Photovoltaic Power System

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Modeling, Design, and Control

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WILEY

This edition first published 2017

Registered Office(s)
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

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Library of Congress Cataloging-in-Publication Data
Names: Xiao, Weidong, 1969- author.
Title: Photovoltaic power system : modeling, design, and control / Weidong Xiao.
Description: Hoboken, NJ : John Wiley & Sons, 2017. | Includes bibliographical references and index.
Identifiers: LCCN 2016056659 (print) | LCCN 2017001056 (ebook) | ISBN 9781119280347 (cloth) | ISBN 9781119280361 (pdf) | ISBN 9781119280323 (epub)
Subjects: LCSH: Photovoltaic power systems.
Classification: LCC TK1087 .X56 2017 (print) | LCC TK1087 (ebook) | DDC 621.31/244–dc23
LC record available at https://lccn.loc.gov/2016056659

Cover Design: Wiley
Cover Images: (Background) © Alessandro2802/Gettyimages; (Circles: Top right corner to bottom left corner) © chapin31/Gettyimages; © PaulPaladin/Gettyimages; Courtesy of author; © Dwight Smith/Shutterstock

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This book is dedicated to my son, William, and daughter, Emily, with deep love.

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Preface

Photovoltaic (PV) power engineering has attracted significant attention in recent years. This book sets out to fulfil an important need in academia and industry for a comprehensive resource covering modeling, design, simulation, and control of PV power systems. Initially developed to support teaching senior-undergraduate and graduate courses, the work also covers practical design issues, that make it useful for industry practitioners seeking to master the subject through self-study and training. The book provides a smooth transition from fundamental knowledge to advanced subjects of interest to academics and to those working on system improvements in industry. A fundamental knowledge of power electronics and linear control theory is required to benefit fully from this book.

This comprehensive treatment covers fundamental and advanced subjects in technologies, power electronics, and control engineering for PV power systems. Throughout, the description of PV power systems follows a clear framework for each section.

The book is divided into ten chapters. The interrelationship of the chapters is illustrated in Figure 1. The step-by-step introduction of the individual system components and controls for PV power systems is covered in Chapters 4–8.With the support of the system classification and the safety guidelines, which are discussed in Chapters 2 and 3, respectively, the overall system integrations for standalone systems and grid-tied systems are set out in Chapters 9 and 10.

Chapter 1 provides a brief introduction to solar power systems. This includes the clarification of vocabulary which proves integral to the remainder of the book.

Chapters 2 and 3 provide comprehensive classifications of PV power system configurations, in particular grid-tied systems, approached according to the level at which the MPPT is applied, MPPT techniques, power-conditioning topologies, and technologies for battery balancing. The reader is assisted, using clear definitions, to develop an understanding of the latest systems and directions of research and development, which later informs research directions for PV power systems. Reader understanding of relevant safety standards, guidance, and regulations is developed to prevent researchers deviating from standard practice in industry. A system of reference is provided for safe practice in engineering and design. Though the codes and guidelines cited are implemented in the USA and Europe, they are universally applicable and allow all readers to practice PV power engineering in a safe manner. These chapters also cover the certification of PV modules, the safety standards of power interfaces, the system requirements for grid interconnection, and the important means of protection. The main conversion units are the PV-side converters, battery-side converters, and grid-side converters. The

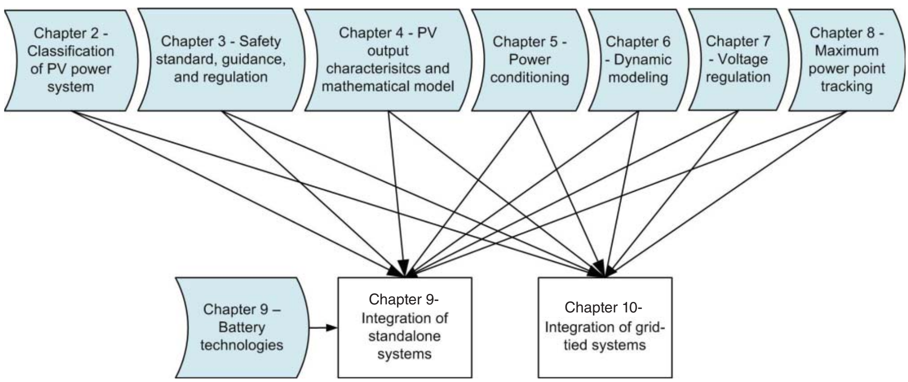

Figure 1 Organization and interconnection of Chapters 2 to 10.

interconnection of the conversion units are the PV link, DC link, and grid link. The PV generation section is divided into the PV source circuits and PV output circuits. Two types of modeling are demonstrated for the reader. Firstly, simulation models that represent a practical system and prove the design concept are discussed in Chapters 4 and 5. Secondly, mathematical models are developed to illustrate the system dynamics used for controller synthesis. Model development and verification are covered in Chapter 6.

Chapter 4 discusses PV output characteristics and mathematical models for simulation and analysis. It builds upon an understanding of PV product datasheets and provides a straightforward approach to building a mathematical model for simulation purposes. When model accuracy becomes the priority, an advanced approach is also provided. The tradeoff between model simplicity and accuracy is extensively considered, discussed, and demonstrated by practical examples.

Chapter 5 provides the information necessary to specify, design, simulate, and evaluate power-conditioning circuits and accessories for PV power applications. The main conversion units are PV-side converters, battery-side converters, and grid-side converters. The important interconnections are the PV link, DC link, and grid link. The description provided comprehensively covers application to all PV power systems. The chapter covers system design, steady-state analysis, and simulation verification. Current modulation for AC grid interconnection is introduced and simulated for design verification. This book places emphasis on computer-aided analysis, design, and evaluation. For universality, all included simulation models are built using the fundamental blocks of Simulink. The analysis reveals the fundamental system dynamics for the purpose of both time-domain simulation and control synthesis. Although provided with software such as Simscape Power Systems, written for power electronics and power systems, this is not used due to the aim to demonstrate the simulation principle and focus on fundamental implementations instead. The control system design, analysis and evaluations are based on the functions of Matlab and Matlab version R2010b. Simulink is used to demonstrate all simulation cases; the same or higher versions of this software can be used to duplicate simulation results or develop results further. Most chapters present practical examples in order to demonstrate designs and verify them, which are presented in case studies. Photographs, diagrams, flowcharts, graphs, equations, and tables are included to provide clear explanations of technical subject matter. Readers can then duplicate results through computer-aided design and analysis, leading to the development and evaluation of new systems.

Chapter 6 focuses on dynamic modeling of PV power systems. The mathematical modeling starts with the state-space averaging, followed by linearization. Dynamic models are developed for the voltage signals at the PV and DC links and the variety of converter topologies is also considered. The dynamics of the developed mathematical models are verified through simulation and comparison. One section is given over to modeling the dynamics of dual active bridges when used as the battery power interface.

