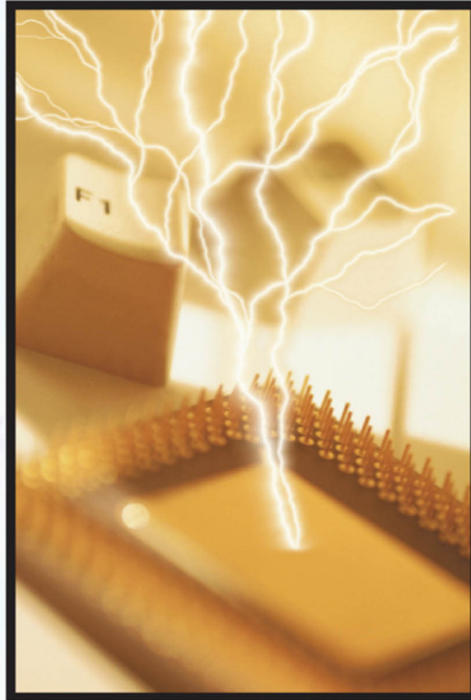




POWER ELECTRONICS Handbook Third Edition

Editor-in-Chief **Muhammad H. Rashid**



IPR2024-00389
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POWER ELECTRONICS HANDBOOK

POWER ELECTRONICS HANDBOOK

DEVICES, CIRCUITS, AND APPLICATIONS

Third Edition

Edited by

Muhammad H. Rashid, Ph.D.,

Fellow IET (UK), Fellow IEEE (USA)

Professor

Electrical and Computer Engineering

University of West Florida

11000 University Parkway

Pensacola, FL 32514-5754, U.S.A.

Phone: 850-474-2976

e-mail: mrashid@uwf.edu



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Butterworth-Heinemann is an imprint of Elsevier
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA
Linacre House, Jordan Hill, Oxford OX2 8DP, UK

Second edition 2007
Third edition 2011

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Library of Congress Cataloging-in-Publication Data

Power electronics handbook : devices, circuits, and applications handbook / edited by
Muhammad H. Rashid. – 3rd ed.

p. cm.

ISBN 978-0-12-382036-5

1. Power electronics – Encyclopedias. I. Rashid, M. H.

TK7881.15.P6733 2010

621.31'7–dc22

2010038332

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

ISBN: 978-0-12-382036-5

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Printed in the USA

10 11 12 10 9 8 7 6 5 4 3 2 1

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Dedication

To those who promote power electronics and inspire students for finding applications for the benefits of the people and the environment in the global community

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Preface for Third Edition

Introduction

The purpose of Power Electronics Handbook is to provide a reference that is both concise and useful for engineering students and practicing professionals. It is designed to cover a wide range of topics that make up the field of power electronics in a well-organized and highly informative manner. The Handbook is a careful blend of both traditional topics and new advancements. Special emphasis is placed on practical applications; thus, this Handbook is not a theoretical one, but an enlightening presentation of the usefulness of the rapidly growing field of power electronics. The presentation is tutorial in nature in order to enhance the value of the book to the reader and foster a clear understanding of the material.

The contributors to this Handbook span the globe, with fifty-four authors from twelve different countries, some of whom are the leading authorities in their areas of expertise. All were chosen because of their intimate knowledge of their subjects, and their contributions make this a comprehensive state-of-the-art guide to the expanding field of power electronics and its applications covering the following:

- the characteristics of modern power semiconductor devices, which are used as switches to perform the power conversions from ac-dc, dc-dc, dc-ac, and ac-ac;
- both the fundamental principles and in-depth study of the operation, analysis, and design of various power converters; and
- examples of recent applications of power electronics

Power Electronics Backgrounds

The first electronics revolution began in 1948 with the invention of the silicon transistor at Bell Telephone Laboratories by Bardeen, Brattain, and Shockley. Most of today's advanced electronic technologies are traceable to that invention, and modern microelectronics has evolved over the years from these silicon semiconductors. The second electronics revolution began with the development of a commercial thyristor

by the General Electric Company in 1958. That was the beginning of a new era of power electronics. Since then, many different types of power semiconductor devices and conversion techniques have been introduced.

The demand for energy, particularly in electrical forms, is ever-increasing in order to improve the standard of living. Power electronics helps with the efficient use of electricity, thereby reducing power consumption. Semiconductor devices are used as switches for power conversion or processing, as are solid state electronics for efficient control of the amount of power and energy flow. Higher efficiency and lower losses are sought for devices used in a range of applications, from microwave ovens to high-voltage dc transmission. New devices and power electronic systems are now evolving for even more effective control of power and energy.

