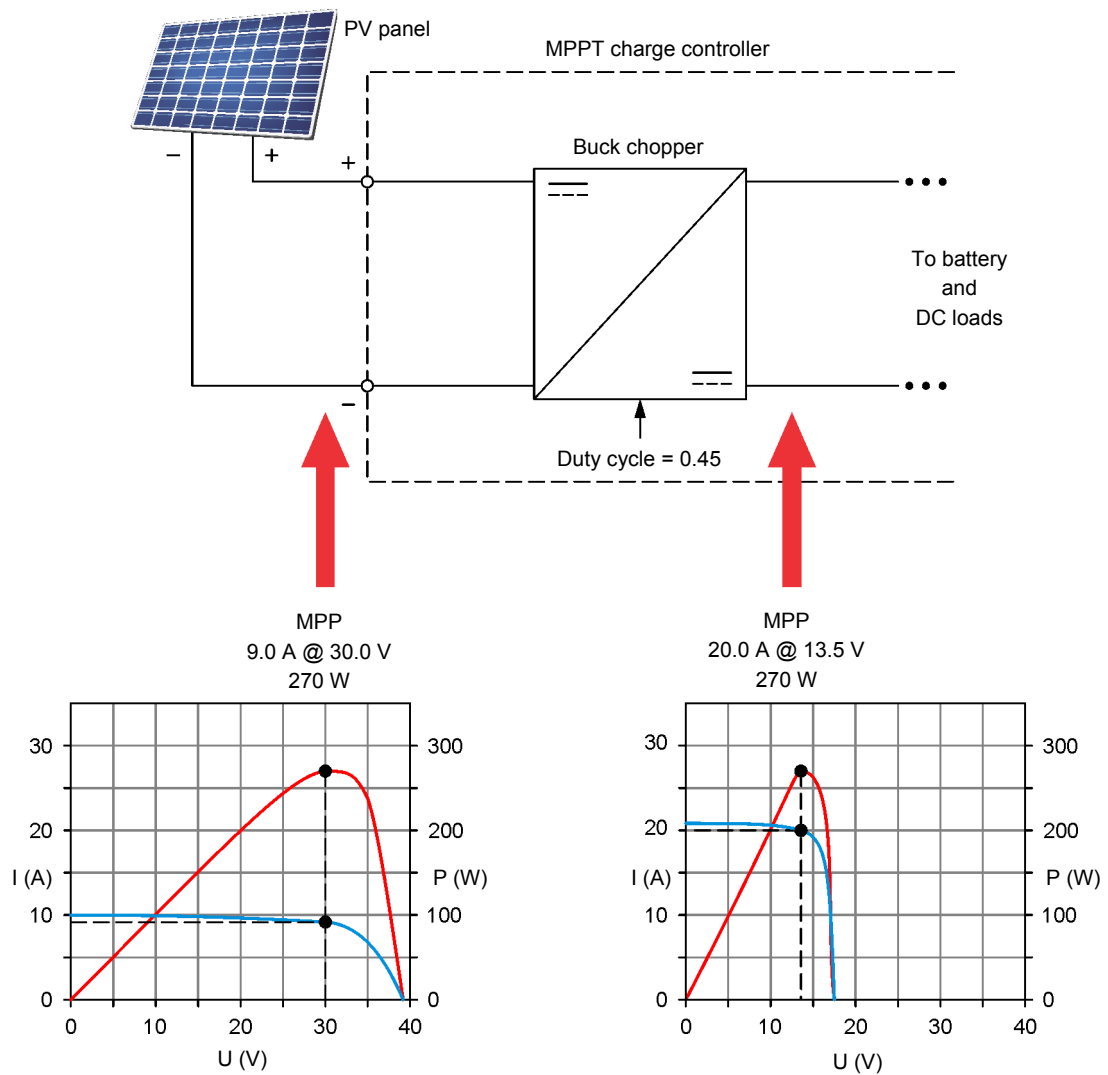


Figure 31. Using an MPPT charge controller in a PV system allows operation at the MPP even if the PV panel voltage at the MPP is significantly higher than the battery (system) voltage.

Comparison of the on-off, PWM, and MPPT charge controllers

Table 7 provides a brief comparison of the on-off, PWM, and MPPT charge controllers. The table compares the following aspects of charge controllers: battery charging performance, possibility of operating at MPP, PV panel voltage requirement, and cost. On-off charge controllers have poor battery charging performance but are cheaper than PWM and MPPT charge controllers. PWM and MPPT charge controllers both have good battery charging performance. Furthermore, MPPT charge controllers operate at MPP when required and allow efficient operation with a PV panel producing voltages significantly higher than the battery (system) voltage. These extra features, however, make MPPT charge controllers more expensive than PWM charge controllers.

Table 7. Comparison of the on-off, PWM, and MPPT charge controllers.

	Type of charge controller		
	On-off	PWM	MPPT
Battery charging performance	Poor	Good	Good
Can operate at MPP when required	No	No	Yes
PV panel voltage independent of battery (system) voltage	No	No	Yes
Cost	Low	Medium	High

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Partial discharge of the battery pack
- Emulated PV panel settings
- Setting up a stand-alone PV system for dc loads
- Operating point of the PV panel in a stand-alone PV system using a PWM charge controller
- Operating point of the PV panel in a stand-alone PV system using an MPPT charge controller

PROCEDURE

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

Setup and connections

In this section, you will set up and connect the equipment required to perform the exercise.

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

Install the equipment in the workstation. You will use this equipment later in this exercise to set up a stand-alone PV system for dc loads.

Make the connections required to earth the equipment properly.



If necessary, check with the instructor to ensure that the connections you made provide proper earthing of the equipment.

2. Make sure that the main power switch of the **4 Quadrant Power Supply and Dynamometer Controller** is set to the **O** (off) position, then connect its **Power Input** to an ac power outlet that is properly protected.

Make sure that the main power switch of the **AC 24V Power Supply** is set to the **O** (off) position, then connect its **Power Input** to an ac power outlet that is properly protected.



If necessary, check with the instructor to ensure that the ac power outlets to which you connect the equipment are properly protected.

3. Connect the **Power Input** of the **Data Acquisition and Control Interface** to the **AC 24V Power Supply**.
4. Ask your instructor to turn on (i.e., to unlock) electric power at your workstation, if applicable.
5. Turn the **AC 24V Power Supply** on.
6. Turn the **4 Quadrant Power Supply and Dynamometer Controller** on, then set the **Operating Mode** switch to **Power Supply**.
7. Connect the USB port of the **Data Acquisition and Control Interface** to a USB port of the host computer.

Connect the USB port of the **4 Quadrant Power Supply and Dynamometer Controller** to a USB port of the host computer.

8. 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 **4 Quadrant Power Supply and Dynamometer Controller** are detected. Make sure that the **Basic Computer-Based Instrumentation** function for the **Data Acquisition and Control Interface** is available. Also make sure that the **Solar Panel Emulator** and **Lead-Acid Battery Charger** functions for the **4 Quadrant Power Supply and Dynamometer Controller** are available. Select the network voltage and frequency of your local ac power network, then click the **OK** button to close the **LVDAC-EMS Start Up** window.

Partial discharge of the battery pack

*Later in this exercise, you will study the operation of a stand-alone PV system when a PWM charge controller is used as well as when an MPPT charge controller is used. In this section, you will partially discharge the **48V Lead-Acid Battery Pack** so that later in the exercise the MPPT charge controller can make the PV panel operate at the MPP.*

9. Measure the open-circuit voltage of the **48V Lead-Acid Battery Pack**. If the voltage is about 50.0 V or less, go to step 13 since the state of charge of the **48V Lead-Acid Battery Pack** should be low enough to perform the exercise. Otherwise, go to the next step to partially discharge the **48V Lead-Acid Battery Pack**.



*In the remainder of this exercise, the **48V Lead-Acid Battery Pack** is also referred to as the battery.*

10. Connect the positive terminal of the 48V Lead-Acid Battery Pack to terminal 1 of the 4 Quadrant Power Supply and Dynamometer Controller.

Connect the negative terminal of the 48V Lead-Acid Battery Pack to terminal N of the 4 Quadrant Power Supply and Dynamometer Controller.

On the 48V Lead-Acid Battery Pack, close the circuit breaker by setting its lever to the I (on) position.

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

- Set the *Function* parameter to *Battery Discharger (Constant-Current Timed Discharge with Voltage Cutoff)*. This function makes the power supply in the 4 Quadrant Power Supply and Dynamometer Controller operate as a battery discharger, i.e., a negative current source that is controlled by parameters associated with battery discharge.
- Set the *Discharge Current* parameter to 4 A. This sets the discharge current of the battery discharger to 4 A.
- Set the *Discharge Duration* parameter to 30 min. This sets the discharge duration to 30 minutes.
- Set the *Cutoff Voltage* parameter to 46 V. This sets the minimum value (46 V) to which the battery voltage can decrease during discharge. This limits battery discharging to prevent damage to the batteries.
- Start battery discharging by setting the *Status* parameter to *Started* or by clicking the *Start/Stop* button.



During the battery discharge, the time left is indicated at the bottom of the Four-Quadrant Dynamometer/Power Supply window.

Make sure that continuous refresh of the meters in the Four-Quadrant Dynamometer/Power Supply window is selected. The discharge current indicated by the ammeter in the Four-Quadrant Dynamometer/Power Supply window should be close to the discharge current set above.

12. Wait until the battery discharge ends. The discharge current indicated by the ammeter in the Four-Quadrant Dynamometer/Power Supply window should be zero. Once the battery discharge is finished, make sure that the battery discharger is stopped (*Status* parameter = *Stopped*).

On the 48V Lead-Acid Battery Pack, open the circuit breaker by setting its lever to the O (off) position.

Disconnect the 48V Lead-Acid Battery Pack from the 4 Quadrant Power Supply and Dynamometer Controller.

Emulated PV panel settings

In this section, you will set the size of the emulated PV panel that will be used to implement a stand-alone PV system for dc loads. You will note the electrical specifications of the emulated PV panel.

13. In LVDAC-EMS, open the **Four-Quadrant Dynamometer/Power Supply** window (if this is not already done), then make the following settings:
 - Set the **Function** parameter to **Solar Panel Emulator**. This function makes the power supply in the **4 Quadrant Power Supply and Dynamometer Controller** operate like a solar (PV) panel. The output terminals of the power supply are the terminals of the emulated PV panel.
 - Make sure that the **Solar Irradiance Control** parameter is set to **Slider**. This allows the solar irradiance to be controlled manually.
 - Set the **Solar Irradiance** parameter to 1000 W/m².
 - Set the **Number of PV modules in series** parameter to 8. Set the **Number of PV modules in parallel** parameter to 16. These two settings set the size of the emulated PV panel to 8 PV modules in series and 16 PV modules in parallel.
 - Make sure that the **Status** parameter is set to **Stopped**. This prevents the emulated PV panel from producing electricity even if the solar irradiation is currently set to 1000 W/m².
14. Observe that the electrical specifications of each PV module in the emulated PV panel are indicated in the **Four-Quadrant Dynamometer/Power Supply** window.



In the remainder of this exercise, the emulated PV panel is also simply referred to as the PV panel.

According to the information provided in the **Four-Quadrant Dynamometer/Power Supply** window, what are the short-circuit current (I_{sc}), open-circuit voltage (U_{oc}), maximum power point (MPP) current, maximum power point (MPP) voltage, and maximum power point (MPP) of the emulated PV panel, at a solar irradiation of 1000 W/m²?

Short-circuit current (I_{sc}): _____ A

Open-circuit voltage (U_{oc}): _____ V

MPP current (I_{MPP}): _____ A

MPP voltage (U_{MPP}): _____ V

MPP: _____ W (_____ A @ _____ V)

The emulated solar panel has the same size as in Exercise 1. You verified in Exercise 1 that this PV panel can be used with the **DC 48V PWM Charge Controller** without causing problems.



*In the remainder of this exercise, the **DC 48V PWM Charge Controller** is also simply referred to as the PWM charge controller.*

Setting up a stand-alone PV system for dc loads

In this section, you will set up a stand-alone PV system for dc loads using the Data Acquisition and Control Interface, emulated PV panel, 48V Lead-Acid Battery Pack, and DC 48V PWM Charge Controller.

15. Use the Data Acquisition and Control Interface, emulated PV panel, 48V Lead-Acid Battery Pack, and DC 48V PWM Charge Controller to set up the stand-alone PV system for dc loads shown in the diagram of Figure 32. This system is the same as in Exercise 1. However, dc loads are not required in this exercise. Consequently, the *Load* terminals of the PWM charge controller are left open. Also, no specific work mode has to be set in the PWM charge controller. The battery and the PV panel should be connected to the PWM charge controller in the proper order. Proceed as follows to connect these components to the PWM charge controller.

- First, connect the 48V Lead-Acid Battery Pack to the *Battery* terminals of the PWM charge controller via current input *I1* of the Data Acquisition and Control Interface. On the 48V Lead-Acid Battery Pack, close the circuit breaker by setting its lever to the *I* (on) position. The PWM charge controller turns on and performs a short start-up routine as soon as the circuit breaker closes. Observe the middle LED (battery status LED) in the set of three LEDs on the PWM charge controller. This LED indicates the battery's state of charge (LED lit in green = full charge, LED lit in orange = middle charge, LED lit in red = low charge, LED blinking red = fully discharged). The battery status LED should be lit in green if the battery is partially discharged, as requested at the beginning of the exercise.



The battery status LED may be lit in orange if the battery is discharged more deeply than requested at the beginning of the exercise.

- Then, connect the emulated PV panel to the *PV panel* terminals of the PWM charge controller.

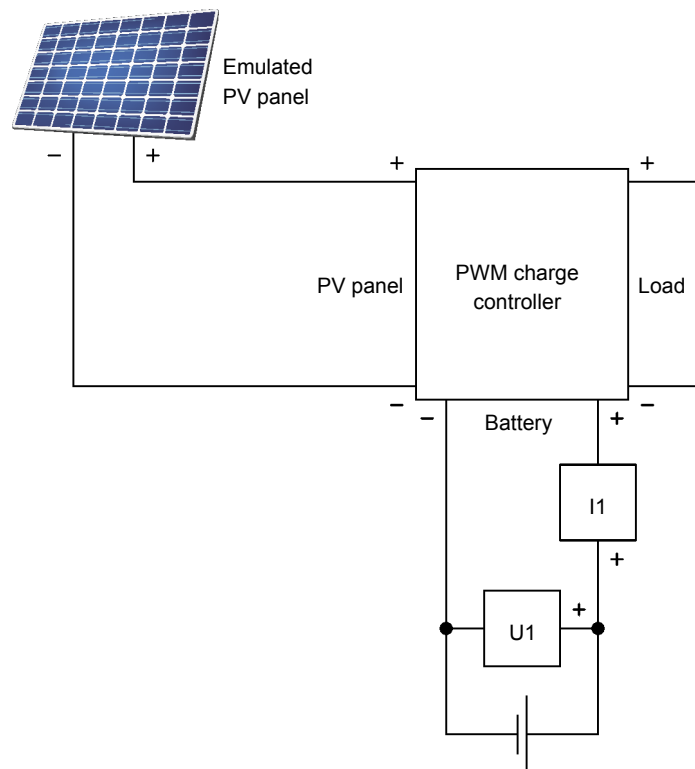


Figure 32. Stand-alone PV system for dc loads (no load connected).

16. In the [Four-Quadrant Dynamometer/Power Supply](#) window, start the [Solar Panel Emulator](#).

Observe the left-hand side LED (charging stage LED) in the set of three LEDs on the PWM charge controller. This LED indicates the stage of battery charging that the controller is in (LED off = no charge, LED blinking fast = bulk stage, LED lit continuously = absorption stage, LED blinking slowly = float stage). The charging stage LED should blink at a fast rate (indicating that the controller is in the bulk stage of battery charging) if the battery is partially discharged, as requested at the beginning of the exercise.

Operating point of the PV panel in a stand-alone PV system using a PWM charge controller

In this section, you will measure the current, voltage, and power at the PV panel as well as the current and voltage at the battery. You will use the results to verify if the PV panel operates near its maximum power point. You will increase the size of the PV panel by increasing the number of PV modules connected in series. You will make sure that the PV panel can still be used with the PWM charge controller without causing problems. You will measure the current, voltage, and power at the PV panel as well as the current and voltage at the battery. You will use the results to verify if the PV panel operates near its maximum power point. Finally, you will compare the results obtained with each of the two PV panels to determine the effect which increasing the number of PV modules in series has on the operating point of the PV panel.

17. Observe that the voltmeter and ammeter in the [Four-Quadrant Dynamometer/Power Supply](#) window indicate the PV panel voltage and current. Also observe that the power meter in the [Four-Quadrant Dynamometer/Power Supply](#) window indicates the amount of power which the PV panel produces.

In [LVDAC-EMS](#), open the [Metering](#) window and set a voltmeter and an ammeter to measure the dc voltage and current at the battery.

The voltmeter, ammeter, and power meter (PV panel voltage, current, and power) in the [Four-Quadrant Dynamometer/Power Supply](#) window as well as the voltmeter and ammeter set in the [Metering](#) window will be used throughout the exercise to monitor the operation of the stand-alone PV system for dc loads.

Make sure that continuous refresh of the meters is enabled in the [Metering](#) window.



The PV panel current is slightly larger than the battery charging current. This is because the PV panel provides the battery charging current and the current required for the operation of the PWM charge controller. The operating current of the PWM charge controller ranges from 0.05 A to 0.08 A, approximately.

18. Record the values of the voltage, current, and power at the PV panel indicated in the [Four-Quadrant Dynamometer/Power Supply](#) window. Also record the values of the voltage and current at the battery indicated in the [Metering](#) window.

PV panel voltage: _____ V

PV panel current: _____ A

PV panel power: _____ W

Battery voltage: _____ V

Battery current: _____ A

In the [Four-Quadrant Dynamometer/Power Supply](#) window, stop the [Solar Panel Emulator](#) to interrupt the production of electricity by the emulated PV panel, and thus, stop battery charging. The charging stage LED on the PWM charge controller should go out to indicate that the battery is no longer charging.

Based on the values you recorded above, does the PV panel operate close to its MPP? Explain briefly.

19. In the **Four-Quadrant Dynamometer/Power Supply** window, increase the size of the emulated PV panel by increasing the number of PV modules connected in series from 8 to 9.

According to the information provided in the **Four-Quadrant Dynamometer/Power Supply** window, what are the short-circuit current (I_{sc}), open-circuit voltage (U_{oc}), maximum power point (MPP) current, maximum power point (MPP) voltage, and maximum power point (MPP) of the emulated PV panel, at a solar irradiation of 1000 W/m^2 ?

Short-circuit current (I_{sc}): _____ A

Open-circuit voltage (U_{oc}): _____ V

MPP current (I_{MPP}): _____ A

MPP voltage (U_{MPP}): _____ V

MPP: _____ W (_____ A @ _____ V)

What is the effect of increasing the number of PV modules connected in series?

20. Table 8 provides the main specifications of the **DC 48V PWM Charge Controller**.

Table 8. Main specifications of the DC 48V PWM Charge Controller.

Parameter	Value
Maximum PV panel input current	7 A
Maximum PV panel input voltage	100 V
System voltage	48 V
Maximum load current	7 A

Based on the above specifications, can the **DC 48V PWM Charge Controller** be used with the emulated PV panel? Explain briefly.



Assume that the minimum operating temperature of the PV panel is 25°C .

- 21.** In the **Four-Quadrant Dynamometer/Power Supply** window, start the **Solar Panel Emulator** to make the emulated PV panel produce electricity. The charging stage LED on the PWM charge controller should start to blink at a fast rate to indicate that the battery is charging and the controller is in the bulk stage of battery charging.

Record the values of the voltage, current, and power at the PV panel indicated in the **Four-Quadrant Dynamometer/Power Supply** window. Also record the values of the voltage and current at the battery indicated in the **Metering** window.

PV panel voltage: _____ V

PV panel current: _____ A

PV panel power: _____ W

Battery voltage: _____ V

Battery current: _____ A

In the **Four-Quadrant Dynamometer/Power Supply** window, stop the **Solar Panel Emulator** to interrupt the production of electricity by the emulated PV panel, and thus, stop battery charging. The charging stage LED on the PWM charge controller should go out to indicate that the battery is no longer charging.

Based on the values you recorded above, does the PV panel operate close to its MPP? Explain briefly.

- 22.** Compare the PV panel voltage, current, and power as well as the battery voltage and current obtained with each of the two emulated PV panels.

Does increasing the number of PV modules connected in series make the PV panel produce significantly more power? Explain why.

Operating point of the PV panel in a stand-alone PV system using an MPPT charge controller

In this section, you will use the specifications of the **DC 48V MPPT Charge Controller** to verify that it can work with the emulated PV panel and battery without causing problems. You will replace the PWM charge controller in the stand-alone PV system with the **DC 48V MPPT Charge Controller**. You will measure the current, voltage, and power at the PV panel as well as the current and voltage at the battery. You will use the results to verify if the PV panel operates near its maximum power point. Finally, you will compare the results obtained with the **DC 48V MPPT Charge Controller** and the PWM charge controller to see if there is any significant difference in the amount of power the PV panel produces and the value of the current charging the battery.

- 23.** On the **48V Lead-Acid Battery Pack**, open the circuit breaker by setting its lever to the **O** (off) position.

Remove the PWM charge controller from the stand-alone PV system. To do so, disconnect the emulated PV panel from the PWM charge controller first. Then, disconnect the battery from the PWM charge controller.

- 24.** Table 9 provides the main specifications of the **DC 48V MPPT Charge Controller**.

Table 9. Main specifications of the DC 48V MPPT Charge Controller.

Parameter	Value
Maximum PV panel input current	7 A
Maximum PV panel input voltage	100 V
System voltage	12 V, 24 V or 48 V, automatic selection

Based on the above specifications, can the **DC 48V MPPT Charge Controller** be used with the emulated PV panel? Explain briefly.



Assume that the minimum operating temperature of the PV panel is 25°C.

Does the **DC 48V MPPT Charge Controller** match the battery (system) voltage?

☐ Yes ☐ No

25. Observe the **DC 48V MPPT Charge Controller**. Notice that a set of three LEDs, labelled *Bulk*, *Absorption*, and *Float*, are provided on the **DC 48V MPPT Charge Controller**. During battery charging, these LEDs indicate the stage of battery charging the **DC 48V MPPT Charge Controller** is in.

Also notice that the **DC 48V MPPT Charge Controller** has only two sets of terminals: one for the PV panel and one for the battery. No set of terminals is provided for dc loads. This is because no battery overdischarge protection is implemented in this particular charge controller. Nevertheless, DC loads can be connected to the battery terminals of the unit via an external battery overdischarge protection device.

On the **DC 48V MPPT Charge Controller**, make sure that the rotary switch located at the bottom of the unit is set to position 2. This sets the **DC 48V MPPT Charge Controller** for operation with a sealed, lead-acid battery.