Chapter 7 concerns the application of linear control theory. The chapter discusses evaluations of relative stability and system robustness. Voltage regulation for the PV and DC links is introduced and analyzed in depth. Examples and simulations are used to demonstrate the effectiveness of proposed approaches and methodology. Based on the system model, advanced control techniques, such as Affine parameterization, anti-windup, and feedforward implementation, are introduced. The implementation of sensing and digital control is briefly discussed at the end of the chapter.

Chapter 8 focuses on MPPT, which is important and unique to PV power systems. A comprehensive overview is provided, and MPPT algorithms are classified and discussed. The chapter introduces a simple algorithm and develops to consider advanced techniques to improve tracking performance. The simulation and implementation of MPPT techniques are also discussed in this chapter.

Chapter 9 discusses the integration of standalone PV power systems. The chapter enables readers to understand the latest progress and choose suitable battery types for standalone applications through the introduction and comparison of battery characteristics. This proceeds onto a discussion of battery characteristics and models and how they relate to system design and analysis. A new classification is proposed to avoid confusion seen in the earlier literature and provide a clear framework for understanding the methodologies used for battery balancing. A method to integrate the MPPT function with the battery cycle charge is proposed. Examples are given to demonstrate the effectiveness of modeling, design, control, and simulation. Simulation models for the controller and power interface are developed at different levels: short term, medium term, long term, and very long term. A simulation of eight-hour system operation is created, demonstrating the state of MPPT, battery voltage regulation, and variation of state of charge corresponding to solar irradiance and cell temperature.

The final chapter, Chapter 10, addresses the integration of grid-tied PV power systems, including two small-scale single-phase interconnections and one utility-level three-phase system. Examples are given demonstrating the effectiveness of the design, integration, control, and simulation with additional consideration for safety protection. The simulation study is divided into two parts: a short-term simulation that aims to capture the fast transient response of switching dynamics and grid disturbances, and a long-term simulation that illustrates the system operation in response to environmental conditions.

Technical Support

One advantage of this book is that all modeling and simulation for the case studies is based on the basic functions of Simulink and Matlab. The modeling and simulation approach is based on system dynamics, which helps readers to understand the fundamental principle behind various simulation tools. The construction of output models, power interfaces and control, and standalone and grid-tied systems are illustrated in detail. Version R2010b or higher of Matlab and Simulink can be used to duplicate the results or to develop new studies. Other software tools are unnecessary.

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1

Introduction

The photovoltaic (PV) effect is the generation of DC electricity from light. Alexandre Edmond Becquerel, a French experimental physicist, discovered the effect in 1839. More recently, scientists have discovered that certain materials, such as silicon, can produce a strong PV effect. In the 1950s, Bell Labs of the USA produced PV cells for space activities. This can be considered as the beginning of the PV power industry. The high cost of PV materials mostly prevented applications elsewhere.

Over the past 20 years, the PV power industry has experienced significant growth. PV power generation has become more and more common. The capacity of PV systems ranges from milliwatts for portable devices such as calculators, to gigawatts for power plants connected to the electricity grid. A grid-connected PV power system can be economically installed, and can be rated as low as just a few hundred watts. The advantages of PV power systems that have led to their rapid growth are:

- green, renewable
- reliability and long lifetime
- advanced manufacturing process
- static, so noise-free operations
- improving efficiency
- decreasing prices
- flexibility of construction
- highly modular nature
- availability of government support and incentives.

Using the latest technologies, the manufacturing of crystalline-based PV cells consumes significant amounts of energy, which prevents further cost reductions. The levelized cost of electricity generated using solar PVs is still high in comparison with conventional generation resources, such as coal, natural gas, and wind, according to a technical report published by the US Department of Energy's National Renewable Energy Laboratory (Stark et al. 2015). The report was based on a study of the USA, Germany, and China. Several large-scale PV power systems were announced in 2016 and projected significantly lower costs, but these must be treated as special cases. The project feasibility and system reliability need to be carefully evaluated until the projects are successfully delivered. It is clear that the price of PV products mostly reflects their quality and reliability. High-quality, certified PV products are usually more expensive than non-certified ones. It is unrealistic to judge a PV power system only on the installation cost since reliable and long-lifetime operations are always expected.

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Companion Website: www.wiley.com/go/xiao/pvpower

Table 1.1 Price schedule of feed-in tariffs in Ontario, Canada.

Type	System capacity (kW)	Price (\$/kWh)*
Rooftop	≤10	0.294
	10–100	0.242
	100–500	0.225
Non-rooftop	≤10	0.214
	10–500	0.209

*Canadian dollars.

The feed-in tariff (FIT) is the major driver of the boom in PV power all over the world. The regulatory incentives are different from country to country, but all are designed to accelerate investment in PV-related technologies. One FIT example can be found on the website of the Ontario Power Authority, Canada. Parts of the FIT price schedule are shown in Table 1.1, which covers projects under 500 kW in capacity. It shows that the government contributes significant funds for PV system installations since the listed price is higher than the charge for residential consumption. It should be noted that the listed price is based on the 2016 schedule. Like FITs in most other countries, it is always subject to change. Another disadvantage of PV power systems lies in their low power density, which limits their use mainly to static applications rather than vehicles. Motor vehicles are usually considered as one of the major contributors to air pollution.

1.1 Cell, Module, Panel, String, Subarray, and Array

A PV cell, also commonly called a solar cell, is the fundamental component of a PV power system. A crystalline-based solar cell features a p-n junction, as shown in Figure 1.1. The manufacturing process includes melting, doping, metallization and texturing. The positive and negative sides of the junction form the DC voltage and supply electricity when a load is connected. However, the voltage of a single p-n junction cell is less than 1 V, which is low for most practical applications. Moreover, it is mechanically fragile, and must be laminated and protected for practical use.

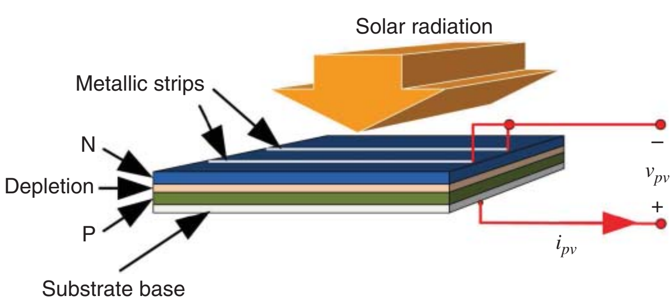


Figure 1.1 Typical crystalline PV cell construction.

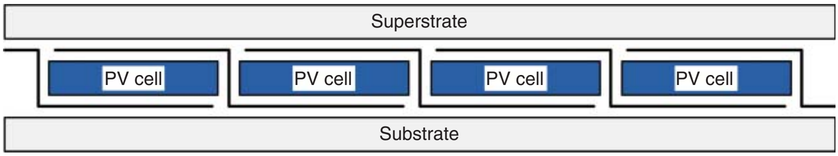


Figure 1.2 Lamination of PV module.