Power electronics has already found an important place in modern technology and has revolutionized control of power and energy. As the voltage and current ratings and switching characteristics of power semiconductor devices keep improving, the range of applications continue to expand in areas, such as lamp controls, power supplies to motion control, factory automation, transportation, energy storage, multimegawatt industrial drives, and electric power transmission and distribution. The greater efficiency and tighter control features of power electronics are becoming attractive for applications in motion control by replacing the earlier electromechanical and electronic systems. Applications in power transmission and renewable energy include high-voltage dc (VHDC) converter stations, flexible ac transmission system (FACTS), static var compensators, and energy storage. In power distribution, these include dc-to-ac conversion, dynamic filters, frequency conversion, and custom power system.

Almost all new electrical or electromechanical equipments, from household air conditioners and computer power supplies to industrial motor controls, contain power electronic circuits and/or systems. In order to keep up, working engineers involved in control and conversion of power and energy into applications ranging from several hundred voltages at a fraction of an ampere for display devices to about 10,000 V at high-voltage dc transmission should have a working knowledge of power electronics.

Organization

The Handbook starts with an introductory chapter and moves on to cover topics on power semiconductor devices, power converters, applications, and peripheral issues. The book is organized into nine areas, the first of which includes chapters on operation and characterizations of the following power semiconductor devices: power diode, thyristor, gate turn-off thyristor (GTO), power bipolar transistor (BJT), power MOSFET, insulated gate bipolar transistor, MOS-controlled thyristor (MCT), and static induction devices. The next topic area includes chapters covering various types of power converters, the principles of operation, and the methods for the analysis and design of power converters. This also includes gate drive circuits and control methods for power converters. The next two chapters cover applications in power supplies, electronic ballasts, HVDC transmission, VAR compensation, pulse power, and capacitor charging.

The following two chapters focus on the operation, theory, and control methods of motor drives and automotive systems. We then move on to two chapters on power quality issues and active filters, and two chapters on computer simulation, packaging and smart power systems. The final chapter is on energy sources, storage, and transmission.

Changes in the Third Edition

The five new contributions are added in keeping with the new development and applications.

- Solid State Pulsed Power Electronics
- Novel AI-Based Soft Computing Applications In Motor Drives
- Energy Sources
- Energy Storage
- Electric Power Transmission

The following eleven chapters are revised, and the contributions are reorganized under nine chapters.

- Introduction to Power Electronics
- Static Induction Devices
- Multilevel Converters
- AC-AC Converters
- Power Electronics in Capacitor Charging Applications
- Solar Power Conversion
- Fuel-Cell Power Electronics for Distributed Generation
- Flexible AC Transmission
- Control Methods for Power Converters

- Fuzzy Logic in Electric Drives
- EMI Effects of Power Converters

Locating Your Topic

A table of contents is presented at the front of the book, and each chapter begins with its own table of contents. The reader should look over these tables of contents to become familiar with the structure, organization, and content of the book.

Audience

The Handbook is designed to provide both students and practicing engineers with answers to questions involving the wide spectrum of power electronics. The book can be used as a textbook for graduate students in electrical or systems engineering, or as a reference book for senior undergraduate students and for engineers who are interested and involved in operation, project management, design, and analysis of power electronic equipment and motor drives.

Acknowledgments

This Handbook was made possible through the expertise and dedication of outstanding authors from throughout the world. I gratefully acknowledge the personnel at Elsevier Publishing who produced the book, including Jill Leonard. In addition, special thanks are due to Ken McCombs, the executive editor for this book. Finally, I express my deep appreciation to my wife, Fatema Rashid, who graciously puts up with my publication activities.

Muhammad H. Rashid, Editor-in-Chief

Any comments and suggestions regarding this book are welcome. They should be sent to

Dr. Muhammad H. Rashid
 Professor
 Department of Electrical and Computer Engineering
 University of West Florida
 11000 University Parkway
 Pensacola, FL 32514-5754, USA
 e-mail: mrashidfl@gmail.com
 Web: <http://uwf.edu/mrashid>

Introduction

Philip T. Krein, Ph.D.

Department of Electrical and
Computer Engineering,
University of Illinois, Urbana,
Illinois, USA

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1.1 Power Electronics Defined¹

It has been said that people do not use electricity, but rather they use communication, light, mechanical work, entertainment, and all the tangible benefits of energy and electronics. In this sense, electrical engineering as a discipline is much involved in energy conversion and information. In the general world of electronics engineering, the circuits engineers design and use are intended to convert information. This is true of both analog and digital circuit design. In radio-frequency applications, energy and information are on more equal footing, but the main function of any circuit is information transfer.