*In the remainder of this exercise, the **DC 48V MPPT Charge Controller** is also simply referred to as the MPPT charge controller.*

26. Connect the MPPT charge controller to the stand-alone PV system. The battery and the PV panel should be connected to the MPPT charge controller in the proper order. Proceed as follows to connect these components to the MPPT charge controller.
- First, connect the battery to the *Battery* terminals of the MPPT charge controller via current input *I1* of the **Data Acquisition and Control Interface**. On the **48V Lead-Acid Battery Pack**, close the circuit breaker by setting its lever to the *I* (on) position. The *Bulk* LED on the MPPT charge controller should blink every 3 s to indicate that the unit is powered but no power is available to start battery charging.
 - Then, connect the emulated PV panel to the *PV Panel* terminals of the MPPT charge controller. The *Bulk* LED on the MPPT charge controller should continue to blink because the emulated PV panel does not produce electricity.
27. In the **Four-Quadrant Dynamometer/Power Supply** window, start the *Solar Panel Emulator* to make the emulated PV panel produce electricity. The *Bulk* LED on the MPPT charge controller should light up continuously to indicate that the bulk phase of battery charging is ongoing.

Let the PV system stabilize, i.e., let the MPPT charge controller find the maximum power point. This generally takes about 3 to 4 minutes.

Once the system has stabilized, record the values of the voltage, current, and power at the PV panel indicated in the **Four-Quadrant Dynamometer/Power Supply** window. Also record the values of the voltage and current at the battery indicated in the **Metering** window.



*To track the maximum power point of the PV panel, the MPPT charge controller varies the operating point of the PV panel at regular intervals. This makes the values of voltage, current, and power indicated in the **Four-Quadrant Dynamometer/Power Supply** window and the **Metering** window fluctuate from time to time. Consequently, record the values of voltage, current, and power when the value of the PV panel power indicated in the **Four-Quadrant Dynamometer/Power Supply** window is maximal.*

PV panel voltage: _____ V

PV panel current: _____ A

PV panel power: _____ W

Battery voltage: _____ V

Battery current: _____ A

Based on the values you recorded above, does the PV panel operate close to its MPP? Explain briefly.

- 28.** In the *Four-Quadrant Dynamometer/Power Supply* window, stop the *Solar Panel Emulator* to interrupt the production of electricity by the emulated PV panel, and thus, stop battery charging. The *Bulk* LED on the MPPT charge controller should blink every 3 s to indicate that the unit is still powered but no power is available to continue battery charging.

Observe the values of the PV panel voltage and battery voltage that you recorded in the previous step. Notice that the PV panel voltage is significantly higher than the battery voltage. Briefly explain why.

Compare the values of the PV panel current and battery current that you recorded in the previous step. Does the MPPT charge controller convert the excess in the PV panel voltage into additional current for charging the battery?

- 29.** Compare the PV panel voltage, current, and power as well as the battery voltage and current obtained using the MPPT charge controller (recorded in step 27) with those obtained using the PWM charge controller (recorded in step 21), then answer the following questions.

What is the effect of using the MPPT charge controller instead of the PWM charge controller on the PV panel voltage, current, and power. Explain briefly.

What is the effect of using the MPPT charge controller instead of the PWM charge controller on the battery current?

Does this demonstrate that when a PV panel is not well matched with the battery (system) voltage, an MPPT charge controller should be used in a stand-alone PV system to ensure that the PV panel is used as efficiently as possible? Explain briefly.

- 30.** In the **Four-Quadrant Dynamometer/Power Supply** window, make sure that the **Solar Panel Emulator** is stopped.

Close **LVDAC-EMS**.

- 31.** On the **48V Lead-Acid Battery Pack**, open the circuit breaker by setting its lever to the **O** (off) position.

Turn the **4 Quadrant Power Supply and Dynamometer Controller** off.

Turn the **AC 24V Power Supply** off.

Turn electric power off at your workstation, if applicable. Remove all circuit connections, finishing with the equipment earthing connections. Return all equipment to its storage location.

CONCLUSION

In this exercise, you became familiar with the topology, operation, and unique features of the MPPT charge controller. You saw that in stand-alone PV systems using an on-off or PWM charge controller, a PV panel matching the battery (system) voltage as closely as possible is required to enable operation close to the maximum power point (MPP). You also saw that using an MPPT charge controller in stand-alone PV systems allows operation at the MPP (when required) even if the PV panel voltage at the MPP does not match the battery (system) voltage. Finally, you learned how the on-off, PWM, and MPPT charge controllers compare in terms of performance and cost.

REVIEW QUESTIONS

1. What type of device is used in an MPPT charge controller to achieve battery charging control?

2. Compare the on-off, PWM, and MPPT charge controllers in terms of battery charging performance.

3. Briefly explain why operation at the MPP is not possible when the PV panel is not well matched with the battery in a stand-alone PV system implemented using an on-off or PWM charge controller.

4. The dc voltage at the PV panel input of an MPPT charge controller is 55.2 V. The duty cycle of the buck chopper in the MPPT charge controller is 0.25. What is the value of the voltage that the MPPT charge controller applies to the battery?

5. Describe two unique features of the MPPT charge controller?

Stand-Alone PV Systems for AC Loads

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the configuration and operation of stand-alone PV systems for ac loads. You will also be familiar with the operation of the stand-alone inverter. You will be able to verify that the PV panel, charge controller, battery, and stand-alone inverter selected for a specific stand-alone PV system can work together without causing problems. You will know common applications of stand-alone PV systems for ac loads. Finally, you will also know that using energy-efficient electric equipment is a means of reducing the size and cost of the stand-alone PV system for ac loads required in any application.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to stand-alone PV systems for ac loads
- Physical representation of a stand-alone PV system for ac loads
- Selection of the PV panel, charge controller, battery, and stand-alone inverter for a specific stand-alone PV system
- Applications of stand-alone PV systems for ac loads
Electric power provision in homes. Electric power provision in small buildings.
- Effect of using energy-efficient electric equipment on the size and cost of stand-alone PV systems for ac loads

DISCUSSION

Introduction to stand-alone PV systems for ac loads

Figure 33 shows a simplified diagram of a stand-alone PV system for ac loads. In fact, the system simply consists of a stand-alone PV system for dc loads, i.e., a PV panel, a battery, and a charge controller, plus a **stand-alone inverter**.



Several elements, such as the PV panel blocking and bypass diodes, PV panel lightning surge arrester, PV panel fused disconnect switch, and load circuit-breaker panel, have been omitted in the simplified diagram of Figure 33 for the sake of clarity.

The charge controller in a stand-alone PV system for ac loads can be of the on-off, PWM, or MPPT type.

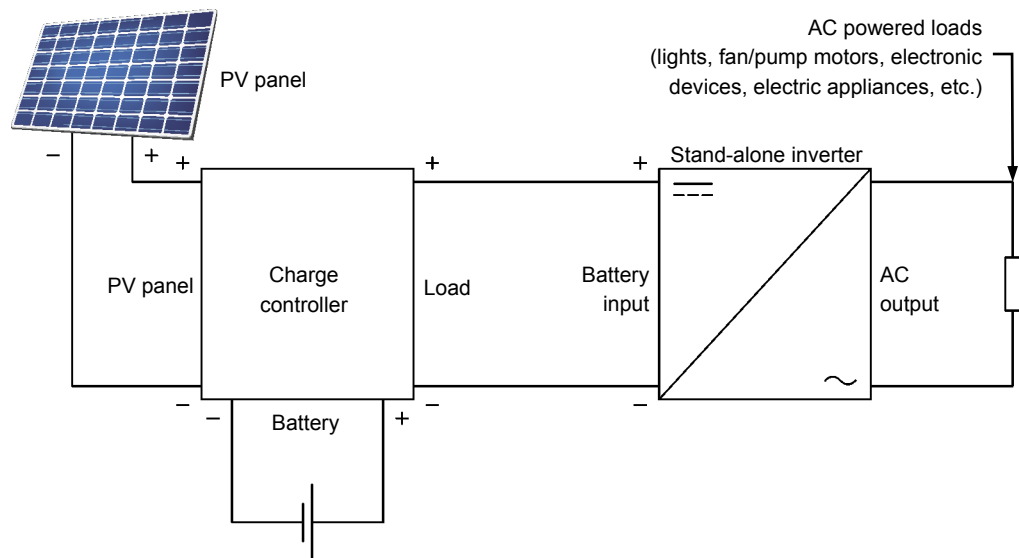


Figure 33. Simplified diagram of a stand-alone PV system for ac loads (stand-alone inverter connected to load terminals of charge controller).

Stand-alone inverters are also referred to as off-grid inverters or PWM inverters.

The PV panel, battery, and charge controller in a PV system for ac loads operate the same way as in a PV system for dc loads. The stand-alone inverter uses electronic circuitry and electronic power switches to convert dc power into conventional ac power. Power losses in the stand-alone inverter are maintained as low as possible, generally resulting in a power efficiency between 80% and 95%. The stand-alone inverter has two distinct sets of terminals: one that serves to feed dc power into the unit (battery input) and one that provides the ac power produced by the unit (ac output). Loads requiring conventional ac power, such as household appliances (e.g., refrigerators, washers, TV sets, computers, etc.), lighting fixtures, fan/pump motors, etc., are connected to the ac output of the stand-alone inverter.

Battery overdischarge protection in stand-alone inverters is sometimes referred to as the battery low shutdown or the low-voltage cutoff.

Battery overdischarge protection is implemented in most stand-alone inverters because dc power comes from a battery in many applications. Battery overdischarge protection in a stand-alone inverter operates similarly to a charge controller. When the battery voltage decreases down to the low-voltage disconnect (LVD) setpoint, the stand-alone inverter stops supplying ac power to the load to prevent overdischarge of the battery. When the battery voltage increases up to the low-voltage reconnect (LVR) setpoint, the inverter resumes supplying ac power to the loads. Consequently, when a stand-alone inverter with battery overdischarge protection is used in a PV system for ac loads, it can be connected in parallel with the battery directly (instead of being connected to the load terminals of the charge controller) without risk. This is shown in Figure 34.

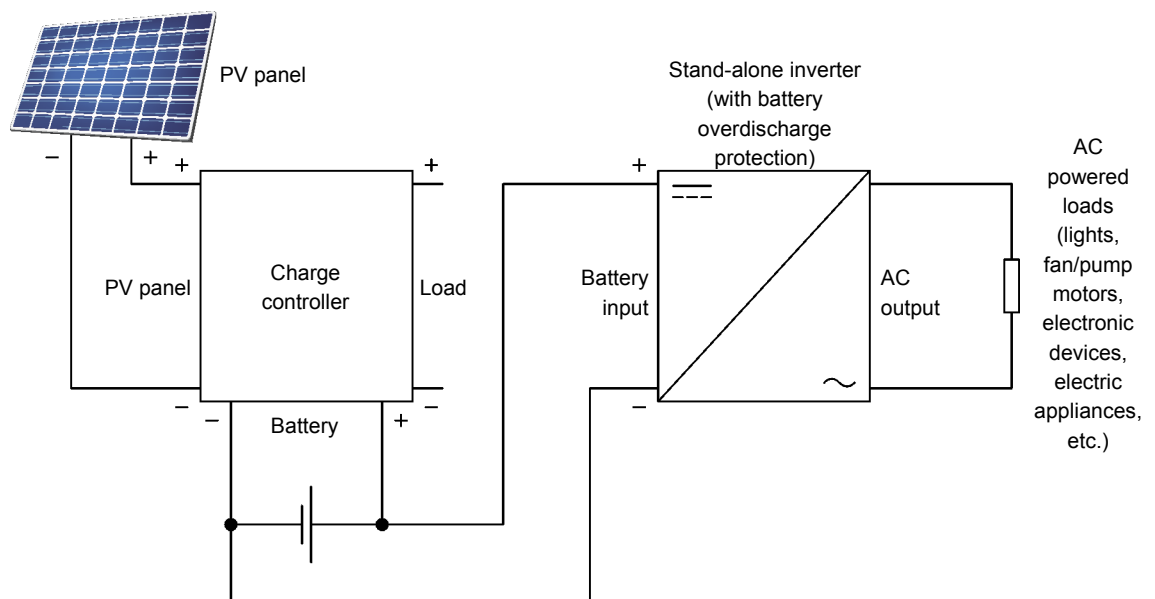


Figure 34. Simplified diagram of a stand-alone PV system for ac loads (stand-alone inverter connected in parallel with battery).

In fact, it is common practice in stand-alone PV systems for ac loads to connect the stand-alone inverter with battery overdischarge protection in parallel with the battery directly, for the reasons presented below.

- The charge controller may perceive the stand-alone inverter as an excessive load connected to its load terminals and automatically disconnect these terminals from the PV panel and battery. This is because a large capacitor in most stand-alone inverters causes a large current inrush when power is applied to the battery input of the inverter. When the value of the inrush current exceeds a certain threshold, the charge controller perceives an overcurrent condition at its load terminals and automatically disconnects these terminals from the PV panel and battery. Consequently, no power can be supplied to the ac loads.
- The power efficiency of the stand-alone PV system is improved slightly. This is because power is routed to the ac loads without passing through the load terminals of the charge controller. This bypasses the power switching device used to implement battery overdischarge protection in the charge controller, thereby slightly reducing power losses in the system.
- The size (i.e., the maximum current rating) of the charge controller can be reduced in certain applications. This is because when the stand-alone inverter is connected to the battery directly, the maximum load current of the charge controller does not have to match the maximum power demand of the ac loads. Consequently, sizing of the charge controller can be based on the short-circuit current (I_{SC}) of the PV panel only. In applications with high-power ac loads, this generally allows the size (maximum current rating) of the charge controller to be reduced.

Physical representation of a stand-alone PV system for ac loads

Figure 35 is an example of the physical representation of a stand-alone PV system for ac loads. In this example, the PV panel is installed on the roof of a building. The PV panel could also be installed on a support located close to the building. The charge controller, battery, and stand-alone inverter are generally located inside the building so they are protected from weather. The charge

controller, the battery, and the stand-alone inverter are located as close as possible to each other in order to minimize the length of the interconnecting leads. Note that because the PV panel is installed outdoors, the leads connecting the PV panel to the charge controller are generally quite long (i.e., much longer than the leads interconnecting the charge controller, battery, and stand-alone inverter).



Several elements, such as the PV panel blocking and bypass diodes, PV panel lightning surge arrester, PV panel fused disconnect switch, and load circuit-breaker panel, have been omitted in the simplified representation of Figure 35 for the sake of clarity.

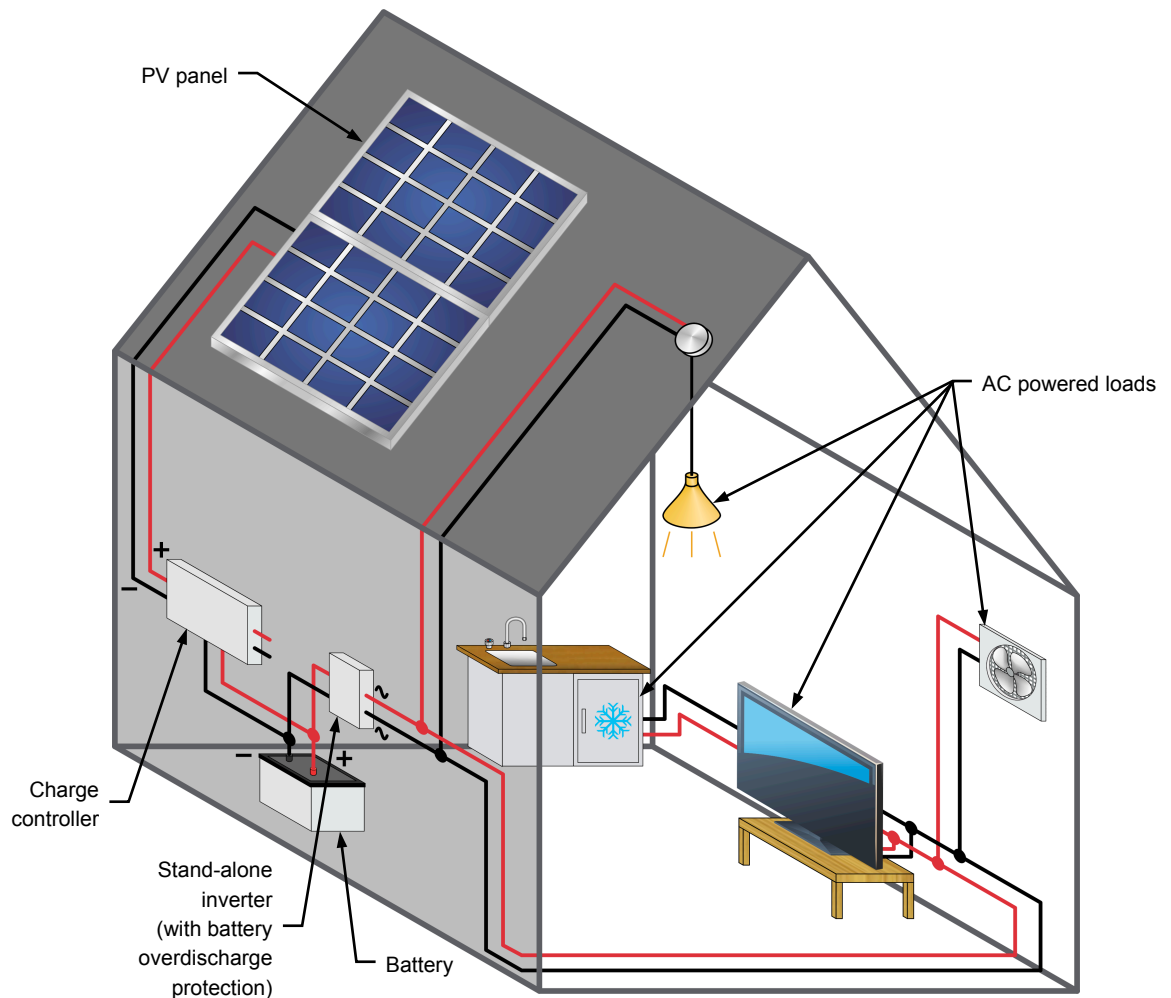


Figure 35. Simplified physical representation of a stand-alone PV system for ac loads.

Selection of the PV panel, charge controller, battery, and stand-alone inverter for a specific stand-alone PV system

Table 10 presents the key specifications that must be considered when making sure that the PV panel, charge controller, battery, and stand-alone inverter selected for a specific stand-alone PV system can work together without causing problems.

Table 10. Key specifications to be considered when making sure that the PV panel, charge controller, battery, and stand-alone inverter selected for a specific stand-alone PV system can work together without causing problems.

Component	Specified parameter	Description of parameter
PV panel	Short-circuit current (I_{sc})	Current that flows through the PV panel when its terminals are short-circuited, measured under standard test conditions (STC).
	Open-circuit voltage (U_{oc})	Voltage which the PV panel produces when its terminals are left open, measured under standard test conditions (STC).
	Rated power	Maximum power point (MPP) of the PV panel, measured under standard test conditions (STC).
	Rated power voltage	Voltage which the PV panel produces when it operates at rated power (i.e., at MPP).
Charge controller	Maximum PV panel input current	Maximum current that can flow through the PV panel input terminals of the charge controller without causing overheating of the unit (and eventual damage to the unit).
	Maximum PV panel input voltage	Maximum voltage that can be applied across the PV panel input terminals of the charge controller without causing damage to the unit.
	Maximum PV panel input power	Maximum power that can be applied at the PV panel input of the charge controller without causing overheating of the unit (and eventual damage to the unit).
	MPP tracking voltage range	Minimum and maximum values of voltage at the PV panel input of the charge controller for which MPP tracking operates.
	System (load) voltage	Nominal voltage across the battery terminals and load terminals of the charge controller.
	Maximum load current	Maximum load current that can flow through the charge controller without causing overheating of the unit (and eventual damage to the unit).
Battery	Nominal voltage	Nominal voltage across the battery terminals.

Component	Specified parameter	Description of parameter
Stand-alone inverter	Battery input voltage range	Minimum and maximum values of voltage across the battery input terminals of the inverter. Voltage must remain within the values above for the inverter to operate.
	Nominal ac output voltage	RMS value of nominal voltage across the ac output terminals of the inverter.
	Nominal ac output frequency	Nominal frequency of the voltage across the ac output terminals of the inverter.
	AC output waveform	Waveform of the voltage across the ac output terminals of the inverter. Can be a pure sine wave or a waveform that resembles a sine wave.
	Maximum ac output power	Maximum power which the inverter can provide at its ac output, continuously.



In most charge controllers, the maximum PV panel input current and the maximum load current have the same value.

Making sure that the PV panel, charge controller, and battery selected for a specific stand-alone PV system can work together without causing problems is the same no matter if the system powers dc loads or ac loads. This has been covered in the discussion of Exercise 1. However, when an MPPT charge controller is used in the stand-alone PV system considered, the following two steps are added to those given in the discussion of Exercise 1. These steps must be performed to ensure that the PV panel and MPPT charge controller can work together optimally.

1. The maximum PV panel input power of the MPPT charge controller must be larger than the rated power of the PV panel. This ensures that damage to the charge controller due to overheating cannot occur.
2. The rated power voltage of the PV panel must be within the MPP tracking voltage range of the MPPT charge controller. This ensures that the charge controller can make the PV panel operate at the MPP.

Furthermore, when the specific stand-alone PV system considered powers ac loads, the following steps must also be performed to make sure that the stand-alone inverter can work with the other components in the system without causing problems.

1. The battery input voltage range of the stand-alone inverter must match the battery (system) voltage. Furthermore, the battery input voltage range of the stand-alone inverter must be large enough to accommodate variations in voltage experienced during battery charging and battery discharging.
2. The nominal ac output voltage and frequency of the stand-alone inverter must be the same as the nominal voltage and frequency of the ac loads to be powered.

3. The waveform of the voltage at the ac output of the stand-alone inverter must be compatible with the ac loads to be powered. Certain ac powered loads (e.g., induction motors) require sinusoidal voltage to operate properly. Stand-alone inverters producing a voltage waveform that is not purely sinusoidal should be avoided in this case.
4. The power rating of any one of the ac loads connected to the system must not exceed the maximum ac output power of the stand-alone inverter, otherwise overheating of the inverter can occur.

Applications of stand-alone PV systems for ac loads

Stand-alone PV systems for ac loads are used for the provision of conventional ac power in some specific applications. This section describes these applications of stand-alone PV systems for ac loads.

Electric power provision in homes

Stand-alone PV systems for ac loads are used to provide conventional ac power in homes that are not connected to the grid. Such homes are generally located in remote locations where grid power is not available because of technical restrictions or because the cost of the power line required to route grid power to the home is prohibitive. The ac powered equipment in this type of application generally consist of conventional household appliances (e.g., refrigerators, microwave ovens, washers, TV sets, etc.) as well as electric equipment that is common in a home (e.g., lighting fixtures, fan/pump motors, etc.).



Figure 36. Home located in a remote location and powered by a stand-alone PV system for ac loads.

Electric power provision in small buildings

Stand-alone PV systems for ac loads are commonly used to provide conventional ac power to low-power electric equipment in small buildings that are not connected to the grid (e.g., farm buildings, green houses, etc.) or that are in remote locations (e.g., hunting/fishing cabins, mountain refuges, etc.). The ac powered equipment in this type of application generally consists of low-power, conventional household appliances (e.g., small refrigerators, AM/FM radios, cell phone/computer battery chargers, etc.) and/or low-power electric equipment (e.g., lighting fixtures, fan/pump motors, etc.).



Figure 37. Small cabin powered by a stand-alone PV system.