To end users, the basic unit is the PV module or solar panel, which can produce higher voltages and more power than a single cell. A PV module consists of cells that are interconnected and laminated together. The old PV panel was usually designed to match the nominal voltage of batteries, since standalone systems were the beginning of the PV industry. For example, traditional 36-cell PV modules used to be popular for direct charging of batteries with a nominal voltage of 12 V. Nowadays, with the increasing numbers of grid-connected systems and the advances in power-conditioning devices, the number of cells in each PV module is no longer limited to matching the nominal voltages of batteries or loads. The manufacturers are more concerned with cost-effective solutions and supply all different sizes of solar panels: usually incorporating 48, 54, 60, or 72 cells. Solar cables and connectors are usually integrated with the module for straightforward interconnection and installation.

To form a PV panel, crystalline-based PV cells are sandwiched by the superstrate and substrate for protection, as illustrated in Figure 1.2. Tempered glass is commonly used as the superstrate, supporting the module lamination and protecting the fragile cells. Glass also has the same ratio of thermal expansion as a crystalline PV cell, since both are made of silicon. Furthermore, tempered glass is strong and has good transparency, with about 94% light transmission. The glass surface is also textured to reduce light reflections. Metal conductors connect the PV cells from the surface to the bottom for series interconnection. The cells are also protected by an encapsulant, which is a material that surrounds the PV cells between the superstrate and substrate.

Figure 1.3 shows a standard PV module and its internal electrical configuration. It consists of 72 cells in series connection. The cells are divided into three groups, which are termed the submodules. Each submodule includes one bypass diode in parallel connection with 24 interconnected solar cells. The bypass diodes are standard components that are integrated in the crystalline-based PV module. The implementation prevents the destructive effects of hot spots, should there be unbalanced generation among the series-connected cells. The overall electrical connection is configured inside the junction box, which is commonly located at the back of the PV panel. The output cable always indicates the polarity of the positive and negative terminals.

Attention should be given to AC PV modules, often simply called AC modules. Just the same as standard PV modules, an AC module is an environmentally protected unit consisting of interconnected solar cells, junction box, superstrate, substrate, electrical interconnections, and other lamination components. However, the module includes an inverter inside the junction box to produce AC power at the output terminal. The concept of an AC module is the same as the microinverter solution, which converts DC to AC at the PV module level. However, the difference is that the microinverter is an independent unit that is electrically connected to the PV module instead of being fully integrated. Microinverters belong to the class of module-integrated parallel inverters (MIPIs), which will be discussed in Section 2.4.1.

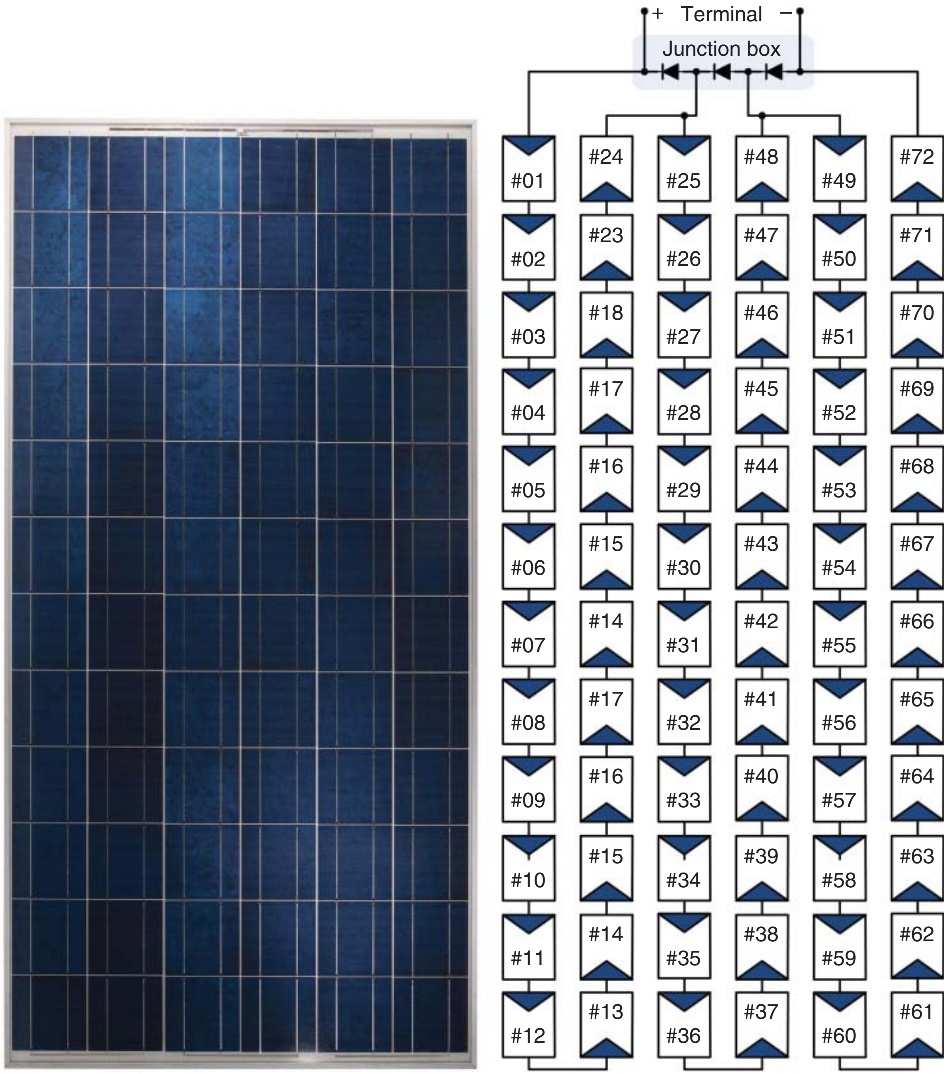


Figure 1.3 72-cell PV module: left, appearance; right, configuration.

It is very important to use the correct terms to describe PV generators: cell, module, panel, string, subarray, and array. Figure 1.4 illustrates how the power capacity is built up from cell level to array level. PV power systems are commonly assembled by configuration of PV modules in series and/or in parallel. The series connection of solar modules in order to stack up the output voltage is commonly referred to as a "string." The parallel connections of PV strings forms an array, in which the power capacity can be built up to the levels of hundreds, thousands, or even millions of watts. In large-scale PV power systems, an array is divided into multiple subarrays.