What about the conversion and control of electrical energy itself? Energy is a critical need in every human endeavor. The capabilities and flexibility of modern electronics must be brought to bear to meet the challenges of reliable, efficient energy. It is essential to consider how electronic circuits and systems can be applied to the challenges of energy conversion and management. This is the framework of *power electronics*, a discipline defined in terms of *electrical*

energy conversion, applications, and electronic devices. More specifically,

DEFINITION *Power electronics* involves the study of electronic circuits intended to control the flow of electrical energy. These circuits handle power flow at levels much higher than the individual device ratings.

Rectifiers are probably the most familiar examples of circuits that meet this definition. Inverters (a general term for dc–ac converters) and dc–dc converters for power supplies are also common applications. As shown in Fig. 1.1, power electronics represents a median point at which the topics of energy systems, electronics, and control converge and combine [1]. Any useful circuit design for an energy application must address issues of both devices and control, as well as of the energy itself. Among the unique aspects of power electronics are its emphasis on large semiconductor devices, the application of magnetic devices for energy storage, special control methods that must be applied to nonlinear systems, and its fundamental place as a central component of today's energy systems and alternative resources. In any study of electrical engineering, power electronics must be placed on a level with digital, analog, and radio-frequency electronics to reflect the distinctive design methods and unique challenges.

Applications of power electronics are expanding exponentially. It is not possible to build practical computers, cell

¹Portions of this chapter are taken from P. T. Krein, *Elements of Power Electronics*. New York: Oxford University Press, 1998. © 1998, Oxford University Press. Used by permission.

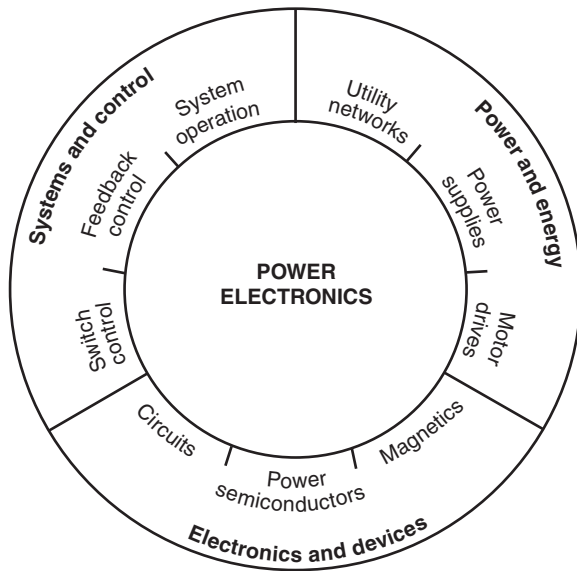


FIGURE 1.1 Control, energy, and power electronics are interrelated.

phones, personal data devices, cars, airplanes, industrial processes, and a host of other everyday products without power electronics. Alternative energy systems such as wind generators, solar power, fuel cells, and others require power electronics to function. Technology advances such as electric and hybrid vehicles, laptop computers, microwave ovens, flat-panel displays, LED lighting, and hundreds of other innovations were not possible until advances in power electronics enabled their implementation. Although no one can predict the future, it is certain that power electronics will be at the heart of fundamental energy innovations.

The history of power electronics [2–5] has been closely allied with advances in electronic devices that provide the capability to handle high power levels. Since about 1990, devices have become so capable that a transition from a “device-driven” field to an “applications-driven” field continues. This transition has been based on two factors: (1) advanced semiconductors with suitable power ratings exist for almost every application of wide interest, and (2) the general push toward miniaturization is bringing advanced power electronics into a growing variety of products. Although the devices continue to improve, their development now tends to follow innovative applications.

1.2 Key Characteristics

All power electronic circuits manage the flow of electrical energy between an electrical source and a load. The parts in a circuit must direct electrical flows, not impede them. A general power conversion system is shown in Fig. 1.2. The function of the power converter in the middle is to control the energy flow between a source and a load. For our purposes, the

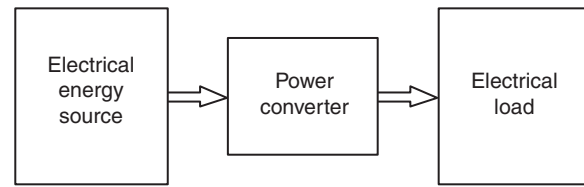


FIGURE 1.2 General system for electric power conversion. (From [2], © 1998, Oxford University Press, Inc.; used by permission.)

power converter will be implemented with a power electronic circuit. Because a power converter appears between a source and a load, any energy used within the converter is lost to the overall system. A crucial point emerges: to build a power converter, we should consider only lossless components. A realistic converter design must approach 100% efficiency.