Effect of using energy-efficient electric equipment on the size and cost of stand-alone PV systems for ac loads

In the discussion of Exercise 1, it has been demonstrated that reducing the total daily energy demand of the loads connected to a stand-alone PV system is highly desirable because it reduces the size, and thus the cost, of the system required in any application. This is generally achieved by using electric equipment that is energy efficient, i.e., loads that require less power to perform the same task. This holds true no matter if the stand-alone PV system supplies power to dc loads or ac loads. For instance, using LED lamps or compact fluorescent lamps (CFLs) instead of conventional incandescent lamps for lighting is a good means of reducing the total daily energy demand, and thus, the size of a stand-alone PV system for ac loads. This is due to the fact that an LED lamp generally uses about 5 to 7 times less energy than a conventional incandescent lamp to produce an equivalent amount of light. Similarly, a CFL generally uses about 4 to 5 times less energy than a conventional incandescent lamp to produce an equivalent amount of light.

In conclusion, let's consider a home where ten 60 W incandescent lamps are required for lighting. Considering that the lamps are lit 4 hours a day, this results in a daily energy demand of 2400 Wh. On the other hand, using LED lamps that

are assumed to consume 5 times less energy than the incandescent lamps results in a daily energy demand of 480 Wh, a substantial reduction of 1920 Wh in the total daily energy demand. Over a complete year, this represents a reduction in the total energy demand of about 701 kWh. Similarly, using CFLs that are assumed to consume 4 times less energy than the incandescent lamps results in a daily energy demand of 600 Wh, a substantial reduction of 1800 Wh in the total daily energy demand. Over a complete year, this represents a reduction in the total energy demand of 657 kWh.



Figure 38. LED lamps use about 5 to 7 times less energy than conventional incandescent lamps to produce an equivalent amount of light. Similarly, compact-fluorescent lamps (CFLs) use about 4 to 5 times less energy than conventional incandescent lamps to produce an equivalent amount of light.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Emulated PV panel settings
- Main components of a stand-alone PV system for ac loads
- Setting up a stand-alone PV system for ac loads
- Operation of the stand-alone inverter
- Comparing the energy consumption of different types of ac lamps
- Battery overdischarge protection function of the stand-alone inverter

WARNING



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

PROCEDURE

Setup and connections

In this section, you will set up and connect the equipment required to perform the exercise.

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

Install the equipment in the workstation. You will use this equipment later in this exercise to set up a stand-alone PV system for ac loads.



*Before continuing this exercise, measure the open-circuit voltage of the **48V Lead-Acid Battery Pack**. If the open-circuit voltage is lower than 51.2 V, ask your instructor for assistance as the **48V Lead-Acid Battery Pack** is probably not fully charged. Appendix D below of this manual indicates how to fully charge the **48V Lead-Acid Battery Pack** before a lab period.*

Make the connections required to earth the equipment properly.



If necessary, check with the instructor to ensure that the connections you made provide proper earthing of the equipment.

2. Make sure that the main power switch of the **4 Quadrant Power Supply and Dynamometer Controller** is set to the **O** (off) position, then connect its **Power Input** to an ac power outlet that is properly protected.

Make sure that the main power switch of the **AC 24V Power Supply** is set to the **O** (off) position, then connect its **Power Input** to an ac power outlet that is properly protected.



If necessary, check with the instructor to ensure that the ac power outlets to which you connect the equipment are properly protected.

3. Connect the **Power Input** of the **Data Acquisition and Control Interface** to the **AC 24V Power Supply**.
4. Ask your instructor to turn on (i.e., to unlock) electric power at your workstation, if applicable.
5. Turn the **AC 24V Power Supply** on.
6. Turn the **4 Quadrant Power Supply and Dynamometer Controller** on, then set the **Operating Mode** switch to **Power Supply**.
7. Connect the USB port of the **Data Acquisition and Control Interface** to a USB port of the host computer.

Connect the USB port of the **4 Quadrant Power Supply and Dynamometer Controller** to a USB port of the host computer.
8. 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 **4 Quadrant Power Supply and Dynamometer Controller** are detected. Make sure that the **Basic Computer-Based Instrumentation** function for the **Data Acquisition and Control Interface** is available. Also make sure that the **Solar Panel Emulator** and **Lead-Acid Battery Charger** functions for the **4 Quadrant Power Supply and Dynamometer Controller** are available. Select the network voltage and frequency of your local ac power network, then click the **OK** button to close the **LVDAC-EMS Start Up** window.

Emulated PV panel settings

In this section, you will set the size of the emulated PV panel that will be used to implement a stand-alone PV system for ac loads.

9. 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 **4 Quadrant Power Supply and Dynamometer Controller** operate like a solar (PV) panel. The output terminals of the power supply are the terminals of the emulated PV panel.
 - Make sure that the **Solar Irradiance Control** parameter is set to **Slider**. This allows the solar irradiance to be controlled manually.
 - Set the **Solar Irradiance** parameter to 1000 W/m².
 - Set the **Number of PV modules in series** parameter to 9. Set the **Number of PV modules in parallel** parameter to 16. These two settings set the size of the emulated PV panel to 9 PV modules in series and 16 PV modules in parallel.
 - Make sure that the **Status** parameter is set to **Stopped**. This prevents the emulated PV panel from producing electricity even if the solar irradiation is currently set to 1000 W/m².

Main components of a stand-alone PV system for ac loads

In this section, you will gather the key specifications of the emulated PV panel, 48V Lead-Acid Battery Pack, DC 48V MPPT Charge Controller, 1AC 230V Stand-Alone Inverter, and AC 230V Lamps module. You will then use these specifications to verify that these pieces of equipment can work together without causing problems.

10. Observe that the electrical specifications of each PV module in the emulated PV panel are indicated in the **Four-Quadrant Dynamometer/Power Supply** window.



In the remainder of this exercise, the emulated PV panel is also simply referred to as the PV panel.

According to the information provided in the **Four-Quadrant Dynamometer/Power Supply** window, what are the short-circuit current (I_{sc}), open-circuit voltage (U_{oc}), maximum power point (MPP) current, maximum

power point (MPP) voltage, and maximum power point (MPP) of the emulated PV panel, at a solar irradiation of 1000 W/m²?

Short-circuit current (I_{sc}): _____ A

Open-circuit voltage (U_{oc}): _____ V

MPP current (I_{MPP}): _____ A

MPP voltage (U_{MPP}): _____ V

MPP: _____ W (_____ A @ _____ V)

11. Observe the **48V Lead-Acid Battery Pack**. What are the battery voltage and battery capacity?



*In the remainder of this exercise, the **48V Lead-Acid Battery Pack** is also referred to as the battery.*

Battery voltage: _____ V

Battery capacity: _____ Ah

12. Table 11 provides the main specifications of the **DC 48V MPPT Charge Controller**.



*In the remainder of this exercise, the **DC 48V MPPT Charge Controller** is also referred to as the MPPT charge controller.*

Table 11. Main specifications of the DC 48V MPPT Charge Controller.

Parameter	Value
Maximum PV panel input current	7 A
Maximum PV panel input voltage	100 V
Maximum PV panel input power	630 W
MPP tracking voltage range	60 V to 90 V
System voltage	12 V, 24 V or 48 V, automatic selection

Based on the above specifications, can the **DC 48V MPPT Charge Controller** be used with the emulated PV panel? Explain briefly.



Assume that the minimum operating temperature of the PV panel is 25°C.

Does the **DC 48V MPPT Charge Controller** match the battery (system) voltage?

☐ Yes ☐ No

- 13.** Table 12 provides the main specifications of the **1AC 230V Stand-Alone Inverter**. Notice that the waveform of the voltage at the ac output of this inverter is a pure sine wave. The **1AC 230V Stand-Alone Inverter** can thus be used to power ac loads of any type.



In the remainder of this exercise, the **1AC 230V Stand-Alone Inverter** is also referred to as the stand-alone inverter.

Table 12. Main specifications of the 1AC 230V Stand-Alone Inverter.

Parameter	Value
Battery input voltage range	42 V to 60 V
Nominal ac output voltage	230 V
Nominal ac output frequency	50 Hz
AC output waveform	Pure sine wave
Maximum ac output power	280 W

Does the battery input voltage range of the **1AC 230V Stand-Alone Inverter** match the battery (system) voltage? Explain briefly.

14. Observe the **AC 230V Lamps** module. Notice that the incandescent lamp, the compact fluorescent lamp, and the LED lamp in the **AC 230V Lamps** module are all rated 230 V – 50/60 Hz. Are these lamps compatible with the **1AC 230V Stand-Alone Inverter**? Explain briefly.

Note the power rating of the incandescent lamp, the compact fluorescent lamp, and the LED lamp in the **AC 230V Lamps** module. Can the **1AC 230V Stand-Alone Inverter** supply ac power to these lamps without a problem? Explain briefly.

Setting up a stand-alone PV system for ac loads

*In this section, you will set up a stand-alone PV system for ac loads using the **Data Acquisition and Control Interface**, emulated PV panel, **48V Lead-Acid Battery Pack**, **DC 48V MPPT Charge Controller**, **1AC 230V Stand-Alone Inverter**, and **AC 230V Lamps** module.*

15. On the **1AC 230V Stand-Alone Inverter**, make sure that the power switch is set to the **O (Off)** position.

Use the **Data Acquisition and Control Interface**, emulated PV panel, **48V Lead-Acid Battery Pack**, **DC 48V MPPT Charge Controller**, **1AC 230V Stand-Alone Inverter**, and **AC 230V Lamps** module to set up the stand-alone PV system for ac loads shown in the diagram of Figure 39. In this system, the ac loads consist of the incandescent lamp, the compact fluorescent lamp, and the LED lamp in the **AC 230V Lamps** module. The battery and the PV panel should be connected to the MPPT charge controller in the proper order. Proceed as follows to connect these components to the MPPT charge controller.

- First, connect the battery to the **Battery** terminals of the MPPT charge controller. On the **48V Lead-Acid Battery Pack**, close the circuit breaker by setting its lever to the **I (on)** position. The **Bulk** LED on the MPPT charge controller should blink every 3 s to indicate that the unit is powered but no power is available to start battery charging.
- Then, connect the emulated PV panel to the **PV Panel** terminals of the MPPT charge controller. The **Bulk** LED on the MPPT charge controller should continue to blink because the emulated PV panel does not produce electricity.

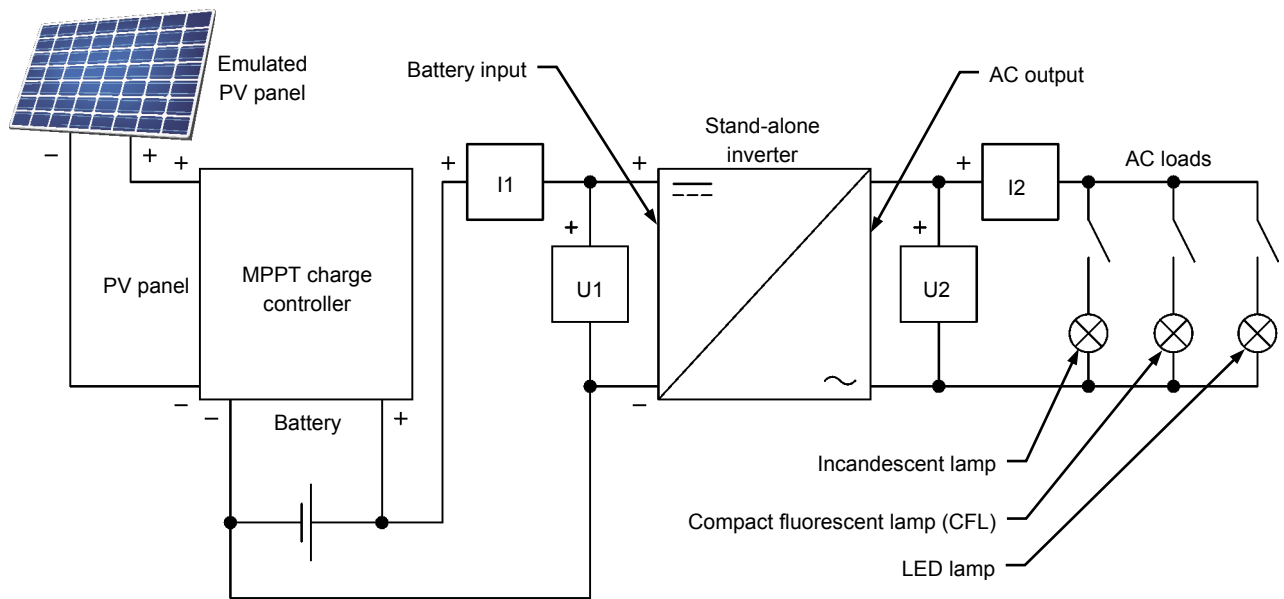


Figure 39. Stand-alone PV system for ac loads.

16. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **Solar Panel Emulator** to make the emulated PV panel produce electricity. The **Bulk** LED on the MPPT charge controller should stop blinking and be lit continuously to indicate that the bulk phase of battery charging is ongoing.

The MPPT charge controller should pass from the bulk stage of battery charging to the float stage of battery charging in about 2 to 3 minutes, if the battery is fully charged as requested at the beginning of the exercise. The **Bulk** and **Absorption** LEDs should be off and the **Float** LED should be lit continuously when the MPPT charge controller is in the float stage of battery charging.

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

In the **Metering** window, set a voltmeter and an ammeter to measure the dc voltage and current at the battery input of the stand-alone inverter. Also, set a voltmeter and an ammeter to measure the voltage and current at the ac output of the stand-alone inverter. Set up a meter to measure power at the battery input of the stand-alone inverter. Finally, set up a meter to measure active power at the ac output of the stand-alone inverter.

Make sure that continuous refresh of the meters is enabled in the **Metering** window.

18. In **LVDAC-EMS**, open the **Oscilloscope**, then make the settings required to observe the voltage and current at the ac output of the stand-alone inverter (voltage input **U2** and current input **I2**). The following vertical sensitivity and time base are suggested: 100 V/div, 0.2 A/div, and 5 ms/div.

Operation of the stand-alone inverter

In this section, you will observe the operation of the stand-alone inverter.

- 19.** On the [AC 230V Lamps](#) module, make sure that all lamp switches are set to the **O** (Off) position.

On the [1AC 230V Stand-Alone Inverter](#), set the power switch to the **I** (On) position. The [1AC 230V Stand-Alone Inverter](#) should emit a short beep sound to indicate that it turns on. Also, the [Status](#) LED on the [1AC 230V Stand-Alone Inverter](#) should light up in green to indicate that the unit operates normally.

- 20.** On the [Oscilloscope](#), select continuous refresh of the display. Observe the waveform of the voltage at the ac output of the stand-alone inverter displayed on the [Oscilloscope](#).

Describe the waveform of the voltage at the ac output of the stand-alone inverter.

- 21.** Use the [Oscilloscope](#) to measure the RMS value and frequency of the voltage at the ac output of the stand-alone inverter.

The RMS value of the voltage at the ac output of the stand-alone inverter should be 230 V, approximately. The frequency of the voltage at the ac output of the stand-alone inverter should be exactly 50.0 Hz.

- 22.** On the [AC 230V Lamps](#) module, turn the three lamps on. Observe that the waveform of the current at the ac output of the stand-alone inverter is distorted severely. This is because the compact fluorescent lamp and the LED lamp draw pulses of current from the stand-alone inverter, as you will see later in this exercise.

Record the values of power at the battery input and ac output of the stand-alone inverter indicated in the [Metering](#) window.

Power at battery input of the inverter (P_{DC}): _____ W

Power at ac output of the inverter (P_{AC}): _____ W

Calculate the power efficiency of the stand-alone inverter using the power values above and the equation below.

$$\eta = \frac{P_{AC}}{P_{DC}} \times 100\%$$

Does the stand-alone inverter convert power at its battery input into ac power efficiently?

Comparing the energy consumption of different types of ac lamps

In this section, you will compare the energy consumption of three ac lamps of different types (incandescent, compact fluorescent, and LED) which produce approximately the same amount of light.

- 23.** On the [AC 230V Lamps](#) module, turn the compact fluorescent lamp and the LED lamp off.

On the [Oscilloscope](#), observe that the waveform of the incandescent lamp current is a sine wave with no significant distortion.

Record the incandescent lamp voltage, current, and power indicated in the [Metering](#) window (i.e., the values indicated by the meters measuring the voltage, current, and power at the ac output of the stand-alone inverter).

Incandescent lamp voltage: _____ V

Incandescent lamp current: _____ A

Incandescent lamp power: _____ W

Use the lamp power you just measured to calculate the daily energy demand of the incandescent lamp. Base your calculation on 4 hours of use per day.

- 24.** Notice the amount of light which the incandescent lamp produces. On the [AC 230V Lamps](#) module, turn the incandescent lamp off, then turn the compact fluorescent lamp on. Do the two lamps produce approximately the same amount of light?

☐ Yes ☐ No

On the [Oscilloscope](#), observe that the waveform of the compact fluorescent lamp current consists of pulses of current (one pulse of current every half-cycle of the voltage waveform). Also, observe that the polarity of the pulses of current alternates from one pulse to the next.

Record the compact fluorescent lamp voltage, current, and power indicated in the [Metering](#) window.

Compact fluorescent lamp voltage: _____ V

Compact fluorescent lamp current: _____ A

Compact fluorescent lamp power: _____ W

Use the lamp power you just measured to calculate the daily energy demand of the compact fluorescent lamp. Base your calculation on 4 hours of use per day.

- 25.** Notice the amount of light which the compact fluorescent lamp produces. On the [AC 230V Lamps](#) module, turn the compact fluorescent lamp off, then turn the LED lamp on. Do the two lamps produce approximately the same amount of light?

☐ Yes ☐ No

On the [Oscilloscope](#), observe that the waveform of the LED lamp current consists of pulses of current (one pulse of current every half-cycle of the voltage waveform). Also, observe that the polarity of the pulses of current alternates from one pulse to the next.

Record the LED lamp voltage, current, and power indicated in the [Metering](#) window.

LED lamp voltage: _____ V

LED lamp current: _____ A

LED lamp power: _____ W

Use the lamp power you just measured to calculate the daily energy demand of the LED lamp. Base your calculation on 4 hours of use per day.

On the [AC 230V Lamps](#) module, turn the LED lamp off.

- 26.** Compare the daily energy demand of the compact fluorescent lamp with that of the incandescent lamp.

Compare the daily energy demand of the LED lamp with that of the incandescent lamp.

Does this confirm that the compact fluorescent lamp and the LED lamp are both more efficient than the incandescent lamp at converting electricity into light? Explain briefly.

- 27.** In the **Four-Quadrant Dynamometer/Power Supply** window, stop the **Solar Panel Emulator** to interrupt the production of electricity by the emulated PV panel.

On the **1AC 230V Stand-Alone Inverter**, set the power switch to the **O (Off)** position to turn the unit off.

Battery overdischarge protection function of the stand-alone inverter

In this section, you will observe the operation of the battery overdischarge protection implemented in the stand-alone inverter.

- 28.** Disconnect the emulated PV panel from the PV system.

On the **48V Lead-Acid Battery Pack**, open the circuit breaker by setting its lever to the **O (off)** position.

- 29.** In the **Four-Quadrant Dynamometer/Power Supply** window, make the following settings:

- Set the **Function** parameter to **DC Voltage Source**. This function makes the power supply in the **4 Quadrant Power Supply and Dynamometer Controller** operate like a variable-voltage dc source. The output terminals of the power supply are the terminals of the dc source.
- Make sure that the **Voltage Control** parameter is set to **Knob**. This allows the dc source voltage to be controlled manually.
- Set the **Voltage** parameter to 51.2 V. This sets the dc source voltage to 51.2 V. This corresponds to the nominal open-circuit voltage of a 48 V lead-acid battery pack that is fully charged.
- Make sure that the **Status** parameter is set to **Stopped**. This ensures that the dc source is disabled (i.e., it produces no voltage).

30. Replace the battery in the PV system by the variable-voltage dc source implemented using the **4 Quadrant Power Supply and Dynamometer Controller**. The equipment should be connected as shown in Figure 40.

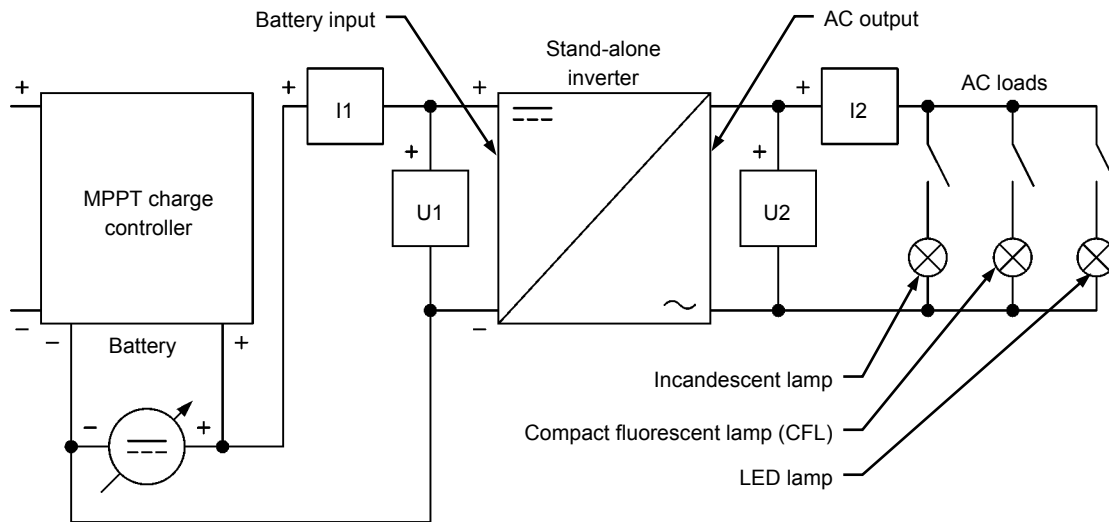


Figure 40. Circuit used to observe the operation of the battery discharge protection implemented in the stand-alone inverter.

Varying the dc source voltage in the circuit above varies the voltage applied across the **Battery** terminals of the MPPT charge controller and the **Battery Input** terminals of the stand-alone inverter. This allows the battery state of charge perceived by the stand-alone inverter to be changed rapidly.

31. In the **Four-Quadrant Dynamometer/Power Supply** window, start the dc source. The **Bulk** LED on the MPPT charge controller should blink every 3 s to indicate that the unit is powered but no power is available to start battery charging.

On the **1AC 230V Stand-Alone Inverter**, set the power switch to the **I** (On) position. The **1AC 230V Stand-Alone Inverter** should emit a short beep sound to indicate that it turns on. Also, the **Status** LED on the **1AC 230V Stand-Alone Inverter** should light up in green to indicate that the unit operates normally.

On the **AC 230V Lamps** module, turn the incandescent lamp on.

32. In the **Four-Quadrant Dynamometer/Power Supply** window, slowly decrease the dc source voltage to 41 V while observing the stand-alone inverter. This decreases the voltage across the **Battery Input** terminals of the stand-alone inverter, thereby emulating a battery whose state of charge becomes very low. In fact, the voltage across the **Battery Input** terminals is now below the low-voltage disconnect (LVD) setpoint (about 42 V) of the stand-alone inverter.

Briefly describe what happens.

Does the stand-alone inverter achieve proper battery overdischarge protection?