A PV array can be monopolar or bipolar. A monopolar array or subarray is a typical DC circuit that has two conductors in the output circuit, with positive (+)

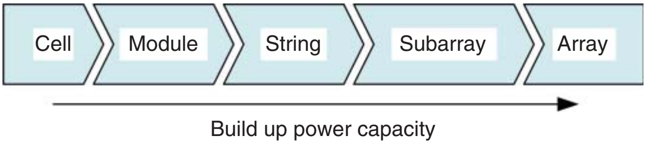


Figure 1.4 PV power capacity built from cell to array.

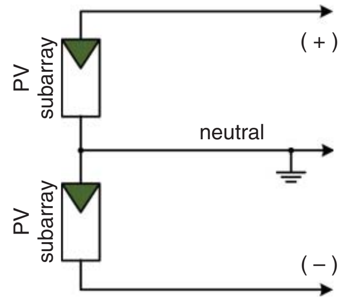


Figure 1.5 Bipolar PV array formed from two monopolar subarrays.

and negative (−) polarities. A bipolar PV array includes a neutral point, as shown in Figure 1.5, and is formed from two monopolar subarrays. Ideally, the two monopolar subarrays should be identical in power and voltage levels. The neutral point is grounded at a central point in the interconnected system. A company called AE Solar Energy used to be the major producer of utility-interaction inverters, which were designed for the bipolar array configuration and large-scale PV power systems. The inverter accommodates the output of the bipolar PV array and is rated at up to ±600 V.

1.2 Blocking Diode

PV components are direct current sources, so the reverse flow of current into the PV source circuit should be prevented. Blocking diodes can be used, installed in series with the PV output string in order to block reverse currents. They are often referred to as "string diodes." To distinguish them from the bypass diode, Figure 1.6 illustrates a typical PV source circuit with the integration of both bypass and blocking diodes, denoted D_{bp} and D_{bl}, respectively. The bypass diodes are standard components that are commonly integrated inside the junction boxes of PV modules, as shown in Figure 1.3. The blocking diodes are parts of the overall PV source circuit, as shown in Figure 1.6, and are optionally implemented when required.

Blocking diodes have been widely used for direct battery-charging applications due to their advantages of effectiveness, safety, reliability, and because they are maintenance-free. However, their disadvantage is a forward voltage drop that results in significant power losses in the PV source circuit. For example, the forward voltage of a typical 600-V/12-A rated diode is about 1 V. Considering that the PV string current is 7 A, each blocking diode introduces about 7 W of conduction loss, which generates heat and creates a hot spot. Furthermore, the failure of a blocking diode will cause a complete loss of the protection function and might lead to the failure of the entire string. The latest PV systems are developed for high efficiency and tend to avoid use of blocking diodes. Since all PV modules show a certain level of tolerance of reverse

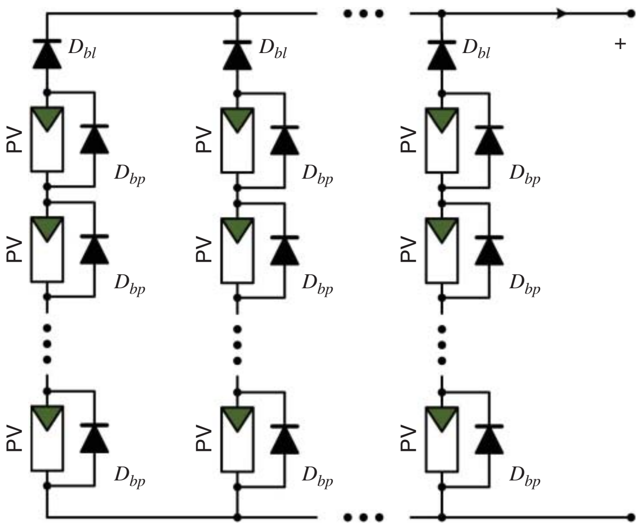


Figure 1.6 PV circuit with bypass diodes and blocking diodes.

current, manufacturers always provide the upper limit of reverse current that causes no damage to the PV product. Fuses and DC circuit breakers have been recently used in series connection with the individual PV string in order to protect the circuit and stop reverse current up to the maximum limit. The power losses are significantly lower than those caused by blocking diodes.

1.3 Photovoltaic Cell Materials and Efficiency

The PV effect can happen in many materials that absorb light and turn a portion of the energy into electricity. Solar cells are made of materials that are designed and formulated to produce strong PV effect. This can be measured by the conversion efficiency of the irradiance to electrical power. If a solar cell is claimed as being 15% efficient, it indicates that the electric power output of a 1 m^2 cell receiving 1000 W/m^2 irradiance at 25°C would be 150 W. Common PV cells are made of mono-crystalline silicon, multi-crystalline silicon, thin films, organic materials, and so on. It should be noted that mono-crystalline and multi-crystalline silicon are also referred to as single-crystalline and poly-crystalline silicon. The crystal growth process during manufacture is behind the formation of the two different types of crystalline-based solar cells. The Czochralski and Siemens processes are commonly used for making PV materials. The process followed includes doping, metallization, and texturing in order to construct solar cells.

The counterparts of crystalline silicon cells are thin-film cells. The common ones are summarized in Table 1.2. One of the most successful companies in the thin-film PV industry is First Solar, which uses cadmium telluride (CdTe) technologies. Even though the efficiency of CdTe-based products is generally lower than that of crystalline silicon cells, the technology has significantly lower material and manufacturing costs.

Organic solar cells are made of thin layers of organic materials. These technologies are under development and are rarely applicable for high power systems.

Table 1.2 Common PV materials.

Composition	Acronym
Mono-crystalline silicon or single-crystalline silicon	Mono-c-Si
Multi-crystalline silicon or poly-crystalline silicon	Poly-c-Si
Cadmium telluride	CdTe
Copper indium gallium selenide	CIGS
Amorphous silicon	a-Si

The efficiency of single junction cells is usually lower than 20% due to physical limits and technical constraints. Multi-junction cells have been invented in order to increase conversion efficiency. These are made up of multiple p-n junctions, which allows absorption of multiple light wavelengths through multiple layers. Efficiencies of over 30% have been reported. Their high price limits their application to aerospace or concentrated PV (CPV) systems, where high power density is particularly desirable. CPV is a technology that focuses sunlight using lenses or mirrors. The implementation minimizes the usage of PV material, which was significantly more expensive 20 years ago. The solar concentration ratio is commonly measured as the number of "suns," where the one-sun condition represents non-concentrated light. With the decreasing cost of PV materials, CPV is no longer as attractive as previously. Due to the specialist nature of multi-junction cells and CPV, the technology will not be further discussed in this book.

1.4 Test Conditions

Photovoltaics are inherently an intermittent energy resource since the electricity production depends on the instantaneous environmental conditions. The output power not only stops at night, but also varies significantly through the day and the season. As an example, Figure 1.7 shows a PV panel's power output, as measured in Vancouver, Canada. Broken clouds caused dramatic variations in the PV power output over the first 2.5 h. The output became significantly low during the last 40 min due to cloud coverage. Therefore, the intermittent nature of PV power production should be always considered when planning either standalone or grid-connected PV power systems.