☐ Yes ☐ No

- 33.** In the **Four-Quadrant Dynamometer/Power Supply** window, slowly increase the dc source voltage to 53 V while observing the stand-alone inverter. This increases the voltage across the **Battery Input** terminals of the stand-alone inverter, thereby emulating a battery which is charging. In fact, the voltage across the **Battery Input** terminals now exceeds the low-voltage reconnect (LVR) setpoint (about 52 V) of the stand-alone inverter.

Briefly describe what happens.

- 34.** On the **AC 230V Lamps** module, turn the incandescent lamp off.

On the **1AC 230V Stand-Alone Inverter**, set the power switch to the **O (Off)** position to turn the unit off.

- 35.** In the **Four-Quadrant Dynamometer/Power Supply** window, stop the dc source.

Close **LVDAC-EMS**.

- 36.** Turn the **4 Quadrant Power Supply and Dynamometer Controller** off.

Turn the **AC 24V Power Supply** off.

Turn electric power off at your workstation, if applicable. Remove all circuit connections, finishing with the equipment earthing connections. Return all equipment to its storage location.

CONCLUSION

In this exercise, you became familiar with the configuration and operation of stand-alone PV systems for ac loads. You also became familiar with the operation of the stand-alone inverter. You learned how to use the specifications of the PV panel, charge controller, battery, and stand-alone inverter selected for a specific stand-alone PV system to verify that they can work together without causing problems. You saw that choosing energy-efficient electric equipment (e.g., using compact fluorescent lamps or LED lamps instead of incandescent lamps) is a means of reducing the size and cost of the stand-alone PV system for ac loads required in any application. You discovered common applications of stand-alone PV systems for ac loads.

REVIEW QUESTIONS

1. What component distinguishes a stand-alone PV system for ac loads from a stand-alone PV system for dc loads?

2. What is the main function of the stand-alone inverter in a PV system?

3. Describe what happens when the voltage at the battery input of the stand-alone inverter in a PV system reaches the LVD setpoint.

4. Name common applications of stand-alone PV systems for ac loads.

5. Compare the compact fluorescent lamp and LED lamp with the incandescent lamp in terms of energy consumption.

Grid-Tied PV Systems

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the configuration and operation of grid-tied PV systems. You will also be familiar with the operation of the grid-tied inverter. You will know that using a grid-tied PV system allows the amount of energy imported from the grid to be reduced. You will be able to describe the PV panel/inverter arrangements most commonly used in grid-tied PV systems. You will know the following three types of grid-tied inverters: the central inverter, the string inverter, and the micro-inverter. You will be able to verify that the PV panel, grid-tied inverter, and energy meter selected for a specific grid-tied PV system can work together without causing problems. You will be familiar with the following two methods of metering energy in grid-tied PV systems: net metering and gross metering. You will know how the operation of micro-inverters can be monitored and set. Finally, you will know that using energy-efficient electric equipment has no impact on the size and cost of grid-tied PV systems.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to grid-tied PV systems
PV panel. Grid-tied inverter. Energy meter.
- Operation of a grid-tied PV system
- PV panel/grid-tied inverter arrangements
Central inverter. String inverters. Micro-inverters.
- Physical representation of a grid-tied PV system
- Selection of the PV panel, grid-tied inverter, and energy meter for a specific grid-tied PV system
- Energy metering in grid-tied PV systems
Net metering. Gross metering.
- Monitoring and setting the operation of micro-inverters
- Effect of using energy-efficient electric equipment on grid-tied PV systems

DISCUSSION

Introduction to grid-tied PV systems

Grid-tied PV systems are commonly used for the provision of electric power in home applications as well as in commercial and industrial applications. Grid-tied PV systems in home applications generally have a power rating between 1 kW and 15 kW. On the other hand, grid-tied PV systems in commercial and industrial applications generally have much larger power ratings. Consequently, some aspects of grid-tied PV systems in commercial and industrial applications differ slightly from grid-tied PV systems in home applications. The present discussion focuses on grid-tied PV systems used in home applications.

Figure 41 shows a simplified diagram of a grid-tied PV system. The system consists of a PV panel, a grid-tied inverter, and an energy meter. In general, no battery is provided in grid-tied PV systems because electricity from the local ac power network is available (as long as there is no power outage) to power the local loads when the PV panel produces no or little electricity.



Several elements, such as the PV panel blocking and bypass diodes, PV panel lightning surge arrester, PV panel fused disconnect switch, and load circuit-breaker panel, have been omitted in the simplified diagram of Figure 41 for the sake of clarity.

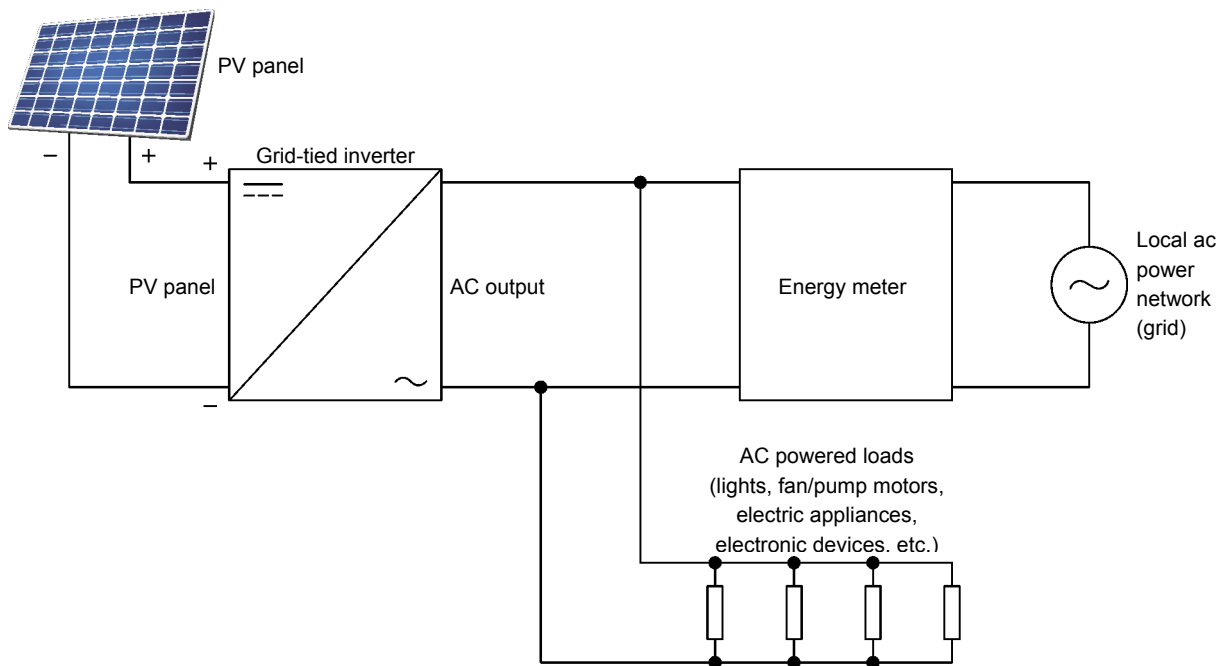


Figure 41. Simplified diagram of a grid-tied PV system.

A single PV panel and a single grid-tied inverter are used in the grid-tied PV system shown in Figure 41. This is the simplest arrangement possible. In most grid-tied PV systems, however, several PV panels are generally used to generate the desired amount of power. Furthermore, a single grid-tied inverter or multiple grid-tied inverters can be used. Consequently, various arrangements of PV panels and grid-tied inverters can be used in grid-tied PV systems. The most common arrangements are covered later in this discussion.

For each of the elements in the grid-tied PV system shown in Figure 41, the remainder of this section states the function of the element, describes what the element consists of, and briefly explains how the element operates.

PV panel

The PV panel converts sunlight into electricity as in any other PV system. In most cases, grid-tied PV systems have a power rating exceeding 1 kW. Consequently, an array of several PV panels is generally used in grid-tied PV systems.

Grid-tied inverter

The **grid-tied inverter** uses electronic circuitry and electronic power switches to convert dc power from the PV panel into ac power. The magnitude and frequency of the voltage at the ac output of the grid-tied inverter are determined by the local ac power network. This is because the ac output of the inverter is connected to the local ac power network via the energy meter which is virtually equivalent to a pair of connection wires. Power losses in the grid-tied inverter are maintained as low as possible, generally resulting in a power efficiency between 80% and 95%. The grid-tied inverter has two distinct sets of terminals: one that serves to feed dc power into the unit (PV panel input) and one that provides the ac power produced by the unit (ac output). In the grid-tied PV system shown in Figure 41, the inverter

supplies ac power to the loads connected to the system. Consequently, less power is drawn from the local ac power network whenever the PV panel produces electricity. This reduces the amount of energy metered, and thus, the electricity bills received from the electricity provider. Note that a grid-tied inverter begins producing ac power only when it detects the local ac power network voltage at its ac output. This differs from a stand-alone inverter which begins producing ac power as soon as dc power is available at its battery input.

The grid-tied inverter in a PV system also performs MPP tracking to maximize the amount of power the PV panel produces no matter what the operating conditions (solar irradiation, PV panel temperature, etc.) are. The grid-tied inverter achieves MPP tracking by continually adjusting the voltage at which the PV panel operates in order to maintain the amount of power produced as high as possible. In fact, MPP tracking in grid-tied inverters is the same as in MPPT charge controllers.

Grid-tied inverters including the automatic disconnection function are often referred to as anti-islanding or non-islanding grid-tied inverters.

Finally, when a fault occurs somewhere in the local ac power network, protective equipment in the network takes actions to quickly isolate the faulty part of the network from the rest of the network. This prevents the healthy part of the network from continuing to supply power to the faulty part of the network. This, however, also results in a power outage for the customers connected to the faulty part of the ac power network. A function called automatic disconnection is implemented in most grid-tied inverters. This function continuously monitors the voltage and current at the ac output of the grid-tied inverter and disconnects the inverter from the system (i.e., from the local ac power network) when a power outage occurs. This prevents the grid-tied inverter from feeding power into the faulty part of the network after a power outage. The protective equipment in the network and the automatic disconnection function in grid-tied inverters ensure that the faulty part of the network is dead (i.e., no power is applied to it) after a power outage, thereby making it safe for the maintenance personnel which makes the repair later. Automatic disconnection of grid-tied inverters is an important function which is often required in the various standards applying to grid-tied PV systems worldwide. In all cases, the grid-tied inverter must comply with the applicable standards as stated in the electrical code of the country where the PV system is installed.

Energy meter

The energy meter measures the energy exchange between the grid-tied PV system and the local ac power network. It can be of the electromechanical type or the electronic type. Periodic readings of the energy meter allow the electricity provider to establish the electricity bill of the customer. Note that some modern energy meters of the electronic type automatically send periodic readings of the metered energy to the provider via a communication link. Also note that energy metering can be performed using a single energy meter or two energy meters. This is explained in detail later in this discussion.

Operation of a grid-tied PV system

A grid-tied PV system operates as follows. When the PV panel produces no electricity (at nighttime), power is drawn from the local ac power network to satisfy the power demand of the ac loads connected to the grid-tied PV system, as shown in Figure 42. In this figure, arrows are used to show the flow of power at different points of the grid-tied PV system. The size of each arrow is proportional to the amount of power at the corresponding point of the grid-tied PV system.

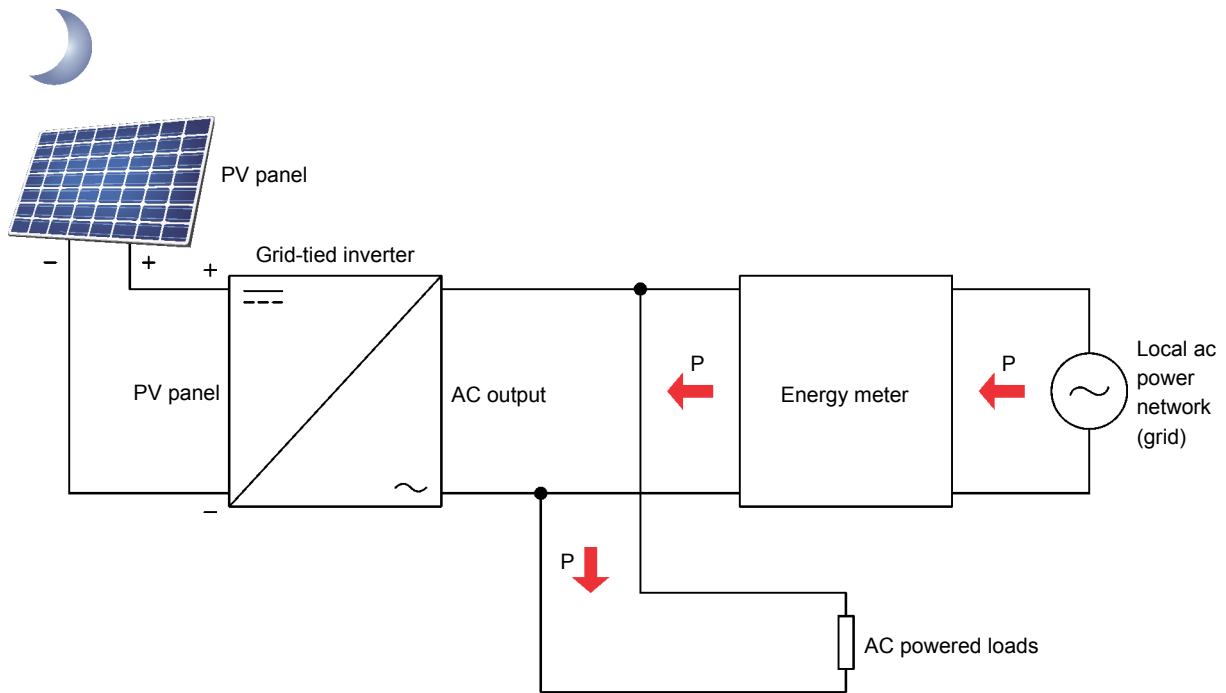


Figure 42. Nighttime operation of a grid-tied PV system. The PV panel produces no electricity and power is drawn from the local ac power network to satisfy the power demand of the loads.

When sunlight strikes the PV panel, it produces dc power that is converted into ac power by the grid-tied inverter. The power provided by the grid-tied inverter feeds the ac loads connected to the system. When the power provided by the grid-tied inverter is less than the power demand of the ac loads, some power is drawn from the local ac power network to satisfy the power demand of the loads, as shown in Figure 43.

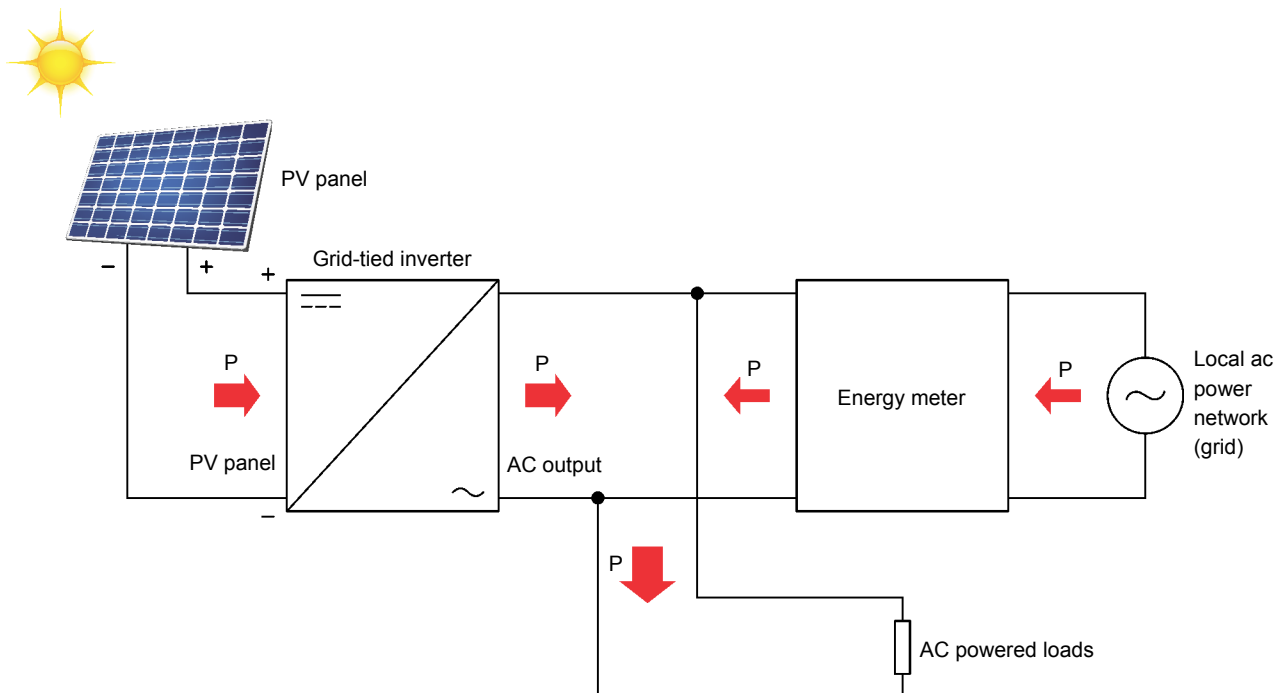


Figure 43. Daytime operation of a grid-tied PV system with the PV panel producing electricity at a rate below the power demand of the loads.

Conversely, when the power provided by the grid-tied inverter exceeds the power demand of the ac loads, the excess power feeds the local ac power network, as shown in Figure 44.

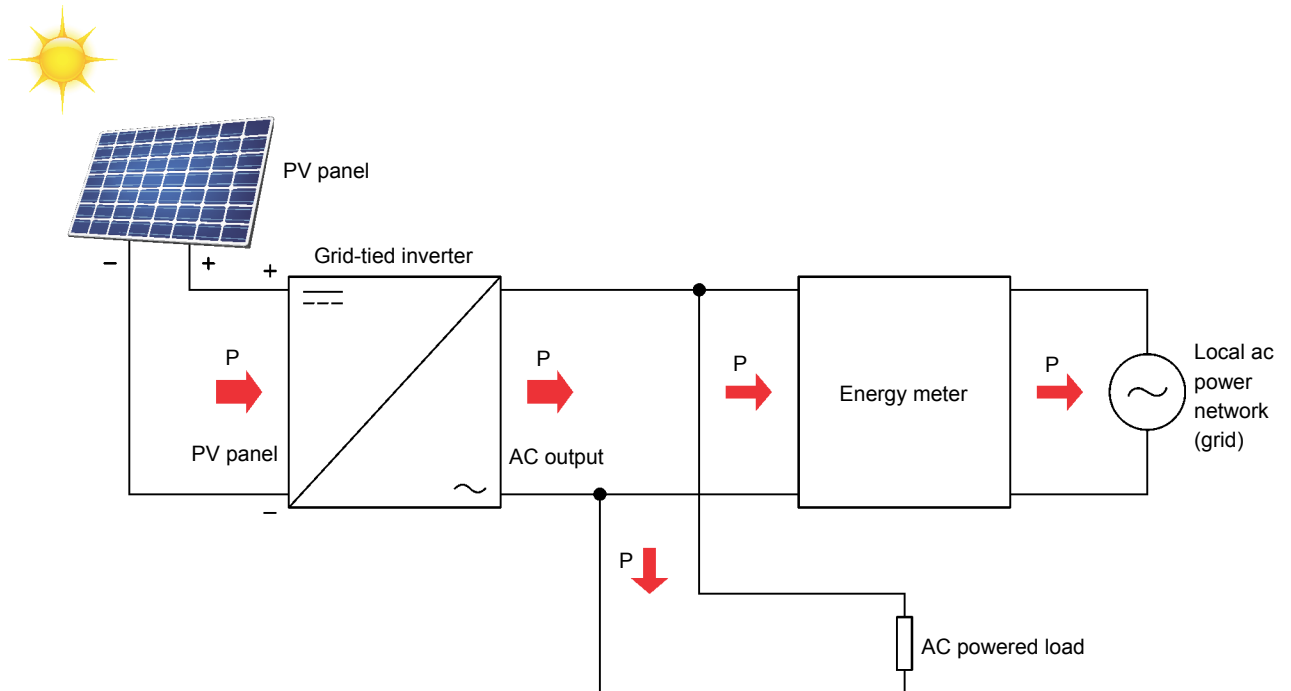


Figure 44. Daytime operation of a grid-tied PV system with the PV panel producing electricity at a rate exceeding the power demand of the loads.

In brief, when the PV panel produces electricity, the grid-tied inverter provides power to the ac loads connected to the system, thereby decreasing the power drawn from the local ac power network. This reduces the amount of energy metered, and thus the electricity bill received from the electricity provider. In fact, reducing the electricity bill is generally the main objective pursued when installing a grid-tied PV system.

PV panel/grid-tied inverter arrangements

In grid-tied PV systems, the amount of power desired (e.g., 4 kW) generally exceeds the amount of power (e.g., 150 W) which a single PV panel can produce. Consequently, an array of PV panels is used in most grid-tied PV systems. Furthermore, conversion of the dc power produced by the PV panels into ac power can be performed using a single grid-tied inverter or multiple grid-tied inverters. Consequently, the PV panels and the grid-tied inverter(s) can be arranged in different ways in grid-tied PV systems. The most common arrangements are presented in the remainder of this section of the discussion.

Central inverter

A single grid-tied inverter converts the dc power from all PV panels in the array into ac power, as shown in Figure 45. In this arrangement, the grid-tied inverter is referred to as a central inverter.

The following observations apply to grid-tied PV systems implemented using a central inverter.

- The central inverter tracks the maximum power point of the whole array of PV panels. Consequently, all PV panels in the array must be the same (i.e., they must have identical I-U curves) in order to optimize the amount of power which the array produces. This is rarely the case in actual PV systems because of slight differences between manufactured panels of the same type, replacement of a PV panel in the array by a similar panel, etc. This generally prevents the PV panel array from producing the maximum amount of power possible.
- Connecting the central inverter to the PV panel array and the rest of the grid-tied PV system is simple.
- Using a central inverter in a grid-tied PV system is generally the most economic arrangement in terms of required investment per amount of power generated (€/kW).
- Using a central inverter in a grid-tied PV system has the disadvantage that the amount of power produced by the PV panel array can be reduced significantly by the shading of just a single PV panel. This is mainly because the central inverter tracks the maximum power point of the whole array of PV panels.
- Failure of the central inverter shuts down the whole grid-tied PV system.

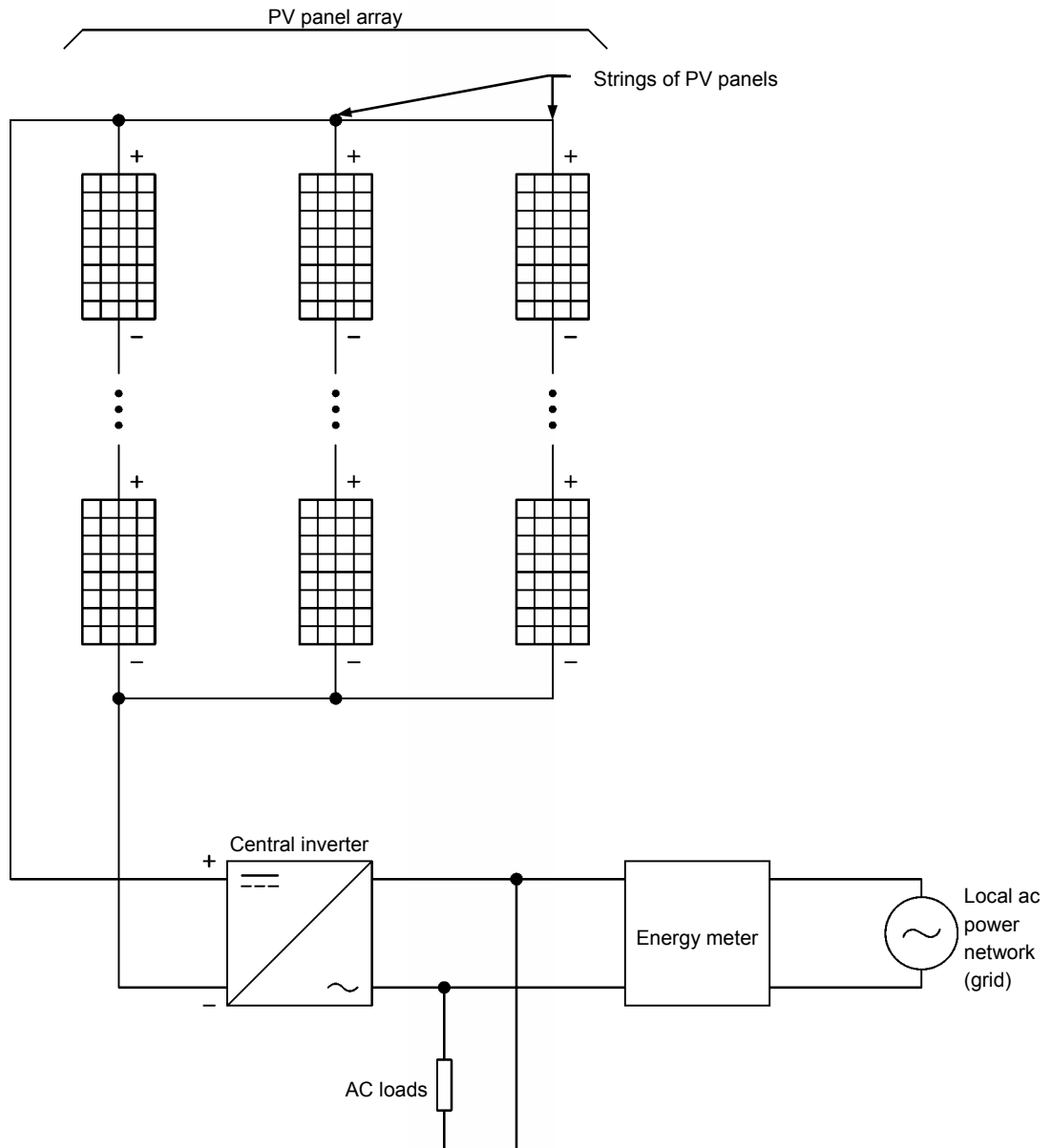


Figure 45. Simplified diagram of a grid-tied PV system implemented using a central inverter.

String inverters

A grid-tied inverter converts the dc power from a string of PV panels in the array into ac power, as shown in Figure 46. One grid-tied inverter is thus required per string of PV panels. In this arrangement, each grid-tied inverter is referred to as a string inverter.

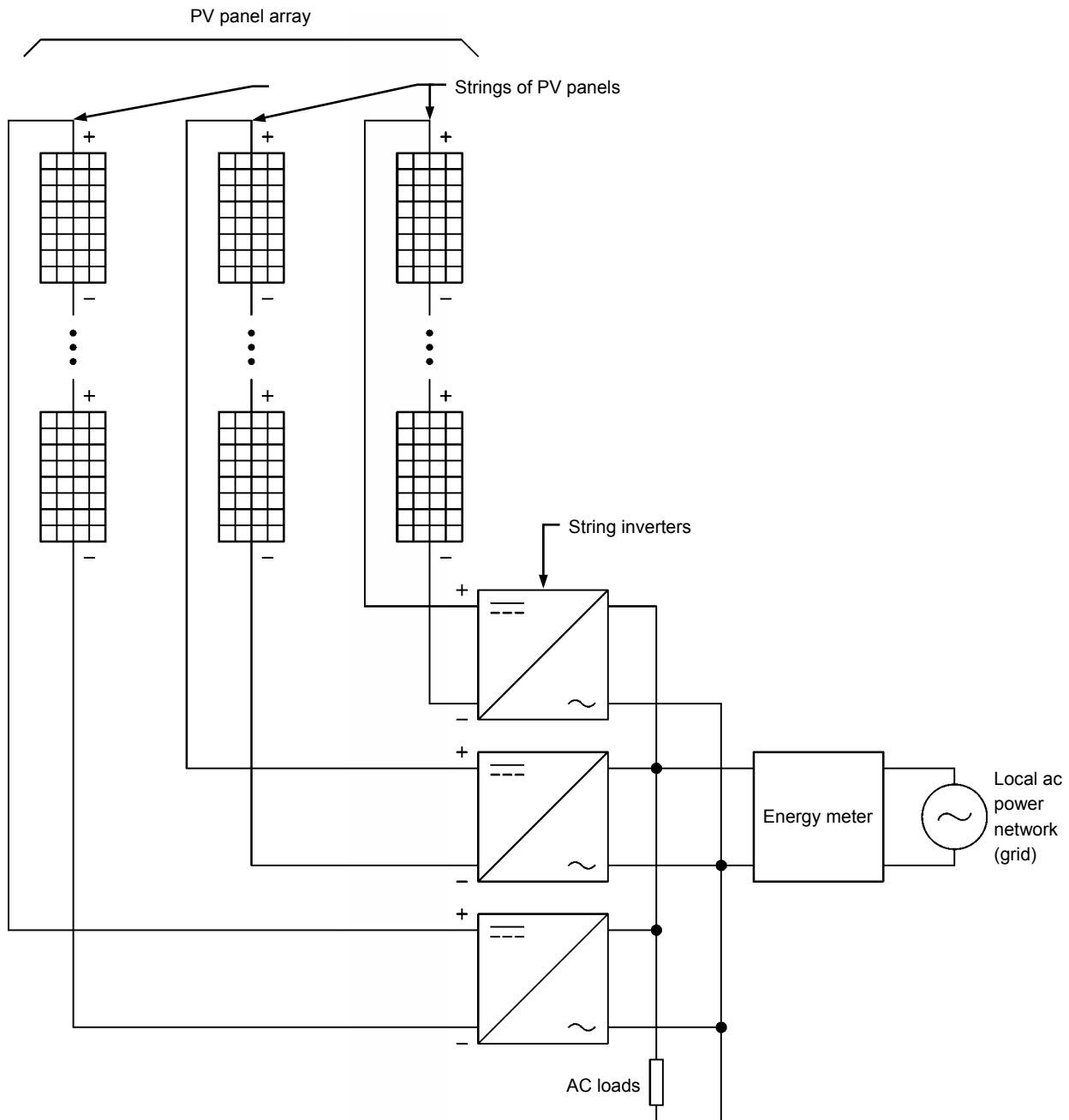


Figure 46. Simplified diagram of a grid-tied PV system implemented using string inverters.

The following observations apply to grid-tied PV systems implemented using string inverters.

- Each string inverter tracks the maximum power point of a string of PV panels in the array. This optimizes the amount of power which each string of PV panels produces. Consequently, using string inverters instead of a central inverter generally yields a slight increase in the amount of energy produced.
- Failure of a string inverter has less consequences than the failure of a central inverter since this shuts down only one string of PV panels in the array instead of the whole system.
- The amount of power produced by the PV panel array can be reduced by shading, similar to when the central inverter arrangement is used. However, the string inverter arrangement is slightly less sensitive to

shading than the central inverter arrangement because MPP tracking is performed individually for each string of PV panels. Consequently, when shading is present, using string inverters instead of a central inverter generally yields a slight increase in the amount of energy produced.

- Using string inverters in a grid-tied PV system is a rather economic arrangement in terms of required investment per amount of power generated (€/kW). Generally, however, this option is not as economic as using a central inverter.
- Connecting the string inverters to the strings of PV panels and the rest of the grid-tied PV system is a little more complex than connecting a central inverter to the array of PV panels and the rest of the grid-tied PV system.

Micro-inverters

A grid-tied inverter converts the dc power from a PV panel in the array into ac power, as shown in Figure 47. A grid-tied inverter is thus required for each PV panel in the array. In this arrangement, each grid-tied inverter is referred to as a micro-inverter.

The following observations apply to grid-tied PV systems implemented using micro-inverters.

- Each micro-inverter tracks the maximum power point of a single PV panel in the array. This optimizes the amount of power which each PV panel produces, and consequently, the amount of power which the whole array of PV panels produces. In fact, using micro-inverters instead of a central inverter or string inverters generally yields a significant increase in the amount of energy produced.
- Failure of a micro-inverter has much less consequences than the failure of a central inverter or a string inverter since it shuts down only one PV panel in the array instead of the whole system or a complete string of PV panels in the array.
- The amount of power produced by the PV panel array can be reduced by shading, similar to when the central inverter arrangement or the string inverter arrangement is used. However, the micro-inverter arrangement is significantly less sensitive to shading than each of these other two arrangements because MPP tracking is performed individually for each PV panel. Consequently, when shading is present, using micro-inverters instead of a central inverter or string inverters generally yields a significant increase in the amount of energy produced.
- Each micro-inverter is generally installed underneath the PV panel to which it is connected, and thus, can sometimes be submitted to high ambient temperatures. Some micro-inverters may be affected when operating at high ambient temperatures.
- Connecting the micro-inverters to the PV panels and the rest of the grid-tied PV systems is significantly complex due to the large number of devices involved. However, busses and connectors integrated in the frame supporting the PV panels are generally available to facilitate connections.
- A dedicated communications gateway (see diagram in Figure 47), located inside the building, is required to monitor and set the operation of the micro-inverters which are installed outdoors with the PV panels. The communications gateway is described in more detail later in this discussion.

- Using micro-inverters in a grid-tied PV system is generally not an economic arrangement in terms of required investment per amount of power generated (€/kW). In most cases, this option is more expensive than using a central inverter or string inverters.

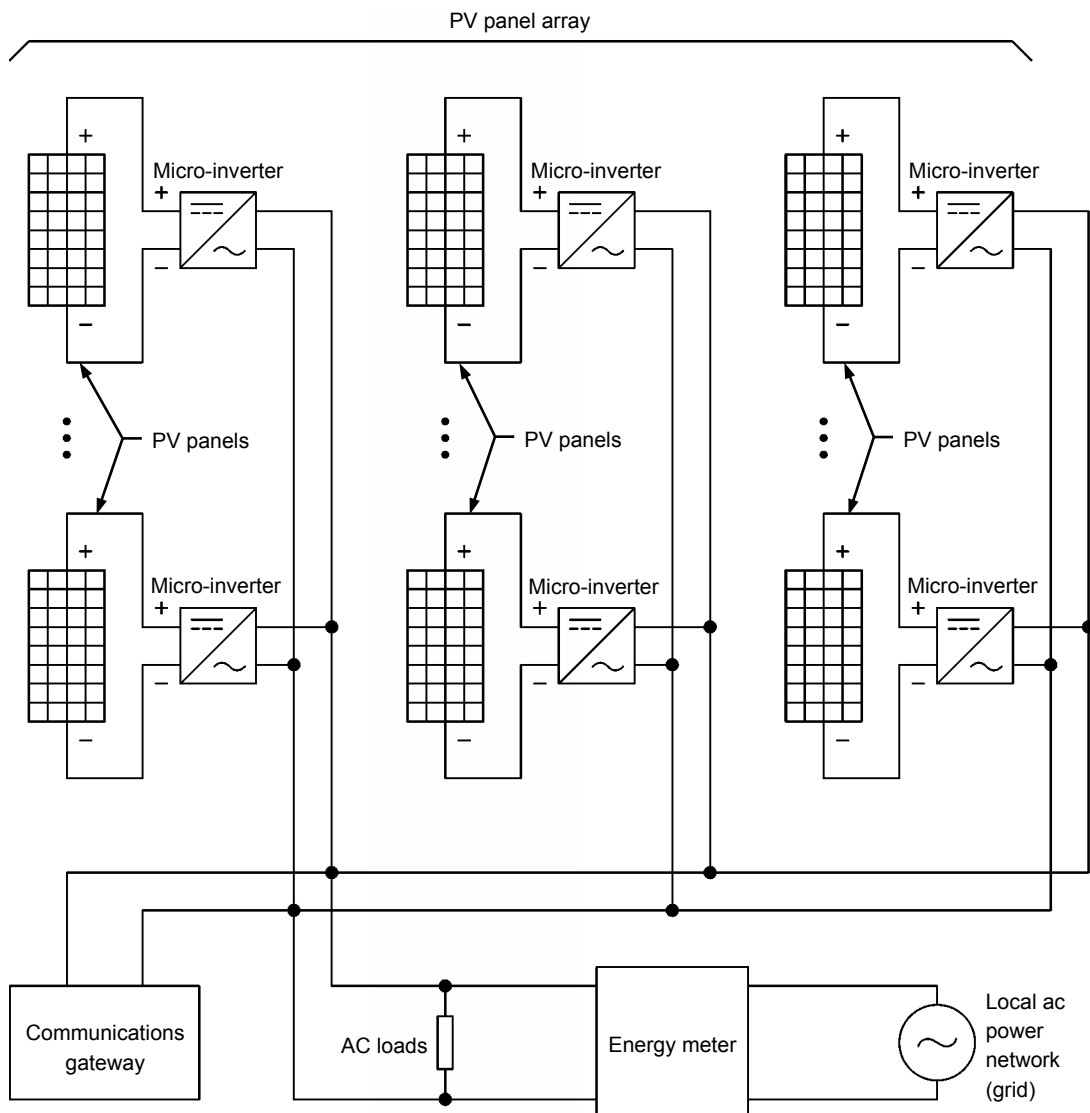


Figure 47. Simplified diagram of a grid-tied PV system implemented using micro-inverters.

To summarize, micro-inverters are better than the central inverter and string inverters at optimizing the amount of power which the PV panel array in a grid-tied PV system produces. Also, micro-inverters are less sensitive to shading than central inverters and string inverters. Finally, failure of a micro-inverter has less consequences than the failure of a central inverter or a string inverter. On the other hand, using micro-inverters is generally more expensive than using a central inverter or string inverters in terms of required investment per amount of power generated (€/kW).

Physical representation of a grid-tied PV system

Figure 48 is an example of the physical representation of a grid-tied PV system. In this example, the PV panel array consists of two strings of series-connected PV panels and is installed on the roof of a building. The PV panel array could also be installed on a support located close to the building. Two string inverters

convert the dc power produced by the PV panel array into ac power. The string inverters are generally installed inside the building and located close to the electrical service panel to facilitate connection to the local ac loads and the local ac power network. Gross energy metering (GEM) is used in this particular grid-tied PV system. GEM uses two energy meters. One energy meter (meter 1) measures the amount of electricity which the grid-tied PV system feeds into the local ac power network. The other energy meter (meter 2) measures the amount of electricity which the local ac loads draw from the local ac power network. Other energy metering arrangements are possible. Energy metering in grid-tied PV systems is explained in detail later in this discussion.



Several elements, such as the PV panel array blocking and bypass diodes, PV panel array lightning surge arrester, PV panel array fused disconnect switch, and load circuit-breaker panel, have been omitted in the simplified representation of Figure 48 for the sake of clarity.

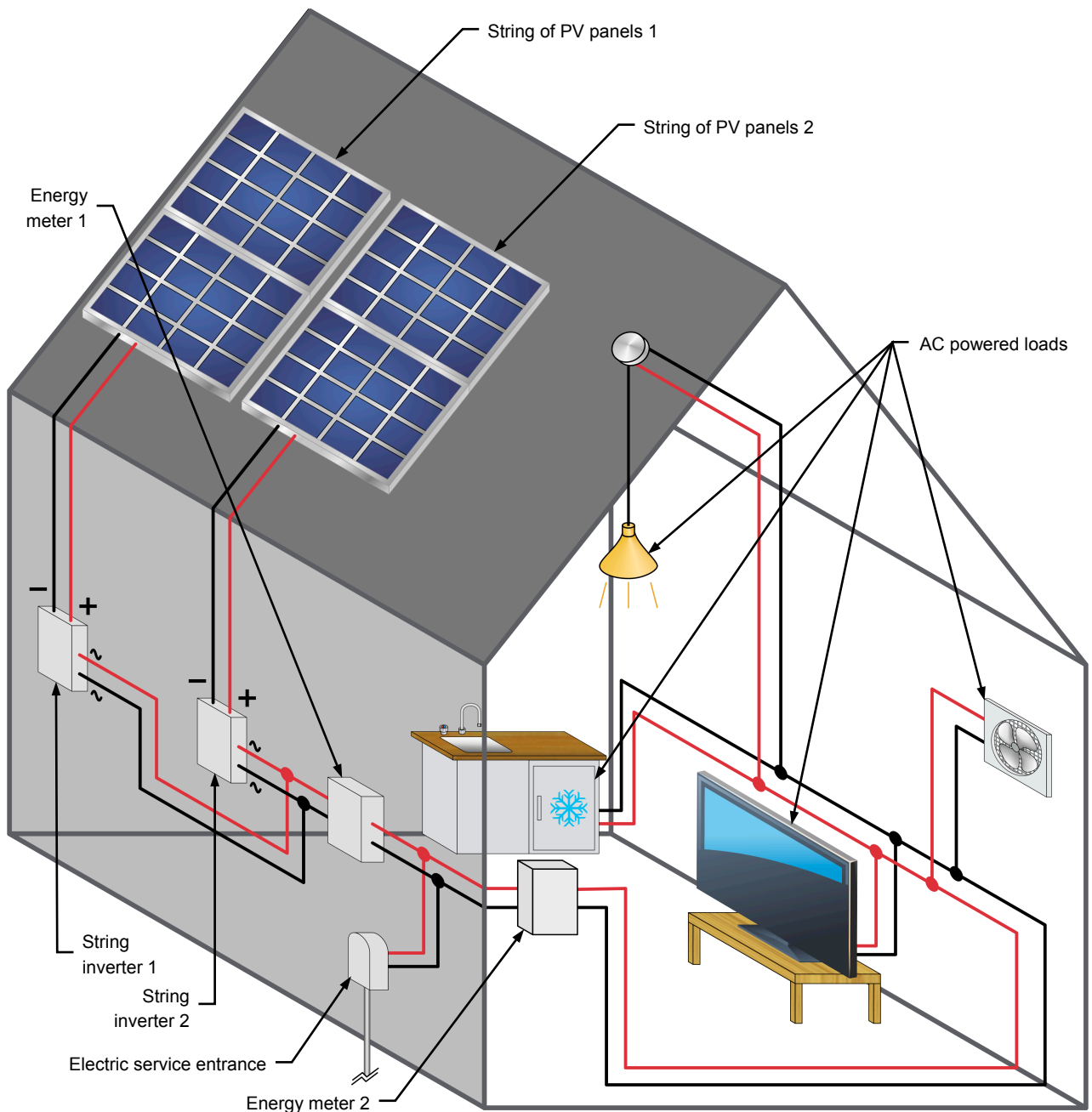


Figure 48. Simplified physical representation of a grid-tied PV system.

Selection of the PV panel, grid-tied inverter, and energy meter for a specific grid-tied PV system

Table 13 presents the key specifications that must be considered when making sure that the PV panel, grid-tied inverter, and energy meter selected for a specific grid-tied PV system can work together without causing problems.

Table 13. Key specifications to be considered when making sure that the PV panel, grid-tied inverter, and energy meter selected for a specific grid-tied PV system can work together without problems.

Component	Specified parameter	Description of parameter
PV panel	Short-circuit current (I_{sc})	Current that flows through the PV panel when its terminals are short-circuited, measured under standard test conditions (STC).
	Open-circuit voltage (U_{oc})	Voltage which the PV panel produces when its terminals are left open, measured under standard test conditions (STC).
	Rated power	Maximum power point (MPP) of the PV panel, measured under standard test conditions (STC).
	Rated power voltage	Voltage which the PV panel produces when it operates at rated power (i.e., at MPP).
Grid-tied inverter	Maximum PV panel input current	Maximum current that can flow through the PV panel input terminals of the inverter without causing overheating of the unit (and eventual damage to the unit).
	Maximum PV panel input voltage	Maximum voltage that can be applied across the PV panel input terminals of the inverter without causing damage to the unit.
	Maximum PV panel input power	Maximum power that can be applied at the PV panel input of the inverter without causing overheating of the unit (and eventual damage to the unit).
	MPP tracking voltage range	Minimum and maximum values of voltage at the PV panel input of the inverter for which MPP tracking operates.
	Nominal ac output voltage	RMS value of nominal voltage across the ac output terminals of the inverter.
	Nominal ac output frequency	Nominal frequency of the voltage across the ac output terminals of the inverter.
	Rated ac output power	Maximum power which the inverter can provide at its ac output, continuously.
	Rated ac output current	Current that flows through the ac output terminals of the inverter when it operates at rated power.

Component	Specified parameter	Description of parameter
Energy meter	Nominal voltage	RMS value of nominal voltage across the measuring terminals of the energy meter.
	Nominal frequency	Nominal frequency of the voltage and current at the measuring terminals of the energy meter.
	Maximum current	RMS value of maximum current which can flow through the energy meter.

The following steps must be performed to make sure that the PV panel, grid-tied inverter, and energy meter selected for a specific grid-tied PV system can work together without causing problems.

1. The maximum PV panel input current of the grid-tied inverter must be larger than the short-circuit current (I_{sc}) of the PV panel. This ensures that damage to the grid-tied inverter due to overcurrent cannot occur.



When a central inverter is used, the short-circuit current of the PV panel array must be considered. When string inverters are used, the short-circuit current of each string of PV panels must be considered.

2. The maximum PV panel input voltage of the grid-tied inverter must be higher than the open-circuit voltage (U_{oc}) of the PV panel. This ensures that the PV panel cannot cause overvoltage at the PV panel input terminals of the grid-tied inverter (and ensuing damage to the inverter). Note that the open-circuit voltage of the PV panel is measured under standard test conditions (STC) which stipulates a PV panel temperature of 25°C. The open-circuit voltage of a PV panel, however, decreases slightly as the temperature increases and vice versa. Consequently, when a grid-tied PV system is subject to operation in cold climate, the value of the open-circuit voltage of the PV panel must be corrected (to take the effect of temperature into account) before checking if the maximum PV panel input voltage of the grid-tied inverter is sufficient, as discussed in Exercise 1 of this manual.



When a central inverter is used, the open-circuit voltage of the PV panel array must be considered. When string inverters are used, the open-circuit voltage of each string of PV panels must be considered.

3. The maximum PV panel input power of the grid-tied inverter must be larger than the rated power of the PV panel. This ensures that damage to the grid-tied inverter due to overheating cannot occur.



When a central inverter is used, the rated power of the PV panel array must be considered. When string inverters are used, the rated power of each string of PV panels must be considered.

4. The rated power voltage of the PV panel must be within the MPP tracking voltage range of the grid-tied inverter. This ensures that the grid-tied inverter can make the PV panel operate at the MPP.



When a central inverter is used, the rated power voltage of the PV panel array must be considered. When string inverters are used, the rated power voltage of each string of PV panels must be considered.