The irradiance is the density of radiation incident on a given surface. It is usually expressed in units of watts per square meter (W/m^2). The PV cell temperature also plays an important role in determining the output. Defined in IEC 60904, the standard test conditions (STC) correspond to a solar irradiance of $1000\ W/m^2$, a device temperature of 25°C, with a reference solar spectral irradiance of air mass 1.5 (AM1.5). The standard is commonly applied to evaluate power capacities and conversion efficiencies of PV cells or modules. The rating of PV power systems is usually based on the accumulation of the PV module capacity at STC. The International Electrotechnical Commission (IEC) is the international standards and conformity assessment body for all fields of electrotechnology. The standards relevant to PV products will be discussed in Chapter 3.

According to IEC 61215, PV performance can also be measured at the nominal operating cell temperature (NOCT), which is defined as the equilibrium mean of solar cell

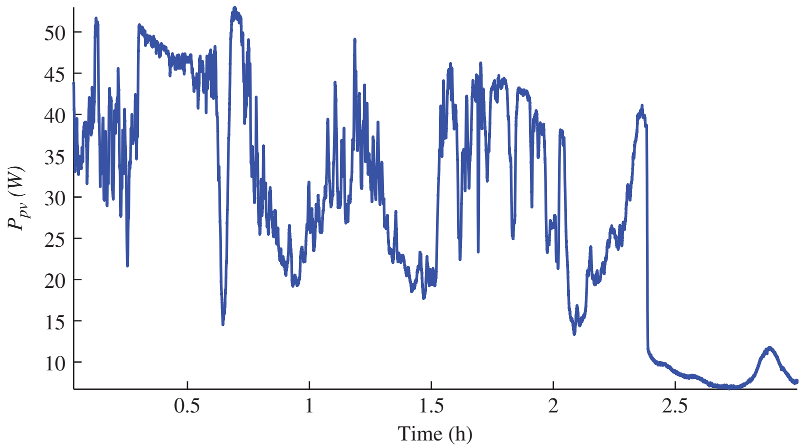


Figure 1.7 PV module 3-h output, as measured on 16 June 2006.

Table 1.3 SRE for measurement of NOCT.

Term	Value
Tilt angle	45° from the horizontal
Total irradiance	800 W/m^2
Ambient temperature	45°C
Wind speed	1 ms^{-1}

junction temperature within an open-rack mounted module in the standard reference environment (SRE), as shown in Table 1.3. Measured at STC and/or NOCT, the values of open-circuit voltage, short-circuit current, and power output of PV cells or modules define the product specifications and performance indices.

It is sometimes confusing to distinguish the terms of solar irradiance, insolation, and radiation, since all are used to describe the sunlight strength. Solar radiation is a general term that refers to the electromagnetic nature of sunlight, which is the radiant energy emitted from the sun. The total radiation on a surface includes the direct radiation from the sun, radiation diffused by the atmosphere, and radiation reflected by other objects. Insolation represents the quantity of solar radiation energy received on a surface of a certain size during a certain amount of time. The units can be kWh/m^2 or Wh/m^2. The strength of radiation is commonly measured by the level of irradiance, of which the unit is kW/m^2 or W/m^2. The term "irradiance" is the instant measure of light density, and will be used in the rest of this book.

1.5 PV Module Test

PV products are usually tested indoors using simulated resources since the outdoor environment is generally hard to control. A fully controlled environment can provide the

Figure 1.8 Laboratory for PV module testing.

standard test conditions, variable irradiance levels, and regulated ambient temperatures. Calibration is also easier indoors than outdoors. A laboratory system for PV module testing is shown in Figure 1.8. It has a dark chamber, a solar simulator, a computer, and a measurement system. The system is located in the Masdar Institute of Science and Technology, Abu Dhabi, UAE.

The dark chamber is designed to mount the light box and PV module for testing. The inside temperature of the dark chamber can be set at a desired level. The solar simulator is a controllable light source that mimics sunlight, with the same or a very similar spectrum, and can be regulated to give different irradiance levels. The laboratory setup can be calibrated for STC with the reference of AM1.5. The light is usually pulsed over a short period to avoid the significant temperature rises that are commonly caused by long-term light exposures. The measurement system includes an electronic load that can be controlled to trace the output (open circuit or short circuit). A high-speed data acquisition system is also included to record data from the PV module output.

1.6 PV Output Characteristics

The output characteristics of PV cells or modules are commonly represented by the current–voltage (I–V) and power–voltage (P–V) curves. In some special cases, the voltage–current (V–I) and power–current (P–I) curves are also used to represent the PV output characteristics. Generally, they are transferable from one to another. Figure 1.9 shows typical I–V and P–V curves for a PV cell output. The normalized curves can also be used to represent the outputs of PV modules, strings, and arrays when all the solar cells are tested under uniform conditions. The curves show the three important points and four important values, as described in Table 1.4. The data are usually presented for STC, which is considered as the nominal rating.

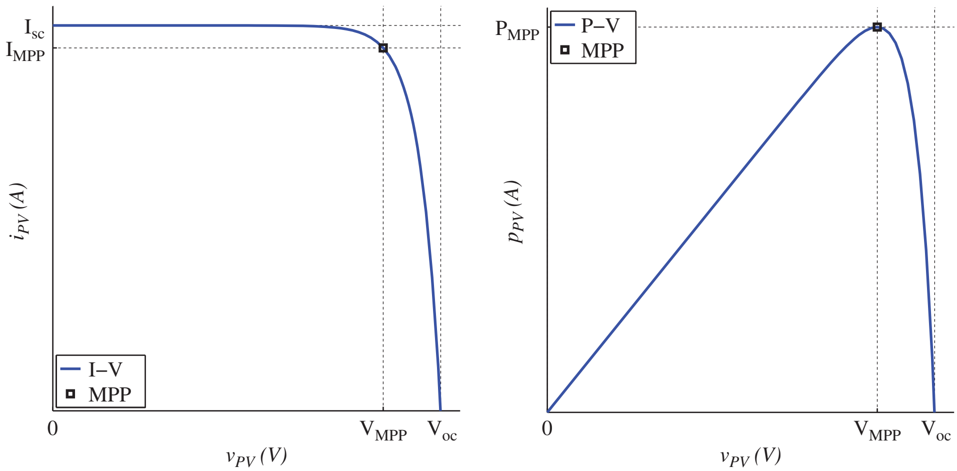


Figure 1.9 PV output characteristics: left, normalized I–V curve; right, normalized P–V curve.

Table 1.4 Four important values representing PV output characteristics.

Symbol	Description
V_{OC}	The open-circuit voltage, measured when the PV output terminal is open-circuit showing zero current.
I_{SC}	The short-circuit current, measured when the PV generator terminal is short-circuited.
I_{MPP}	The current measured at the MPP.
V_{MPP}	The voltage at the MPP.