5. The rated ac output power of the grid-tied inverter must be equal to or larger than the rated power of the PV panel. This ensures that damage to the grid-tied inverter due to overheating cannot occur.



When a central inverter is used, the rated power of the PV panel array must be considered. When string inverters are used, the rated power of each string of PV panels must be considered.

6. The nominal ac output voltage and frequency of the grid-tied inverter must match the nominal voltage and frequency of the local ac power network, respectively.
7. The nominal voltage and frequency of the energy meter must match the nominal voltage and frequency of the local ac power network, respectively.
8. The maximum current of the energy meter must be larger than the rated ac output current of the grid-tied inverter and/or the maximum load current. This ensures accurate energy metering.



When string inverters are used, the sum of the rated ac output currents of all string inverters must be considered. When micro-inverters are used, the sum of the rated ac output currents of all micro-inverters must be considered.

Energy metering in grid-tied PV systems

Energy metering is required in grid-tied PV systems for billing purposes. The energy metering arrangement to be used is determined by the local electric utility. In most cases, either one of the following two energy metering arrangements is used: net metering or gross metering. The remainder of this discussion describes these two energy metering arrangements.

Net metering

Net energy metering (NEM) is also simply referred to as net metering.

The simplified diagram in Figure 49 shows a grid-tied PV system using **net energy metering (NEM)**. NEM uses a single energy meter, located between the local ac power network and the grid-tied inverter and local ac loads, to measure the net amount of energy exchanged between the grid-tied PV system and the local ac power network. In this arrangement, the energy meter must be bidirectional. This means that the meter can turn backward (i.e., the amount of metered energy can decrease) when the grid-tied PV system feeds (exports) electricity into the local ac power network. Consequently, net metering values electricity exported to the network at the same price as electricity imported from the network. Net metering is commonly used in the United States.

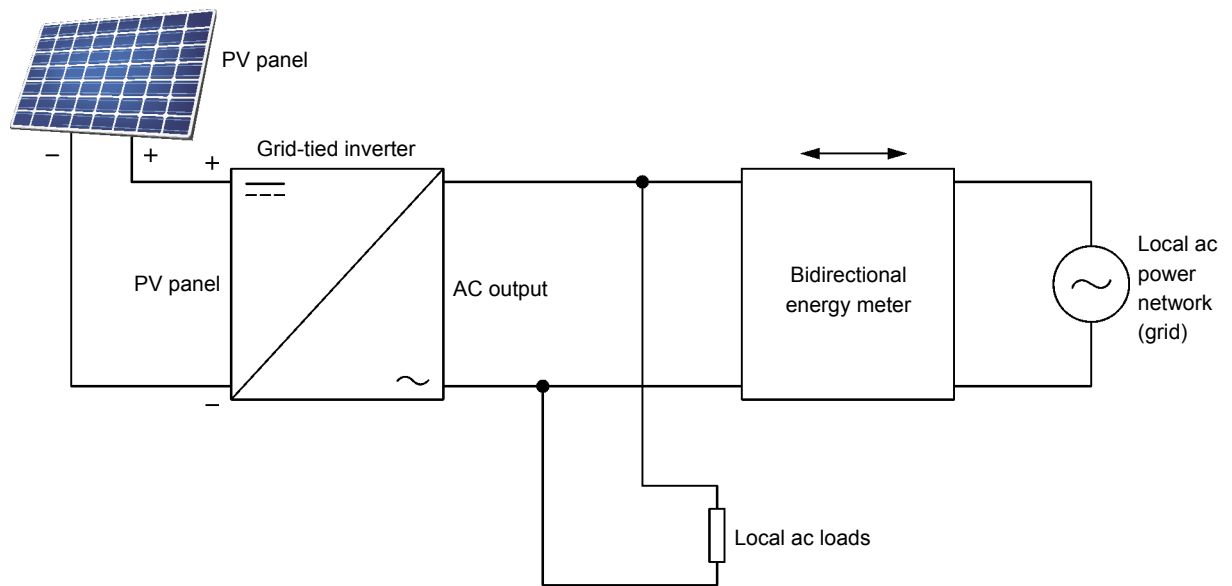


Figure 49. Simplified diagram of a grid-tied PV system using net metering.

The simplified diagram in Figure 50 shows a variant of net metering which is referred to as net metering/self-consumption. This energy metering arrangement uses two unidirectional energy meters that are located between the local ac power network and the grid-tied inverter and local ac power loads (i.e., the same location as in the net metering arrangement). One energy meter (meter 2 in the diagram of Figure 50) measures the amount of electricity imported from the local ac power network when the power demand of the local ac loads exceeds the amount of power produced by the grid-tied PV system. The second energy meter (meter 1 in the diagram of Figure 50) measures the amount of electricity exported to the network when the power demand of the local ac loads is below the amount of power produced by the grid-tied PV system. This allows the electric utility to value electricity exported to the network at a price that differs from that of electricity imported from the network. In general, the price of electricity exported to the network is set below the price of electricity imported from the network to incentivize customers to increase self-consumption, hence the name net metering/self-consumption.

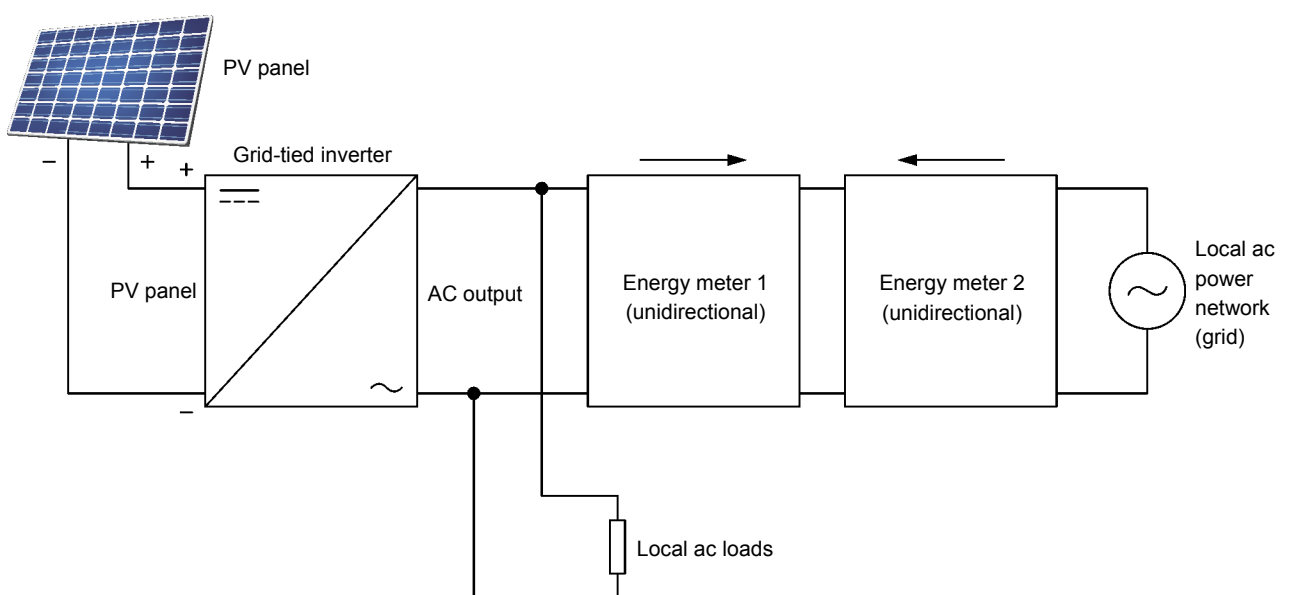


Figure 50. Simplified diagram of a grid-tied PV system using net metering/self-consumption.

Gross metering

Gross energy metering (GEM) is also simply referred to as gross metering.

The simplified diagram in Figure 51 shows a grid-tied PV system using **gross energy metering (GEM)**. With GEM, all electricity produced by the grid-tied PV system is exported to the local ac power network and all electricity consumed by the local ac loads is imported from the local ac power network. GEM uses two unidirectional energy meters. One energy meter (meter 1 in the diagram of Figure 51) is located between the local ac power network and the grid-tied inverter to measure the amount of electricity exported to the network. The other energy meter (meter 2 in the diagram of Figure 51) is located between the local ac power network and the local ac loads to measure the amount of electricity imported from the network. Generous government-subsidized prices for electricity exported to the network have contributed to make GEM common in Germany and Australia.

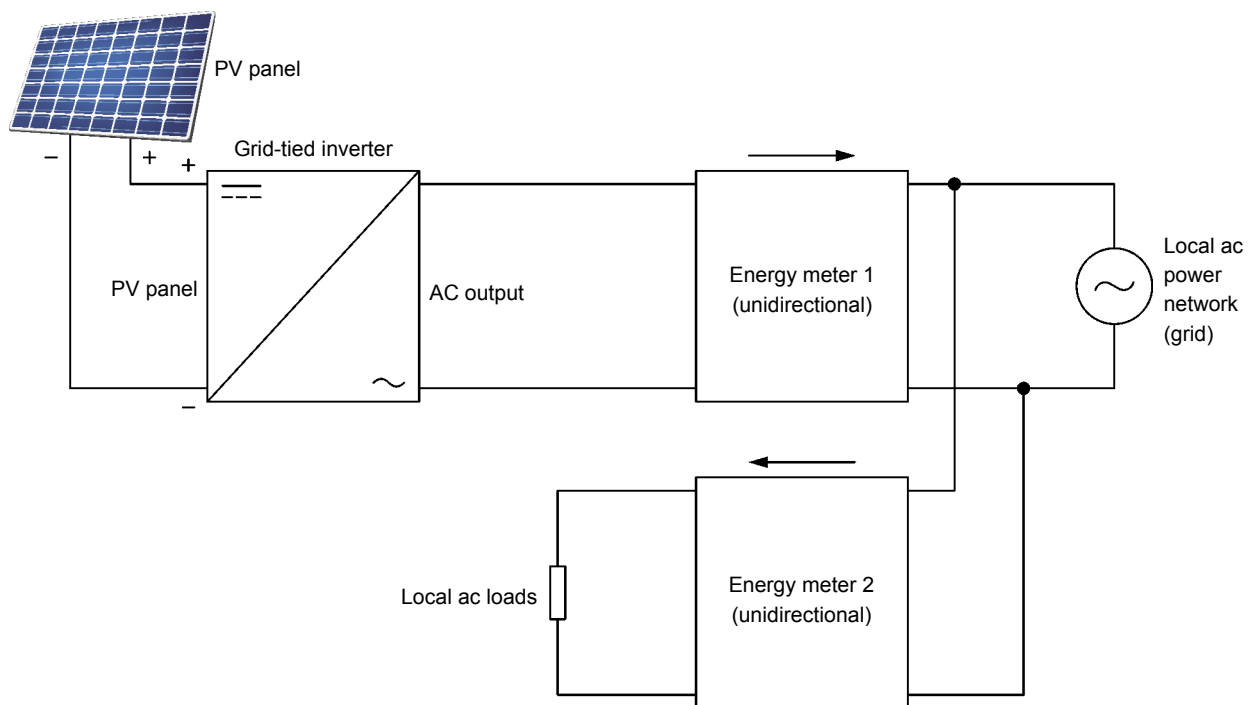


Figure 51. Simplified diagram of a grid-tied PV system using gross metering.

Monitoring and setting the operation of micro-inverters

The micro-inverters in a grid-tied PV system are installed close to the PV panels. In general, the PV panels are located on the roof of a building, thereby rendering access to the micro-inverters difficult. To facilitate access to settings and data in the micro-inverters, a communications gateway is commonly included in grid-tied PV systems. The communications gateway enables bidirectional communication with the micro-inverters, thereby making it easy to monitor and set the operation of the micro-inverters.

The simplified diagram in Figure 52 shows a grid-tied PV system using micro-inverters, with the communications gateway installed. The communications gateway is plugged into one of the ac power outlets in the building. This supplies ac power to the communications gateway. This also connects the communications gateway to the ac power lines in the building, and thus, to the micro-inverters. The communications gateway uses the ac power lines to exchange information with the micro-inverters. For instance, the communications gateway gathers data related to the energy production of each micro-inverter via

the ac power lines. Also, when the user of the grid-tied PV system changes the micro-inverter settings, the communications gateway routes the new settings to each of the micro-inverters via the ac power lines.

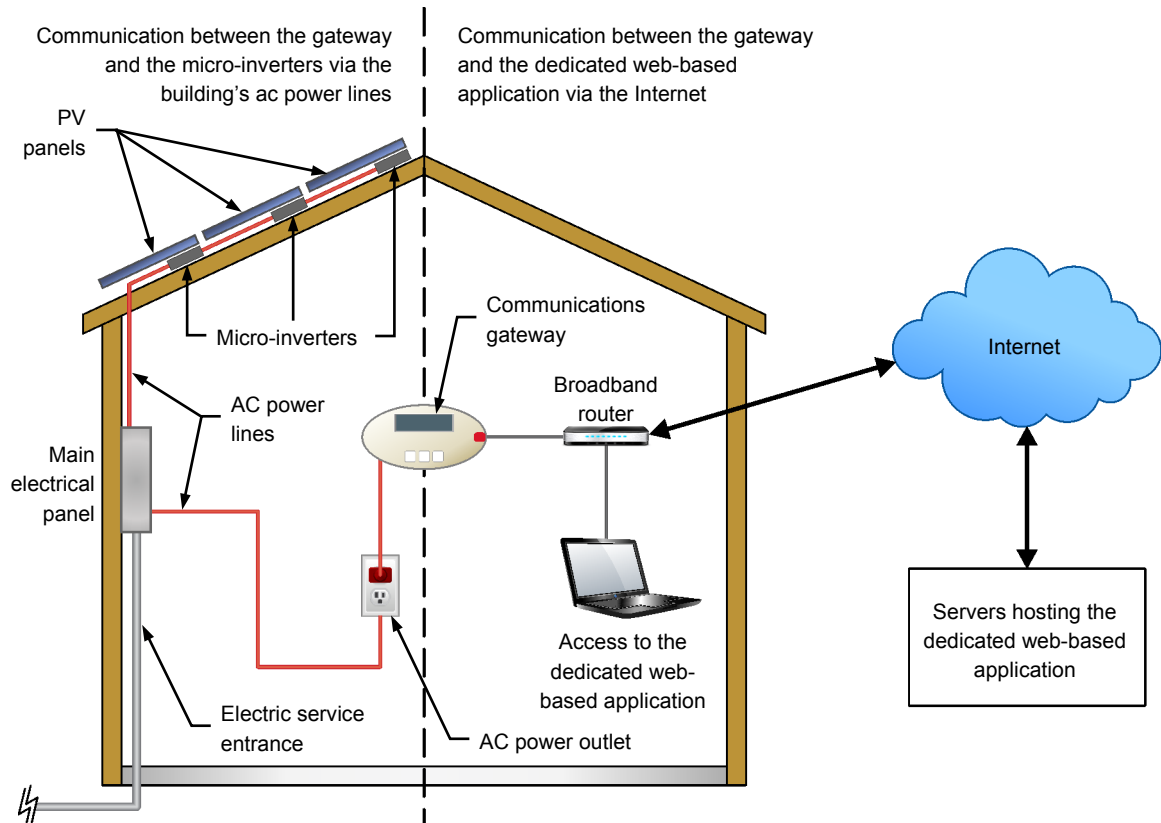


Figure 52. Simplified diagram of a grid-tied PV system using micro-inverters, with the communications gateway installed.

The communications gateway is provided with an Ethernet port. This port is connected to the site's local area network (LAN), thereby enabling the communications gateway to exchange information with any computer connected to the LAN. This allows the operator of the grid-tied PV system to access the communications gateway directly using the web browser of any computer connected to the LAN (this requires the gateway's IP address), to monitor the status of each micro-inverter, to consult data related to the energy production of each micro-inverter, or to change settings in the micro-inverters.

Furthermore, when the LAN provides access to the Internet, as is shown in Figure 52, the communications gateway exchanges information with a dedicated web-based application. For instance, the communications gateway routinely forwards the energy production data received from the micro-inverters to the dedicated web-based application via the Internet. Also, when the operator of the grid-tied PV system changes the micro-inverter settings using the dedicated web-based application, the application relays the new settings to the communications gateway via the Internet. Using the dedicated web-based application allows the operator of the grid-tied PV system to monitor the status of each micro-inverter, to consult data related to the energy production of each micro-inverter or to change settings in the micro-inverters from any computer or mobile device connected to the Internet. In other words, this allows the operator to monitor and set the operation of the micro-inverters in the grid-tied PV system no matter where he or she is located.

Effect of using energy-efficient electric equipment on grid-tied PV systems

In grid-tied PV systems, using energy-efficient electric equipment, such as LED lamps or compact fluorescent lamps, reduces the local energy consumption. This improves the balance between the energy supplied to the network and the energy drawn from the network, thereby resulting in an increased profitability for the owner of the grid-tied PV system. This increase in profitability either takes the form of lower electricity bills or higher credits from the local electric utility. Contrary to stand-alone PV systems, using energy-efficient electric equipment does not have a significant impact on the size of grid-tied PV systems. In general, the size of grid-tied PV systems is mostly governed by economic factors and the space available for installing PV panels.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Emulated PV panel settings
- Main components of a grid-tied PV system
- Setting up a grid-tied PV system using gross metering
- Operation of the grid-tied PV system using gross metering
- Automatic disconnection of the grid-tied inverter during a power outage
- Setting up a grid-tied PV system using net metering/self-consumption
- Operation of the grid-tied PV system using net metering/self-consumption



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

PROCEDURE

Setup and connections

In this section, you will set up and connect the equipment required to perform the exercise.

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

Install the equipment in the workstation. You will use this equipment later in this exercise to set up a grid-tied PV system.

Make the connections required to earth the equipment properly.



If necessary, check with the instructor to ensure that the connections you made provide proper earthing of the equipment.

2. Make sure that the main power switch of the **4 Quadrant Power Supply and Dynamometer Controller** is set to the **O** (off) position, then connect its **Power Input** to an ac power outlet that is properly protected.

Make sure that the main power switch of the **AC 24V Power Supply** is set to the **O** (off) position, then connect its **Power Input** to an ac power outlet that is properly protected.

Make sure that circuit breakers **F1** and **F2** of the **3AC 400V/DC 230V Power Supply** are set to the **O** (Off) position, then connect the unit to a three-phase ac power outlet that is properly protected.



If necessary, check with the instructor to ensure that the ac power outlets to which you connect the equipment are properly protected.

3. Connect the **Power Input** of the **Data Acquisition and Control Interface** to the **AC 24V Power Supply**.
4. Ask your instructor to turn on (i.e., to unlock) electric power at your workstation, if applicable.
5. Turn the **AC 24V Power Supply** on.
6. Turn the **4 Quadrant Power Supply and Dynamometer Controller** on, then set the **Operating Mode** switch to **Power Supply**.
7. Connect the USB port of the **Data Acquisition and Control Interface** to a USB port of the host computer.

Connect the USB port of the **4 Quadrant Power Supply and Dynamometer Controller** to a USB port of the host computer.

8. 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 **4 Quadrant Power Supply and Dynamometer Controller** are detected. Make sure that the **Basic Computer-Based Instrumentation** function for the **Data Acquisition and Control Interface** is available. Also make sure that the **Solar Panel Emulator** function for the **4 Quadrant Power Supply and Dynamometer Controller** is available. Select the network voltage and frequency of your local ac power network, then click the **OK** button to close the **LVDAC-EMS Start Up** window.

Emulated PV panel settings

In this section, you will set the size of the emulated PV panel that will be used to implement a grid-tied PV system.

9. 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 **4 Quadrant Power Supply and Dynamometer Controller** operate like a solar (PV) panel. The output terminals of the power supply are the terminals of the emulated PV panel.
 - Make sure that the **Solar Irradiance Control** parameter is set to **Slider**. This allows the solar irradiance to be controlled manually.
 - Set the **Solar Irradiance** parameter to 1000 W/m².
 - Set the **Number of PV modules in series** parameter to 4. Set the **Number of PV modules in parallel** parameter to 42. These two settings set the size of the emulated PV panel to 4 PV modules in series and 42 PV modules in parallel.
 - Make sure that the **Status** parameter is set to **Stopped**. This prevents the emulated PV panel from producing electricity even if the solar irradiation is currently set to 1000 W/m².

Main components of a grid-tied PV system

*In this section, you will gather the key specifications of the emulated PV panel, **1AC 230V Grid-Tied Inverter**, and **1AC 230V Energy Meter**. You will then use these specifications to verify that these pieces of equipment can work together without causing problems.*

10. Observe that the electrical specifications of each PV module in the emulated PV panel are indicated in the **Four-Quadrant Dynamometer/Power Supply** window.



In the remainder of this exercise, the emulated PV panel is also simply referred to as the PV panel.

According to the information provided in the **Four-Quadrant Dynamometer/Power Supply** window, what are the short-circuit current (I_{sc}), open-circuit voltage (U_{oc}), maximum power point (MPP) current, maximum power point (MPP) voltage, and maximum power point (MPP) of the emulated PV panel, at a solar irradiation of 1000 W/m²?

Short-circuit current (I_{sc}): _____ A

Open-circuit voltage (U_{oc}): _____ V

MPP current: _____ A

MPP voltage: _____ V

MPP: _____ W (_____ A @ _____ V)

11. Table 14 provides the main specifications of the **1AC 230V Grid-tied Inverter**. Note that the **1AC 230V Grid-tied Inverter** is in fact a micro-inverter. It requires a communications gateway to operate.



*In the remainder of this exercise, the **1AC 230V Grid-Tied Inverter** is also referred to as the **grid-tied inverter**.*

Table 14. Main specifications of the **1AC 230V Grid-Tied Inverter.**

Parameter	Value
Maximum PV panel input current	7 A
Maximum PV panel input voltage	42 V
Maximum PV panel input power	270 W
MPP tracking voltage range	27 V to 39 V
Nominal ac output voltage	230 V
Nominal ac output frequency	50 Hz
Rated ac output power	215 W
Rated ac output current	0.94 A

12. Based on the specifications above, can the **1AC 230V Grid-tied Inverter** be used with the emulated PV panel? Explain briefly.



Assume that the minimum operating temperature of the PV panel is 25°C.

13. Based on the specifications above, do the nominal ac output voltage and frequency of the **1AC 230V Grid-tied Inverter** match the nominal voltage and frequency of the local ac power network? Explain briefly.

14. Table 15 provides the main specifications of the **1AC 230V Energy Meter**.

Table 15. Main specifications of the **1AC 230V Energy Meter**.

Parameter	Value
Nominal voltage	230 V
Nominal frequency	50.0 Hz
Maximum current	16 A

15. Based on the specifications above, do the nominal voltage and frequency of the **1AC 230V Energy Meter** match the nominal voltage and frequency of the local ac power network? Explain briefly.

Based on the specifications above and the fact that the maximum load current is assumed to be less than 1 A, is the maximum current of the **1AC 230V Energy Meter** high enough to ensure accurate energy measuring? Explain briefly.

Setting up a grid-tied PV system using gross metering

In this section, you will set up a grid-tied PV system using gross metering. You will use the **Data Acquisition and Control Interface**, emulated PV panel, **1AC 230V Grid-Tied Inverter**, **1AC 230V Energy Meter** (2 units), **3AC 400V/DC 230V Power Supply**, and **AC 230V Lamps** module to set up the system.

16. Use the **Data Acquisition and Control Interface**, emulated PV panel, **1AC 230V Grid-Tied Inverter**, **1AC 230V Energy Meter** (2 units), **3AC 400V/DC 230V Power Supply**, and **AC 230V Lamps** module to set up the grid-tied PV system shown in the circuit diagram of Figure 53. Note that the system uses gross energy metering. Read the following instructions before setting up the grid-tied PV system.
- The ac loads in the system consist of the incandescent lamp, the compact fluorescent lamp, and the LED lamp in the **AC 230V Lamps** module. Make sure that the three lamp switches on the **AC 230V Lamps** module are set to the **O** (off) position.
 - Energy meters 1 and 2 are implemented using two **1AC 230V Energy Meter** modules.
 - Make sure that you use terminals **L1'** and **N** of the **3AC 400V/DC 230V Power Supply** to connect the grid-tied PV system to the local ac power network.
 - A communications gateway is required to make all **1AC 230V Grid-Tied Inverter** modules in the laboratory classroom operate. Make sure that a **Communications Gateway** is installed in the laboratory classroom. Appendix E explains how to properly set up the **Communications Gateway**. Ask for the assistance of your instructor if necessary.

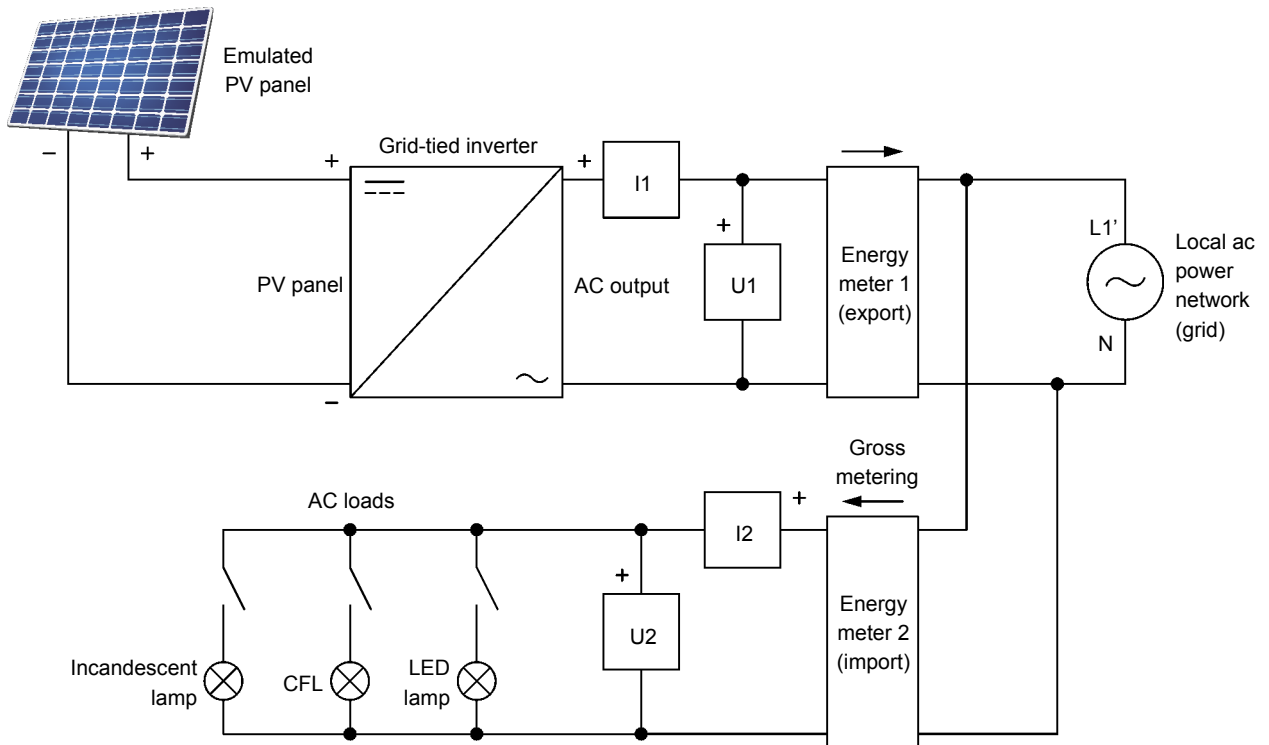


Figure 53. Grid-tied PV system using gross metering.

17. On the **1AC 230V Energy Meter** module used to implement energy meter 1 (export meter), set the **Power Flow** switch so that the meter measures the energy exported to the network.

On the **1AC 230V Energy Meter** module used to implement energy meter 2 (import meter), set the **Power Flow** switch so that the meter measures the energy imported from the network.

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

In the **Metering** window, set up a voltmeter and an ammeter to measure the voltage and current at the ac output of the grid-tied inverter. Set up a voltmeter and an ammeter to measure the voltage and current at the ac loads. Set up a meter to measure active power at the ac output of the grid-tied inverter. Finally, set up a meter to measure active power at the ac loads.

Make sure that continuous refresh of the meters is enabled in the **Metering** window.

19. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **Solar Panel Emulator** to make the emulated PV panel produce electricity. Notice that the LED indicator on the **1AC 230V Grid-Tied Inverter** lights up in green after a few seconds and remains lit for about 90 s. After that, the LED indicator should go out for a few seconds, blink six times (in green), go out for a few seconds, then flash in red at regular intervals. This indicates that the **1AC 230V Grid-Tied Inverter** detected no local ac power network. This is normal since the **3AC 400V/DC 230V Power Supply** is turned off.

Observe that no voltage nor current is present at the ac output of the grid-tied inverter although the emulated PV panel supplies power to its PV panel input. Briefly explain why.

- 20.** On the **3AC 400V/DC 230V Power Supply**, set circuit breaker **F1** to the **I** (on) position to turn the three-phase ac power source on. This connects the grid-tied PV system to the local ac power network. Once the **1AC 230V Grid-Tied Inverter** detects the presence of the local ac power network, it begins communicating with the **Communications Gateway**. After a certain time (generally about 2 minutes), the **1AC 230V Grid-Tied Inverter** should start producing ac power (see the values of voltage, current, and power indicated by the meters set in the **Metering** window). The LED indicator on the **1AC 230V Grid-Tied Inverter** should be lit in red and flash in green at regular intervals.



*The LED indicator on the **1AC 230V Grid-Tied Inverter** is lit in red and flashes in green at regular intervals to warn users that a ground fault is present at the PV panel input. This is normal and due to the fact that the negative terminal of the emulated PV panel (i.e., terminal **N** of the **4 Quadrant Power Supply and Dynamometer Controller**) is connected to the neutral of the local ac power network.*

Observe that the voltmeter and ammeter in the **Four-Quadrant Dynamometer/Power Supply** window indicate the PV panel voltage and current. Also observe that the power meter in the **Four-Quadrant Dynamometer/Power Supply** window indicates the amount of power which the PV panel produces.

Let the PV system stabilize, i.e., wait until the grid-tied inverter makes the PV panel operate at the maximum power point. This generally takes about 5 minutes. Once the PV system has stabilized, the value of the power produced by the PV panel and the value of the power at the grid-tied inverter output should be stable and maximal.

Operation of the grid-tied PV system using gross metering

In this section, you will observe the operation of the grid-tied PV system using gross metering.

- 21.** Each of the two **1AC 230V Energy Meter** modules in the grid-tied PV system measures voltage, current, power, and energy. By default, the **1AC 230V Energy Meter** displays the amount of metered energy, expressed in kWh. You can display the values of energy expressed in Wh, power, voltage, and current which the **1AC 230V Energy Meter** measures by briefly depressing (less than 1 s) the small button on the unit. After about 30 s, the **1AC 230V Energy Meter** automatically returns to the display of metered energy expressed in kWh.

On energy meter 1, display the amount of metered energy expressed in Wh. Observe that all ac power produced by the grid-tied inverter is sent to the local ac power network. This is confirmed by the continuous increase of the energy value indicated by energy meter 1 (export meter).

Does the grid-tied inverter make the PV panel operate at the maximum power point (MPP)? Explain briefly.

Is the grid-tied inverter efficient in converting dc power into ac power? Explain briefly.

- 22.** In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Solar Irradiance** parameter to 250 W/m². This divides the solar irradiance by 4.

On energy meter 1, display the amount of metered energy expressed in Wh. Observe that the energy value indicated by energy meter 1 (export meter) continues to increase at a regular pace. Notice the pace at which the energy value increases.

Measure the voltage, current, and power at the PV panel input and ac output of the grid-tied inverter.

PV panel input voltage: _____ V

PV panel input current: _____ A

PV panel input power: _____ W

AC output voltage: _____ V

AC output current: _____ A

AC output power: _____ W

- 23.** In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Solar Irradiance** parameter to 1000 W/m². This multiplies the solar irradiance by 4.

On energy meter 1, display the amount of metered energy expressed in Wh. Observe that the energy value indicated by energy meter 1 (export meter) increases more rapidly than in the previous step (i.e., when the solar irradiance was set to 250 W/m²).

Measure the voltage, current, and power at the PV panel input and ac output of the grid-tied inverter.

PV panel input voltage: _____ V

PV panel input current: _____ A

PV panel input power: _____ W

AC output voltage: _____ V

AC output current: _____ A

AC output power: _____ W

Compare the values of power at the ac output of the grid-tied inverter measured at solar irradiance values of 250 W/m² and 1000 W/m². Observe that increasing the solar irradiance increases the power at the ac output of the grid-tied inverter. What does the increase in the power at the ac output of the grid-tied inverter mean in terms of energy production? Explain briefly.

Compare the values of voltage, current, and power at the PV panel input of the grid-tied inverter measured at solar irradiance values of 250 W/m² and 1000 W/m². Does the grid-tied inverter track the MPP of the PV panel properly? Explain briefly.

- 24.** In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Solar Irradiance** parameter to 0 W/m².

Observe that power at the ac output of the grid-tied inverter decreases to zero.

On energy meter 1, display the amount of metered energy expressed in Wh. Observe that the energy value indicated by energy meter 1 (export meter) stops increasing. This is simply because the grid-tied PV system no longer produces electricity.

- 25.** Observe that the voltage at the ac load is 230 V but that the current and power at the ac loads are null.

On energy meter 2, display the amount of metered energy expressed in Wh. Observe that the energy value indicated by energy meter 2 (import meter) is fixed. Briefly explain why.

26. On the **AC 230V Lamps** module, successively turn on the LED lamp, compact fluorescent lamp (CFL), and incandescent lamp. While doing this, observe the current and power at the ac loads as well as the energy value (expressed in Wh) indicated by energy meter 2 (import meter). Notice that all power consumed by the ac loads comes from the local ac power network. This is confirmed by the continuous increase of the energy value indicated by energy meter 2 (import meter).

27. In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Solar Irradiance** parameter to 1000 W/m². The LED indicator on the **1AC 230V Grid-Tied Inverter** should light up in green after a few seconds and remain lit during for 90 s. After that, the LED indicator should go out for a few seconds, blink six times (in green), go out for a few seconds, then flash in red at regular intervals.

Let the PV system stabilize, i.e., wait until the grid-tied inverter makes the PV panel operate at the maximum power point. This generally takes about 5 minutes. Once the PV system has stabilized, the value of the power produced by the PV panel and the value of the power at the grid-tied inverter output should be stable and maximal.

On energy meters 1 and 2, display the amount of metered energy expressed in Wh. Observe that the energy values indicated by energy meters 1 and 2 both increase steadily. Briefly explain why.

Automatic disconnection of the grid-tied inverter during a power outage

In this section, you will observe the operation of the automatic disconnection function in the grid-tied inverter.

28. On the **3AC 400V/DC 230V Power Supply**, set circuit breaker **F1** to the **O** (off) position to turn the three-phase ac power source off. This simulates a power outage. Describe what happens. Briefly explain why.

Briefly explain why the grid-tied inverter reacts to a power outage this way.

- 29.** On the **3AC 400V/DC 230V Power Supply**, set circuit breaker **F1** to the **I** (on) position to turn the three-phase ac power source on. This simulates recovery of electric power after a power outage. Observe that the three lamps light up immediately.

Also, observe that after a certain time (about 5 minutes), the grid-tied inverter resumes the production of ac power automatically.

- 30.** On the **AC 230V Lamps** module, turn the three lamps off.

In the **Four-Quadrant Dynamometer/Power Supply** window, stop the **Solar Panel Emulator** to interrupt the production of electricity by the emulated PV panel.

On the **3AC 400V/DC 230V Power Supply**, set circuit breaker **F1** to the **O** (off) position to turn the three-phase ac power source off.

Setting up a grid-tied PV system using net metering/self-consumption

*In this section, you will set up a grid-tied PV system using net metering/self-consumption. You will use the **Data Acquisition and Control Interface**, emulated PV panel, **1AC 230V Grid-Tied Inverter**, **1AC 230V Energy Meter** (2 units), **3AC 400V/DC 230V Power Supply**, and **AC 230V Lamps** module to set up the system.*

- 31.** Modify the equipment connections to set up the grid-tied PV system shown in the circuit diagram of Figure 54. Note that the system uses net metering/self-consumption.

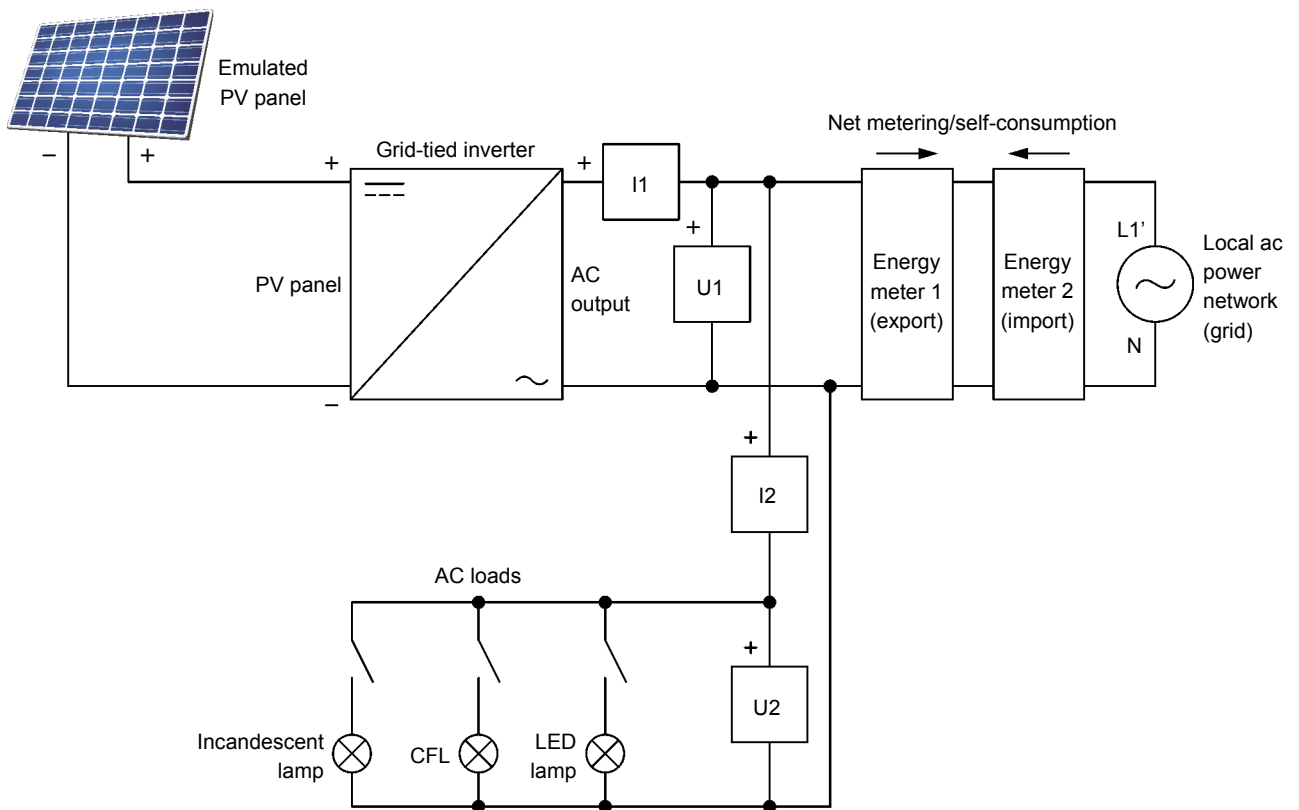


Figure 54. Grid-tied PV system using net metering/self-consumption.

32. On the **1AC 230V Energy Meter** module used to implement energy meter 1 (export meter), set the **Power Flow** switch so that the meter measures the energy exported to the network.

On the **1AC 230V Energy Meter** module used to implement energy meter 2 (import meter), set the **Power Flow** switch so that the meter measures the energy imported from the network.

33. In the **Four-Quadrant Dynamometer/Power Supply** window, start the **Solar Panel Emulator** to make the emulated PV panel produce electricity. Notice that the LED indicator on the **1AC 230V Grid-Tied Inverter** lights up in green after a few seconds and remains lit during for 90 s. After that, the LED indicator should go out for a few seconds, blink six times (in green), go out for a few seconds, then flash in red at regular intervals. This indicates that the **1AC 230V Grid-Tied Inverter** detected no local ac power network. This is normal since the **3AC 400V/DC 230V Power Supply** is turned off.
34. On the **3AC 400V/DC 230V Power Supply**, set circuit breaker **F1** to the **I** (on) position to turn the three-phase ac power source on. This connects the grid-tied PV system to the local ac power network. Once the **1AC 230V Grid-Tied Inverter** detects the presence of the local ac power network, it begins communicating with the **Communications Gateway**. After a certain time (generally about 2 minutes), the **1AC 230V Grid-Tied Inverter** should start producing ac power. The LED indicator on the **1AC 230V Grid-Tied Inverter** should be lit in red and flash in green at regular intervals.

Let the PV system stabilize, i.e., wait until the grid-tied inverter makes the PV panel operate at the maximum power point. This generally takes about 5 minutes. Once the PV system has stabilized, the value of the power produced by the PV panel and the value of the power at the grid-tied inverter output should be stable and maximal.

Operation of the grid-tied PV system using net metering/self-consumption

In this section, you will observe the operation of the grid-tied PV system using net metering/self-consumption.

- 35.** Observe the values of power at the ac output of the grid-tied inverter and at the ac loads.

On energy meters 1 and 2, display the amount of metered energy expressed in Wh. Observe the energy values indicated by energy meters 1 and 2 (export and import meters, respectively).

Is the grid-tied PV system exporting electricity to the local ac power network or importing electricity from the local ac power network? Explain briefly.

- 36.** In the **Four-Quadrant Dynamometer/Power Supply** window, set the **Solar Irradiance** parameter to 400 W/m².

Measure the power at the ac output of the grid-tied inverter.

AC output power: _____ W

- 37.** On the **AC 230V Lamps** module, successively turn on the LED lamp and compact fluorescent lamp (CFL). While doing this, observe the power at the ac output of the grid-tied inverter, the power at the ac loads, and the energy values (expressed in Wh) indicated by energy meters 1 and 2.

Measure the power at the ac loads when the LED lamp and compact fluorescent lamp (CFL) are turned on.

Load power (LED lamp + CFL): _____ W

Is the grid-tied PV system still exporting electricity to the local ac power network? Explain briefly.

- 38.** On the **AC 230V Lamps** module, turn the incandescent lamp on. While doing this, observe the power at the ac output of the grid-tied inverter, the power at the ac loads, and the energy values (expressed in Wh) indicated by energy meters 1 and 2.

Measure the power at the ac loads when the three lamps (LED lamp, CFL, and incandescent lamp) are turned on.

Load power (all lamps on): _____ W

Is the grid-tied PV system still exporting electricity to the local ac power network? Explain briefly.

- 39.** On the **AC 230V Lamps** module, turn the three lamps off.

In the **Four-Quadrant Dynamometer/Power Supply** window, stop the **Solar Panel Emulator** to interrupt the production of electricity by the emulated PV panel.

On the **3AC 400V/DC 230V Power Supply**, set circuit breaker **F1** to the **O** (off) position to turn the three-phase ac power source off.

- 40.** Close **LVDAC-EMS**.

Turn the **4 Quadrant Power Supply and Dynamometer Controller** off.

Turn the **AC 24V Power Supply** off.

Turn electric power off at your workstation, if applicable. Remove all circuit connections, finishing with the equipment earthing connections. Return all equipment to its storage location.

CONCLUSION

In this exercise, you became familiar with the configuration and operation of grid-tied PV systems. You also became familiar with the operation of the grid-tied inverter. You learned that using a grid-tied PV system allows the amount of energy imported from the grid to be reduced. You saw the PV panel/inverter arrangements most commonly used in grid-tied PV systems. You became familiar with the following three types of grid-tied inverters: the central inverter, the string inverter, and the micro-inverter. You learned how to use the specifications of the PV panel, grid-tied inverter, and energy meter selected for a specific grid-tied PV system to verify that they can work together without causing problems. You saw the following two methods of metering energy in grid-tied PV systems: net metering and gross metering. You learned how the operation of micro-inverters can be monitored and set. You saw that using energy-efficient electric equipment has no impact on the size and cost of grid-tied PV systems.

REVIEW QUESTIONS

1. Briefly explain how gross energy metering (GEM) works in grid-tied PV systems.

2. Summarize the advantages and disadvantages of using micro-inverters in grid-tied PV systems instead of a central inverter or string inverters.

3. Briefly describe the main functions which the grid-tied inverter in a PV system performs.

4. Briefly explain how net energy metering (NEM) works in grid-tied PV systems.

5. Briefly describe the automatic disconnection function of the grid-tied inverter and its role in grid-tied PV systems.

Equipment Utilization Chart

The following equipment is required to perform the exercises in this manual.

Equipment		Exercise			
Order no.	Description	1	2	3	4
595055	DC 48V Lamps	1			
595056	AC 230V Lamps			1	1
594904	1AC 230V Energy Meter				2
595059	48V Lead-Acid Battery Pack	1	1	1	
595051	DC 48V PWM Charge Controller	1	1		
595050	DC 48V MPPT Charge Controller		1	1	
594825	3AC 400V/DC 230V Power Supply				1
595052	1AC 230V Stand-Alone Inverter			1	
595053	1AC 230V Grid-Tied Inverter				1
595054	Communications Gateway ⁽¹⁾				1
595028	4 Quadrant Power Supply and Dynamometer Controller ⁽²⁾	1	1	1	1
581438	Lead-Acid Battery Charger Function Set		1		
581440	Solar Panel Emulator Function Set	1	1	1	1
595912	Data Acquisition and Control Interface ⁽³⁾	1	1	1	1
772050	AC 24V Power Supply	1	1	1	1
595916	Connection Leads	1	1	1	1
(1) A single Communications Gateway per laboratory classroom is required.					
(2) Includes the Standard Functions (Manual Control) and the Standard Functions (Computer-Based Control).					
(3) Includes the Basic Computer-Based Instrumentation Function Set (2 voltage inputs + 2 current inputs).					

Most of the equipment listed in the chart above is designed to be installed in a DIN A4 workstation. Using a DIN A4 workstation, though recommended, is not strictly required since the equipment can also be laid on a horizontal work surface such as a desk or a table. For more information, refer to the Safety Instructions and Commissioning manual of the Electric Power Technology Training Equipment.