The P_{MPP} is the highest power level for a certain environmental condition, and is calculated as $P_{MPP} = V_{MPP} \times I_{MPP}$.

The P–V curve clearly shows the maximum power point (MPP), which represents the highest power output (P_{MPP}) that the PV generator can produce under certain environmental conditions. The MPP is located in the “knee” area of the I–V curve, and is represented by the current (I_{MPP}) and voltage (V_{MPP}), as shown in Figure 1.9. The open-circuit voltage, V_{OC} is the highest voltage level of the PV generator under a given test condition. The short-circuit current, I_{SC}, is the highest current level of the PV generator under the test condition. The power output is zero at either open-circuit or short-circuit conditions.

It is usually safe to connect PV generator terminals in short circuit since the output current is always limited by the short-circuit level, which depends on the instantaneous environmental conditions, particularly the irradiance. Short circuits can be used for safety protection when any electrical shock happens. It should be noted that the values of V_{OC}, I_{SC}, I_{MPP}, and V_{MPP} vary with environmental conditions. As a result, maximum

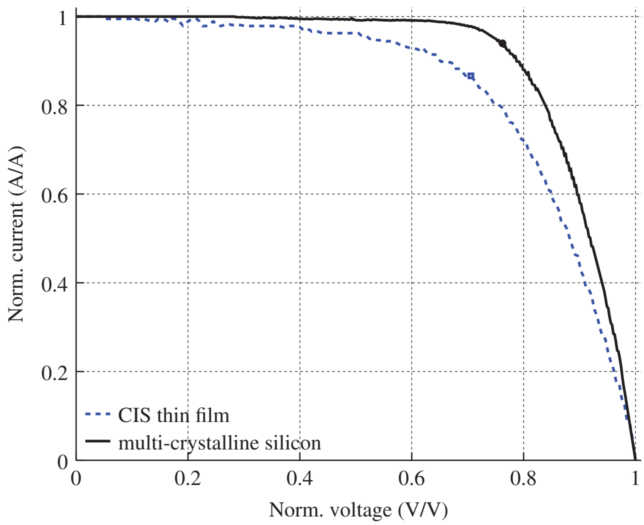


Figure 1.10 Normalized I–V curve to represent the PV generator outputs and the difference in fill factor. CIS, copper indium diselenide.

power point tracking (MPPT) is required to locate the instantaneous MPP depending on the solar irradiance, cell temperature, or other uncertainties.

The shape of the I–V and P–V curves also depends on the cell technology and manufacturing process used. Figure 1.10 shows the measured I–V curves from two different PV modules: models ST10 and BP350, made of copper indium diselenide and multi-crystalline materials, respectively. The I–V curve of the ST10 model looks gentler than that of the BP350. The ratios of MPP voltages are 71.59% and 76.24% of the open-circuit voltage for the ST10 and BP350 respectively. The MPP currents are 86.63% and 93.96% of the short-circuit currents, for the ST10 and BP350, respectively.

The fill factor (FF) is a term that is used to describe the shape of the PV output. Its value is calculated as:

$$FF = \frac{I_{MPP} \times V_{MPP}}{I_{SC} \times V_{OC}} \tag{1.1}$$

The FF has been used as an indicator in PV material research since the ideal PV cell has a rectangular shaped I–V curve, with FF = 1. PV material research has tried to push achievable FF values higher, but it is not a significant measure for practical PV power applications since the performance of PV cells is evaluated on many other measures too, such as cost effectiveness and reliability. The FF values of crystalline-based PV cells are generally higher than those of thin-film devices.

The FF should be considered when optimizing the MPPT parameters since it corresponds to the difference in the PV output curves. The values of FF for the ST10 and BP350 modules are 0.62 and 0.66, respectively. It should be noted that the value of FF depends on the testing conditions: irradiance and temperature and so on. For a fair comparison among various PV materials, the FF values should be evaluated at STC.

1.7 PV Array Simulator

Outdoor evaluation of PV systems enables behavior of real PV arrays to be examined in natural sunlight. However, the outdoor environment is commonly considered difficult because the solar irradiance and ambient temperature are not controllable (Xiao et al. 2013). To perform a fair comparison of PV systems, simulators are commonly used.

Researchers tend to use controllable light and power sources to simulate the sunlight and PV generator outputs, respectively. A PV array simulator is a DC power supply, the output of which mimics PV output characteristics. It should not be confused with a solar or sun simulator, which is the artificial light source that was introduced in Section 1.5. It is common to use solar simulators to test PV outputs at the cell and module levels, but they are impractical at string and array levels.

The PV array simulator can be used for indoor testing of power interfaces developed for PV applications. The output is programmable, to give specific values of the open-circuit voltage, short-circuit current, the MPP, and the corresponding I–V curves. The level of solar irradiance and the cell temperature can also be predefined and programmed to simulate environmental variations.

PV array simulators have been developed in the kilowatt power range for simulating PV strings and arrays. Examples include the products manufactured by Chroma ATE Inc. Others are only at the hundreds-of-watts level, and are used to simulate the output of PV modules. One popular set of models is the E4350 and E4360 series produced by Agilent Technologies. An E4350B model is shown in Figure 1.11. The output ratings are given as:

- maximum output power: 480 W
- maximum output voltage to simulate the open-circuit voltage: 65 V
- maximum output current to simulate the short-circuit current: 8 A
- peak-to-peak voltage ripple: 125 mV.

One key feature of a PV array simulator is the accuracy with which it simulates the I–V curve and represents the open-circuit voltage, short-circuit current, and the MPP. Another important measure, often neglected by users, is the speed of dynamic

Figure 1.11 Agilent 4350B PV array simulator.

response: the time in transition from one steady state to another. A real PV module or array is formed by semiconductors and shows a significantly high dynamic bandwidth. This can be explained by noting that the I–V output curve responds immediately whenever the load condition changes. However, it is impossible for a switching-mode power supply to mimic the same response. They are constrained in their response time or dynamic bandwidth.

It has been reported that a PV array simulator is too slow to test high-speed MPPT performance. For example, according to the product manual, the settling time of the E4350B is 25 ms. It is impossible to test an MPPT algorithm with a tracking speed of more than 40 Hz. However, a lot of MPPT algorithms and corresponding power-conditioning circuits have been developed for significantly higher speeds.

Another drawback results from the well-known disadvantages of switching-mode power supplies: self-resonance, output waveform ripples, and noise. Conventional DC power supplies show the tradeoff between the filter size and dynamic response. The filter can be sized with significant inductance and capacitance to mitigate ripples. However, the approach lowers the speed of the dynamic response. As a result, for the latest technologies, it is recommended that a PV array simulator be used for proof of concept. However, for accurate comparison of PV system performance, including both dynamics and steady-state performance, the suitability of PV array simulators should be carefully considered. It should be kept in mind that the PV array simulator is an imperfect electronic device and that it can interact with electronic power converters during tests.