Glossary of New Terms

Buck chopper	Power electronic circuit that converts a dc voltage into a dc voltage of lower value. It generally consists of an electronic power switching device (a MOSFET or an IGBT in most cases), a capacitor, a diode, and an inductor. Voltage conversion is achieved by turning the electronic power switching device on and off at a high frequency. Pulse-width modulation (PWM) allows the value of the low voltage to be adjusted.
Charge controller	Power control device that controls battery charging, prevents battery overcharging, and prevents the battery from being discharged too deeply. It uses electronic circuitry and power switching devices such as contact relays and/or electronic power switches to achieve the functions mentioned above.
Daily energy demand	Amount of energy consumed every day, generally expressed in Wh/day or kWh/day. The daily energy demand is obtained by multiplying power (expressed in W or kW) by the time (expressed in hours) this power is used every day (i.e., over a 24-hour period).
Grid-tied inverter	Electronic device that converts dc power into ac power. The ac output of the device is connected to the local ac power network. Consequently, the magnitude and frequency of the voltage at the ac output of the device are determined by the local ac power network. Grid-tied inverters are implemented using electronic power switches (MOSFETs, IGBTs, etc.).
Grid-tied PV system	PV system that is connected to the local ac power network.
Gross energy metering (GEM)	Method of metering the amount of energy which an electrical installation exchanges with the local ac power network. With GEM, all electricity produced by the installation is exported to the local ac power network and metered using a unidirectional energy meter. Also, all electricity consumed by the installation is imported from the local ac power network and metered using a second unidirectional energy meter.
Maximum power point (MPP)	Operating point at which an electric power generator, such as a PV panel or a wind turbine, produces the maximum amount of power.
MOSFET	An insulated-gate field-effect transistor in which the gate is made of metal and the insulating layer between the gate electrode and channel is native oxide material. MOSFET stands for metal-oxide-semiconductor field-effect transistor.
MPP tracking (MPPT)	A control algorithm that automatically tracks the MPP of an electric power generator, such as a PV panel or a wind turbine. The generator voltage and current are continually measured to monitor the amount of power which the generator produces. The algorithm periodically changes the operating point of the generator to see if the amount of power produced can be improved.
Net energy metering (NEM)	Method of metering the amount of energy which an electrical installation exchanges with the local ac power network. NEM uses a single energy meter (bidirectional unit is required) located between the electrical installation and the local ac power network to measure the net amount of energy exchanged.

Photovoltaic (PV) system	System that uses one or several photovoltaic (PV) panels and power control/conversion devices to convert sunlight into electricity. The electricity produced can be used to power electric equipment (local loads) or to feed the local ac power network.
Pulse-width modulation (PWM)	Modulation technique in which the width of pulses of voltage or current can be varied to adjust the average value of the voltage or current. The frequency of the pulses of voltage or current largely depends on the application and can range from a few hertz to megahertz. PWM is used in numerous electronic power control devices (charge controllers, stand-alone inverters, grid-tied inverters, variable-speed motor drives, etc.).
Solid-state relay (SSR)	A solid-state relay is an electronic device used to switch a large amount of power to a load, using a low-power control signal. The SSR is functionally comparable to the contact relay, except that it uses semiconductors (usually a pair of thyristors or MOSFETs) instead of mechanical contacts to switch power to the load.
Stand-alone inverter	Electronic device that converts dc power into ac power. Stand-alone inverters are implemented using electronic power switches (MOSFETs, IGBTs, etc.).
Stand-alone PV system	PV system that is not connected to the local ac power network.

Safe Handling of PV Panels

PV panels produce electricity whenever exposed to sunlight. Contrary to other devices producing electricity (e.g., synchronous generators in electric power stations, diesel generators, etc.), PV panels exposed to sunlight cannot be turned off. Maximum voltage is present across a PV panel exposed to sunlight (even in low light conditions) when its connection wires are open. This situation, which is common during the installation of PV panels, represents an electric shock hazard when the voltage across a PV panel exceeds about 30 V. Voltage increases when PV panels are connected in series to form an array, thereby rendering the electric shock hazard even more dangerous. To eliminate the risk of an electric shock in this situation, the PV panels should be covered with an opaque material throughout their installation in order to prevent electricity from being generated. If this is not possible, however, great caution must be exercised when working on the connections of PV panels (see general safety recommendations at the end of this appendix).

Electric arcs are another electrical hazard related to PV panels exposed to sunlight. An electric arc may occur when connecting or disconnecting a PV panel exposed to sunlight (i.e., producing electricity) while it is under load. Electric arcs must be avoided because they can cause burns or start a fire. Covering the PV panels with an opaque material stops electricity generation and prevents electric arcs from occurring. When this option is not possible, however, electric arcs occurring when connecting or disconnecting PV panels that are under load can be greatly mitigated by disconnecting the entire PV panel array from the rest of the PV system using the disconnect switch installed for this purpose. This removes any electrical load from the PV panel array, thereby reducing the load current to zero and allowing the connection to any of the PV panels to be made or broken with minimal arcing. Note that the disconnect switch must be tagged and locked out to ensure it remains open while working on the PV panel connections. Remember that once disconnected, maximum voltage is present across a PV panel exposed to sunlight. Always exercise great caution when working on the connections of PV panels that are still producing electricity.



PV panels must never be installed close to equipment or in locations where flammable gases can be produced or collected. Minor electric arcs may occur when modifying the connections of PV panels, even when the PV panel array disconnect switch is open. Any electrical arcing, even minimal, may cause a fire or an explosion.

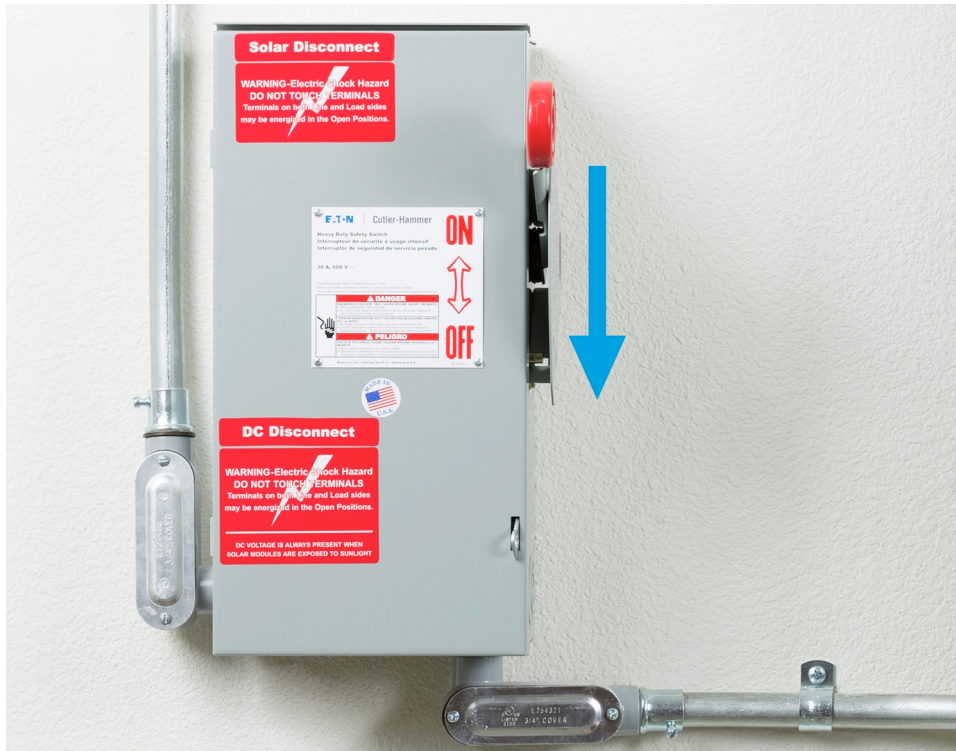


Figure 55. To mitigate electric arcs that may occur when connecting or disconnecting PV panels exposed to sunlight while under load, the entire PV panel array must be disconnected from the rest of the PV system using the disconnect switch installed for this purpose.

Finally, the general safety recommendations below should always be respected when manipulating, installing, or replacing PV panels.

- Before working on PV panels or any other part of a PV system, remove any metallic jewelry (e.g., rings, earrings, metallic wristwatch, etc.) to avoid accidental contact with live electrical equipment.
- Use appropriate safety equipment (e.g., insulated tools, insulating gloves, suitable eye protection, etc.) approved for work on electrical installations.
- Do not attempt to manipulate or install PV panels in adverse conditions (e.g., strong winds, rain, presence of ice or snow, etc.) to avoid injuries or damage to the PV panels.
- Wear non-slip gloves when manipulating PV panels to protect your hands from cuts caused by potentially sharp edges of PV panel frames.
- Do not allow children or unauthorized persons near the installation site or storage area of PV panels.
- Observe all instructions and safety precautions that apply to the other components used in the PV system.

Preparation of the 48V Lead-Acid Battery Pack

This appendix explains how to prepare (fully charge) each **48V Lead-Acid Battery Pack** before a laboratory period. The **4 Quadrant Power Supply and Dynamometer Controller** is used to charge either a single battery pack or several battery packs (connected in parallel) at a time.

Charging procedure

The charging procedure below can be performed overnight so that the equipment is ready to be used by another group of students the following day.

Perform the following steps:

1. To charge a single **48V Lead-Acid Battery Pack**, start the procedure at step 2. To charge several **48V Lead-Acid Battery Pack** modules (connected in parallel) at the same time, start the procedure at step 3.
2. Connect the positive (red) terminal of the **48V Lead-Acid Battery Pack** to terminal **1** of the **4 Quadrant Power Supply and Dynamometer Controller**.

Connect the negative (black) terminal of the **48V Lead-Acid Battery Pack** to terminal **N** of the **4 Quadrant Power Supply and Dynamometer Controller**.

Connect one of the protective earthing (PE) terminals of the **48V Lead-Acid Battery Pack** to one of the PE terminals of the **4 Quadrant Power Supply and Dynamometer Controller**.

Go to step 4.

3. Connect the **Parallel Charging Input** (red) terminal of each **48V Lead-Acid Battery Pack** to terminal **1** of the **4 Quadrant Power Supply and Dynamometer Controller**.

Connect the negative (black) terminal of each **48V Lead-Acid Battery Pack** to terminal **N** of the **4 Quadrant Power Supply and Dynamometer Controller**.

Make the connections required to earth each **48V Lead-Acid Battery Pack** properly.



If necessary, check with the instructor to ensure that the connections you made provide proper earthing of the equipment.

Go to the next step.

4. Make sure that the main power switch of the **4 Quadrant Power Supply and Dynamometer Controller** is set to the **O** (off) position, then connect its **Power Input** to an ac power outlet that is properly protected.



*If necessary, check with the instructor to ensure that the ac power outlet to which you connect the **4 Quadrant Power Supply and Dynamometer Controller** is properly protected.*

5. Set the **Operating Mode** switch of the **4 Quadrant Power Supply and Dynamometer Controller** to the **Power Supply** position.
6. Turn the **4 Quadrant Power Supply and Dynamometer Controller** on by setting its main power switch to the **I** (on) position.
7. On the **4 Quadrant Power Supply and Dynamometer Controller**, select the **Pb-Acid Battery Float Charger** function using the **Function** button, then set the charging voltage to 55.2 V using the **Command** knob.
8. Make sure that the lever of the circuit breaker on each **48V Lead-Acid Battery Pack** is set to the **I** (on) position.
9. Start battery charging by depressing the **Start/Stop** push button on the **4 Quadrant Power Supply and Dynamometer Controller**. The display should indicate **Started**, signifying that battery charging has begun.
10. Once battery charging is completed, stop the **Pb-Acid Battery Float Charger** by depressing the **Start/Stop** push button, then turn the **4 Quadrant Power Supply and Dynamometer Controller** off.
11. Disconnect each **48V Lead-Acid Battery Pack** from the **4 Quadrant Power Supply and Dynamometer Controller**, keeping the equipment earthing connections.

Test each **48V Lead-Acid Battery Pack** for sulfation as described in the **Sulfation test** section of this appendix.

Sulfation test



*This test must be performed on a single **48V Lead-Acid Battery Pack** at a time.*

Perform the following steps:

1. Connect the positive (red) terminal of the **48V Lead-Acid Battery Pack** to terminal **1** of the **4 Quadrant Power Supply and Dynamometer Controller**.

Connect the negative (black) terminal of the **48V Lead-Acid Battery Pack** to terminal **N** of the **4 Quadrant Power Supply and Dynamometer Controller**.

Connect one of the protective earthing (PE) terminals of the **48V Lead-Acid Battery Pack** to one of the PE terminals of the **4 Quadrant Power Supply and Dynamometer Controller**.

2. Make sure that the main power switch of the **4 Quadrant Power Supply and Dynamometer Controller** is set to the **O** (off) position, then connect its **Power Input** to an ac power outlet that is properly protected.



*If necessary, check with the instructor to ensure that the ac power outlet to which you connect the **4 Quadrant Power Supply and Dynamometer Controller** is properly protected.*

3. Set the **Operating Mode** switch of the **4 Quadrant Power Supply and Dynamometer Controller** to the **Power Supply** position.
4. Turn the **4 Quadrant Power Supply and Dynamometer Controller** on by setting its main power switch to the **I** (on) position.
5. On the **4 Quadrant Power Supply and Dynamometer Controller**, select the **Current Source (-)** function (negative current source) using the **Function** button, then set the current command to -4 A using the **Command** knob.
6. Make sure that the lever of the circuit breaker on the **48V Lead-Acid Battery Pack** is set to the **I** (on) position.
7. Start the negative current source by depressing the **Start/Stop** push button on the **4 Quadrant Power Supply and Dynamometer Controller**. The display should indicate **Started**, signifying that the negative current source is started.
8. Observe the voltage across the **48V Lead-Acid Battery Pack**. If the **48V Lead-Acid Battery Pack** is unable to maintain the voltage above 48 V during one minute, it may be sulfated.
9. Stop the negative current source by depressing the **Start/Stop** push button of the **4 Quadrant Power Supply and Dynamometer Controller**.

On the **48V Lead-Acid Battery Pack**, open the circuit breaker by setting its lever to the **O** (off) position.

Disconnect the **48V Lead-Acid Battery Pack** from the **4 Quadrant Power Supply and Dynamometer Controller**.

10. Repeat the sulfation test above if you have other **48V Lead-Acid Battery Pack** modules to test. Otherwise, go to the next step.

11. Turn the 4 Quadrant Power Supply and Dynamometer Controller off.
12. Faulty 48V Lead-Acid Battery Pack modules can be desulfated by using a desulfator, otherwise the batteries in these modules must be replaced.

Battery maintenance

In order to optimize the cycle life of the batteries in the 48V Lead-Acid Battery Pack and to prevent sulfation, the module should be charged as soon as possible after a discharge cycle (e.g., after completion of a laboratory exercise). The 48V Lead-Acid Battery Pack should never be stored with the batteries discharged for an extended period of time.

Setting up the Communications Gateway

Introduction

In this manual, the [1AC 230V Grid-Tied Inverter](#) is used to set up a grid-tied PV system. A [Communications Gateway](#) is required to make the [1AC 230V Grid-Tied Inverter](#) operate. In fact, a single [Communications Gateway](#) is required to make all [1AC 230V Grid-Tied Inverter](#) modules in the laboratory classroom operate. The following procedure explains how to properly set up the [Communications Gateway](#) in the laboratory classroom.

Procedure

1. Connect the [Communications Gateway](#) to an ac power outlet of the laboratory classroom that is properly protected. To enable communication with the [1AC 230V Grid-Tied Inverter](#) modules, the ac power outlet to which the [Communication Gateway](#) is connected must be powered by the same phase of the classroom's electrical installation to which each grid-tied PV system is connected (e.g., phase L1 of the classroom's electrical installation).
2. Observe the display of the [Communications Gateway](#) and wait until the unit completes its start-up routine. At some point, the [Home](#) screen will appear on the display of the [Communications Gateway](#). This screen displays the IP address (e.g., 169.254.120.1) of the [Communications Gateway](#), the present power production (W), the total energy production reported to the [Communications Gateway](#) (kWh), etc.
3. During the first 20 minutes of operation, the [Communications Gateway](#) performs a communications check.

During the communications check, the [Communications Gateway](#) establishes communication (via the ac power lines) with each [1AC 230V Grid-Tied Inverter](#) in the laboratory classroom that has already been used with the unit. The purpose of the communications check is to verify the communication level (i.e., the signal strength) achieved through the ac power lines.

During the communications check, the display of the [Communications Gateway](#) alternates between the [Home](#) screen and the [Communications Check](#) screen. The [Communications Check](#) screen indicates the communication level using vertical bars (level is proportional to number of bars) as well as the number of devices (i.e., the number of [1AC 230V Grid-Tied Inverter](#) modules) with which the [Communication Gateway](#) established communication.

Observe the display of the [Communications Gateway](#). The number of devices indicated in the [Communications Check](#) screen should increase whenever a [1AC 230V Grid-Tied Inverter](#) that has already been used with the [Communications Gateway](#) is turned on (i.e., fed with dc power) and connected to the ac power network. Ultimately, the number of devices indicated in the [Communications Check](#) screen should equal the number of [1AC 230V Grid-Tied Inverter](#) modules that are currently in use in the

laboratory classroom, thereby confirming that the [Communications Gateway](#) has established communication with each of these modules. In this case, the [Communications Gateway](#) is set up properly and no other action is required. Otherwise, continue the procedure at the next step.



When a [1AC 230V Grid-Tied Inverter](#) that has already been used with the [Communications Gateway](#) is turned on and connected to the ac power network after the communications check, you can start another cycle of communications check to verify communications with this unit. To do so, press and hold the [Menu](#) button of the [Communications Gateway](#) (button is on the right-hand side of the unit). Release the [Menu](#) button when the display of the [Communications Gateway](#) reads “Enable Communications Check”.

4. The number of devices indicated in the [Communications Check](#) screen is less than the number of [1AC 230V Grid-Tied Inverter](#) modules that are currently in use in the laboratory classroom.

Make sure that each [1AC 230V Grid-Tied Inverter](#) in the laboratory classroom is turned on (i.e., fed with dc power) and connected to the ac power network.

Also make sure that the ac power outlet to which the [Communication Gateway](#) is connected is powered by the same phase of the classroom's electrical installation to which each grid-tied PV system is connected.

Wait a few minutes, then observe the display of the [Communications Gateway](#). If the number of devices indicated in the [Communications Check](#) screen corresponds to the number of [1AC 230V Grid-Tied Inverter](#) modules that are currently in use in the laboratory classroom, the [Communications Gateway](#) is set up properly and no other action is required. Otherwise, continue the procedure at the next step.



If necessary, start another cycle of communications check to verify communications with the [1AC 230V Grid-Tied Inverter](#) modules.

5. The number of devices indicated in the [Communications Check](#) screen is still less than the number of [1AC 230V Grid-Tied Inverter](#) modules that are currently in use in the laboratory classroom. This may be due to the fact that some of the [1AC 230V Grid-Tied Inverter](#) modules in the laboratory classroom have never been used with the [Communications Gateway](#). Continue the present procedure to make the [Communications Gateway](#) detect new [1AC 230V Grid-Tied Inverter](#) modules in the classroom.

Connect the Ethernet port of the [Communications Gateway](#) to the Ethernet port of a computer. Use the Ethernet cable supplied with the [Communications Gateway](#).

Open an Internet browser on the computer. Enter the IP address of the [Communications Gateway](#) in the Internet browser.

Once the browser has successfully connected with the [Communications Gateway](#), the [System Overview](#) screen should appear on the computer display.

6. In the [System Overview](#) screen, click [Administration](#) to access the [Administration](#) menu. The default login credentials for the [Administration](#) menu are:

User name: admin

Password: admin

The [System Administration](#) screen, which contains the [Administration](#) menu, should appear on the computer display.

7. In the [Administration](#) menu, click [Device Scan Control](#). The [System Administration>Device Scan Control](#) screen should appear on the computer display.

In the [System Administration>Device Scan Control](#) screen, enter a duration (e.g., 10 minutes) in the [Scan Duration](#) and [Priority Duration](#) fields, then click the [Start Scan](#) button. This causes the [Communications Gateway](#) to start scanning for new [1AC 230V Grid-Tied Inverter](#) modules.

Observe the display of the [Communications Gateway](#). At some point, it should indicate that a priority scan is active as well as the number of devices (i.e., the number of [1AC 230V Grid-Tied Inverter](#) modules) detected. The number of devices indicated should increase as the [Communications Gateway](#) detects new [1AC 230V Grid-Tied Inverter](#) modules in the laboratory classroom.

8. To view a listing of the devices (i.e., the [1AC 230V Grid-Tied Inverter](#) modules) detected, click [Inventory](#) in the [System Administration>Device Scan Control](#) screen. The [Inventory](#) screen should appear on the computer display.

Each device detected is identified by its serial number (12-digit number) in the [Inventory](#) screen. After a certain time, all the [1AC 230V Grid-Tied Inverter](#) modules that are currently in use in the laboratory classroom should be listed in the [Inventory](#) screen. When so, the [Communications Gateway](#) is set up properly.



Once all [1AC 230V Grid-Tied Inverter](#) modules in the laboratory classroom are listed in the [Inventory](#) screen, you can stop device scanning by clicking the [Stop Scan](#) button in the [System Administration>Device Scan Control](#) screen.

9. Close the [Inventory](#) screen.

Disconnect the Ethernet port of the [Communications Gateway](#) from the Ethernet port of the computer.

Leave the [Communications Gateway](#) connected to the ac power outlet during the whole lab session.

10. End of procedure.

Index of New Terms



The bold page number indicates the main entry. Refer to the Glossary of New Terms on page 131 for definitions of new terms.

buck chopper	50 , 51, 52, 53, 54, 56
charge controller	1, 7, 12 , 13, 14, 15, 16, 17, 18, 20, 21, 22, 23, 24, 25, 26, 29, 49, 50, 52, 53, 54, 56, 73, 74, 75, 76, 78
daily energy demand	8 , 29, 30, 80
grid-tied inverter	1, 4, 5, 95, 96 , 97, 98, 99, 101, 103, 106, 107, 108, 109, 110
grid-tied PV system	2 , 4, 5
gross energy metering (GEM)	110
maximum power point (MPP)	49, 50 , 99, 100, 102, 103
MOSFET	22 , 25, 54
MPP tracking (MPPT)	49
net energy metering (NEM)	108
photovoltaic (PV) system	1
pulse-width modulation (PWM)	22
solid-state relay (SSR)	22 , 25
stand-alone inverter	1, 73 , 74, 75, 76, 78, 79, 97
stand-alone PV system	1 , 5, 7, 8, 9, 10, 12, 13, 14, 15, 16, 26, 27, 28, 29

Acronyms

The following acronyms are used in this manual:

AC	alternating current
CFL	compact fluorescent lamp
DC	direct current
DOD	depth of discharge
GEL	gelled electrolyte
GEM	gross energy metering
LED	light-emitting diode
LVD	low-voltage disconnect
LVR	low-voltage reconnect
MOSFET	metal-oxide semiconductor field-effect transistor
MPP	maximum power point
MPPT	maximum power point tracking
NEM	net energy metering
PV	photovoltaic
PWM	pulse-width modulation
SOC	state of charge
SSR	solid-state relay
STC	standard test conditions
VR	voltage regulation
VRR	voltage regulation reconnect

Bibliography

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