1.8 Power Interfaces

In some cases, the PV generator is directly coupled to the load without any power interface. The majority of PV power systems are equipped with power-conditioning circuits for the interfaces between the generators and loads. A converter is the equipment that changes electrical voltage levels or waveforms.

Switching-mode power converters have high conversion efficiency and compact size, and are commonly used for PV power interfaces, battery power interfaces, and grid power interfaces. In power electronics, hundreds of converter topologies have been developed. Table 1.5 lists the DC/DC topologies that are commonly used for power interfaces on the PV side and battery side.

Table 1.6 lists the converter topologies that are commonly used for DC-to-AC conversion. They are also known as inverters, and change not only the voltage level but also the waveform. The input is from the DC source – PV generators or batteries – and the output can be connected to the AC grid or an AC load. The analysis, design, simulation, dynamic modeling, and control of the topologies are explained in Chapters 5–7.

1.9 Standalone Systems

Standalone PV systems supply power to local loads, and so are independent of the grid distribution network. Their history can be traced back to the 1950s, when PV technology was widely used for space power supplies. Solar radiation is more intense

Table 1.5 Converters used for DC/DC power interfaces.

Topology	Isolation	Description
Boost converter	No	Ratio of DC output voltage to DC input voltage not less than 1.
Buck converter	No	Ratio of DC output voltage to DC input voltage not larger than 1.
Full-bridge isolated buck converter	Yes	When the winding turn ratio of the transformer is reset to 1:1, it produces the DC output voltage lower in magnitude than the DC input voltage.
Buck–boost converter	No	The voltage conversion ratio is flexible: higher, lower, or equal to 1. However, the input and output port do not share a common ground point.
Flyback converter	Yes	When the winding turn ratio of the transformer is reset to 1:1, the analysis can be based on the principle of the buck–boost converter.
Tapped inductor converter	No	The operation follows the principle used for the boost topology except for the tapping connection of the inductor. Potential for high step-up conversion ratio of voltage.
Dual active bridge	Yes	A bidirectional DC/DC converter that can be used as the battery power interface to support DC grids or DC links.

Table 1.6 Converters for DC/AC power interfaces.

Topoloty	Description
H-bridge inverter	Conversion from DC to single phase AC.
Voltage source inverter (VSI)	Conversion from DC to three-phase AC, controlled by AC voltage regulation.
Current source inverter (CSI)	Based on the same circuit as VSI, and used for DC to three-phase AC conversion, but controlled by AC current regulation.

in space because it is not attenuated by the atmosphere and not blocked by clouds. The outer atmosphere is considered an ideal environment for solar PV power generation. However, their recent application has mostly been on Earth. The major applications of standalone systems include satellites, spacecraft, space stations, remote homes, villages, street lights, communication sites, water pumps, and vehicles. Nowadays, these systems are mainly installed in areas where grid connections are unavailable. Grid-connected PV systems have clear advantages for massive solar power production since the utility grid is a significant energy buffer that can accommodate the intermittency of solar power generation.

Standalone PV systems can supply either DC, AC, or both, depending on the load requirement. In some applications, PV generators can supply loads directly or through power interfaces without significant energy storage. Power-conditioning equipment might be needed for voltage conversion in directly coupled systems. The majority of

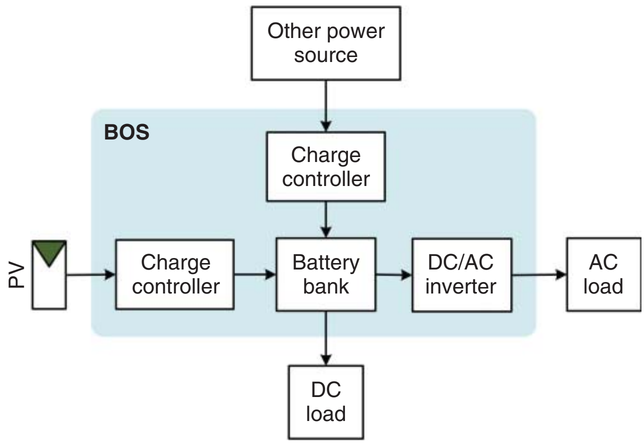


Figure 1.12 Typical standalone system configuration, with PV generator and energy storage. BOS, balance of system.

applications require energy storage, because of the intermittent nature of PV power generation.

Hybrid systems take power from wind turbines, fuel cells or conventional engine-based generators, as well as solar power, as shown in Figure 1.12. Without other resources, a PV-battery system is not a hybrid system, because the energy storage system is an energy buffer, but not another electrical production source. The balance of system (BOS) consists of all equipment between the power sources and the loads. Charge controllers are commonly required to charge the battery bank. Filters, means of disconnection, and protection devices are also important components of the BOS, but they are not illustrated in Figure 1.12.

The DC/AC voltage source inverter (VSI) produces AC waveforms from DC sources. The majority of AC loads are supplied with a sine wave AC source. Some take square waves or modified square waves, allowing simple and low-cost topologies to be used in the VSI. The waveforms are illustrated in Figure 1.13, based on a frequency of 50 Hz. The

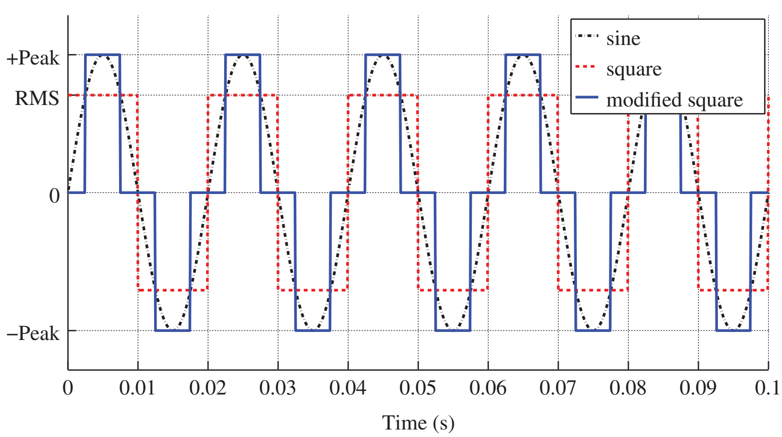


Figure 1.13 Typical waveforms output by voltage source inverter.

total harmonic distortion of the square waveform is 48.3%. It should be noted that the pure sine-wave output requirement for standalone PV systems is no longer as demanding as before, because most modern devices tend to use DC supplies and are more tolerant of differing power supplies. However, in certain environments, noise and electromagnetic interference might be concerns where the AC output does not have a pure sinusoidal waveform.

The most impressive PV standalone system is Solar Impulse 2, a lightweight airplane solely powered by solar energy. Starting from Abu Dhabi on 9 March 2015, it completed the first entirely solar-powered flight around the world. The distance of 40 000 km is considered as the longest solo solar flight ever achieved. The historic voyage took more than 27 months, with the plane touching down again in Abu Dhabi on 26 July 2016. The flight record is summarized in Table 1.7.

A Swiss team initialized the ambitious idea of developing an aircraft purely powered by solar energy with battery support. The mission aimed to promote clean technologies. The plane was powered by 17 000 solar cells built into the body and wings. The longest and the most difficult non-stop flight took 5 days (118 h) and 7212 km from Nagoya, Japan to Honolulu, USA. To date, this is a world record for an uninterrupted flight. It was achieved by the pilot, Andre Borschberg. A photo taken in March 2015 when the Solar Impulse 2 was stationed in Abu Dhabi, is shown in Figure 1.14.

From certain points of view, the aircraft should be classified as a motorized glider. The wingspan is 73 m, which is bigger than that of a Boeing 747 jumbo jet. However,

Table 1.7 Record of Solar Impulse journey.

Leg	From	To	Distance (km)	Start date	Total (h)	Average speed (km/h)
1	Abu Dhabi, UAE	Muscat, Oman	772	3/09/15	13	34
2	Muscat, Oman	Ahmedabad,India	1468	3/10/15	15	97
3	Ahmedabad,India	Varanasi,India	1170	3/18/15	13	89
4	Varanasi,India	Mandalay, Myanmar	1536	3/19/15	13	104
5	Mandalay, Myanmar	Chongqing, China	1450	3/30/15	20	71
6	Chongqing, China	Nanjing, China	1241	4/21/15	17	71
7	Nanjing, China	Nagoya, Japan	2852	5/30/15	44	65
8	Nagoya, Japan	Hawaii, USA	7212	6/28/15	118	61
9	Hawaii, USA	San Francisco, USA	4086	4/21/16	62	65
10	San Francisco, USA	Phoenix, USA	1113	5/02/16	16	70
11	Phoenix, USA	Tulsa, USA	1570	5/12/16	18	86
12	Tulsa, USA	Dayton, USA	1113	5/21/16	16.6	67
13	Dayton, USA	Lehigh valley, USA	1044	5/25/16	16.8	62
14	Lehigh valley, USA	New York, USA	265	6/11/16	4.7	57
15	New York, USA	Seville, Spain	6765	6/20/16	71	95
16	Seville, Spain	Cairo, Egypt	3745	7/11/16	48.8	77
17	Cairo, Egypt	Abu Dhabi, UAE	2694	7/24/16	48.6	55

Source: www.solarimpulse.com.

Figure 1.14 Solar Impulse 2.

the plane can host only one pilot and weights approximately the same as a family car. From Table 1.7, the flight speed varies from 34 km/h to 104 km/h, and the average speed is about 70 km/h, slower than the majority of vehicles traveling on express highways. It usually takes less than 5 h to drive a car from Abu Dhabi to Muscat and less than one hour for commercial flights. However, Table 1.7 shows that Solar Impulse 2 took 13 h. Furthermore, the solar-powered aircraft is very sensitive and vulnerable to weather conditions because of its lightness: it weighs only 2300 kg. The onboard battery bank was seriously damaged during the 7212-km flight from Nagoya to Hawaii. The damage caused significant delays.

There is no doubt that Solar Impulse inspired the world towards the use of clean technologies and renewable energy. People around the world admire the courage and the effort of the founders and pilots in promoting solar energy for aviation. However, the technical data show that Solar Impulse aircraft might be a bad application of PV technology. The current power density of PV materials is generally too low to serve as the sole power source for either ground vehicles or aircraft. Due to size constraints, transport vehicles generally demand high power density by weight and volume, which rules out current PV technologies. However, this cannot stop the PV power generation being used as a secondary power source in hybrid systems for transportation. For example, PV power might be used to reduce fuel consumption in ground vehicles or to enable unmanned aerial vehicles to stay longer in the sky.

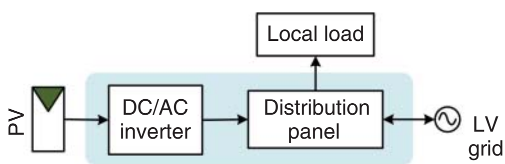
Recently, another standalone system that does not integrate with battery storage has become popular. PV power is used as an ancillary source for isolated electric networks based on fossil-fueled generation. The aim is fuel saving in remote places where the fuel cost is high and fossil-fueled generation causes air pollution. It is also a cost-effective solution because no batteries are used.

Without a significant energy buffer, system integration can be a challenge when PV power penetration is more than 25%. However, high penetration can achieve high fuel savings. Since the load fluctuations might produce significant disturbances, control and coordination of wind and PV power interfaces becomes critical to maintaining grid frequency and voltage. Communication is generally required to optimally coordinate the operations of the generators. Utility-scale examples can be found at www.sma.de, in the shape of PV–diesel hybrid systems. Battery storage is optional, and not mandatory in such systems. Current battery technologies are expensive, when the short lifespans and the operating-environment constraints are considered.

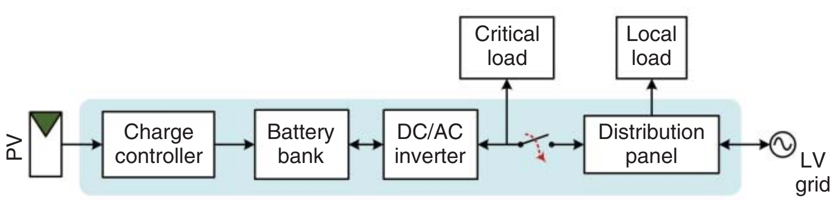
1.10 AC Grid-connected Systems

One drawback of a standalone system is that the PV array is usually oversized, so as to accommodate the worst-case scenarios in terms of solar power generation. Solar energy is wasted if the generated power cannot be stored or consumed. Recently, an increasing number of systems have been connected to the AC electric distribution network. The electrical production and distribution network – the grid – is a utility system, which is external to and not controlled by the PV system. Such systems are also called interactive systems or grid-connected systems, and can be operated for full-time maximum power injection. Figure 1.15 shows three examples of grid-connected systems, with and without battery storage. The key component in grid-connected PV systems is the utility-interactive inverter, which performs the DC/AC conversion and the required interconnection functions.

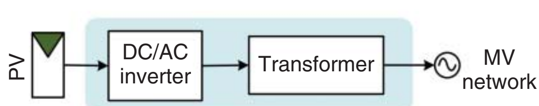
A simple grid-connected system, mainly used for small-scale applications, is illustrated in Figure 1.15a. Local loads can be supplied through the grid interconnection.



(a)



(b)



(c)

Figure 1.15 Grid-connected PV power systems with PV generators and inverters: (a) simple system; (b) grid-connected system with battery storage; (c) PV power plant.