A power converter connected between a source and a load also affects system reliability. If the energy source is perfectly reliable (it is available all the time), then a failure in the converter affects the user (the load) just as if the energy source had failed. An unreliable power converter creates an unreliable system. To put this in perspective, consider that a typical American household loses electric power only a few minutes a year. Energy is available 99.999% of the time. A converter must be better than this to prevent system degradation. An ideal converter implementation will not suffer any failures over its application lifetime. Extreme high reliability can be a more difficult objective than high efficiency.

1.2.1 The Efficiency Objective – The Switch

A circuit element as simple as a light switch reminds us that the extreme requirements in power electronics are not especially novel. Ideally, when a switch is on, it has zero voltage drop and will carry any current imposed on it. When a switch is off, it blocks the flow of current regardless of the voltage across it. The *device power*, the product of the switch voltage and current, is identically zero at all times. A switch therefore controls energy flow with no loss. In addition, reliability is also high. Household light switches perform over decades of use and perhaps 100,000 operations. Unfortunately, a mechanical light switch does not meet all practical needs. A switch in a power supply may function 100,000 times each second. Even the best mechanical switch will not last beyond a few million cycles. Semiconductor switches (without this limitation) are the devices of choice in power converters.

A circuit built from ideal switches will be lossless. As a result, switches are the main components of power converters, and many people equate power electronics with the study of switching power converters. Magnetic transformers and lossless storage elements such as capacitors and inductors are also valid components for use in power converters. The complete

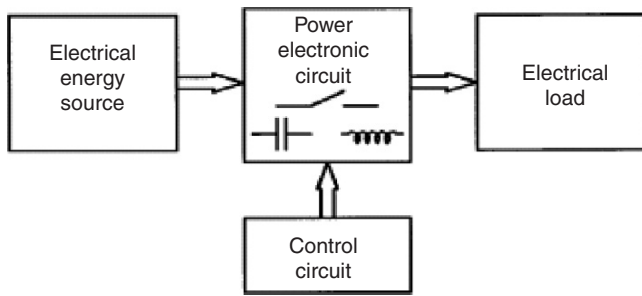


FIGURE 1.3 A basic power electronic system. (From [2], © 1998, Oxford University Press, Inc.; used by permission.)

concept, shown in Fig. 1.3, illustrates a *power electronic system*. Such a system consists of an electrical energy source, an electrical load, a *power electronic circuit*, and a control function.

The power electronic circuit contains switches, lossless energy storage elements, and magnetic transformers. The controls take information from the source, the load, and the designer, and then determine how the switches operate to achieve the desired conversion. The controls are built up with low-power analog and digital electronics.

Switching devices are selected based on their *power handling* rating – the product of their voltage and current ratings – rather than on power dissipation ratings. This is in contrast to other applications of electronics, in which power dissipation ratings dominate. For instance, a typical stereo receiver performs a conversion from ac line input to audio output. Most audio amplifiers do not use the techniques of power electronics, and the semiconductor devices do not act as switches. A commercial 100-W amplifier is usually designed with transistors big enough to dissipate the full 100 W. The semiconductor devices are used primarily to reconstruct the audio information rather than to manipulate the energy flows. The sacrifice in energy is large – a home theater amplifier often functions at less than 10% energy efficiency. In contrast, emerging *switching amplifiers* do use the techniques of power electronics. They provide dramatic efficiency improvements. A home theater system implemented with switching amplifiers can exceed 90% energy efficiency in a smaller, cooler package. The amplifiers can even be packed inside the loudspeakers.

Switches can reach extreme power levels, far beyond what might be expected for a given size. Consider the following examples.

EXAMPLE 1.1 The NTP30N20 is a metal oxide semiconductor field effect transistor (MOSFET) with a drain current rating of 30 A, a maximum drain source breakdown voltage of 200 V, and a rated power dissipation of up to 200 W under ideal conditions. Without a heat sink, however, the device can handle less than 2.5 W of dissipation. For power electronics purposes, the power handling rating is $30 \text{ A} \times 200 \text{ V} = 6 \text{ kW}$. Several manufacturers have developed controllers for domestic refrigerators, air

conditioners, and high-end machine tools based on this and similar devices. The second part of the definition of power electronics in Section 1.1 points out that the circuits handle power at levels much higher than that of the ratings of individual devices. Here a device is used to handle 6000 W – compared with its individual rating of no more than 200 W. The ratio 30:1 is high, but not unusual in power electronics contexts. In contrast, the same ratio in a conventional audio amplifier is close to unity.

EXAMPLE 1.2 The IRGPS60B120KD is an insulated gate bipolar transistor (IGBT) – a relative of the bipolar transistor that has been developed specifically for power electronics – rated for 1200 V and 120 A. Its power handling rating is 144 kW which is sufficient to control an electric or hybrid car.

1.2.2 The Reliability Objective – Simplicity and Integration

High-power applications lead to interesting issues. In an inverter, the semiconductors often manipulate 30 times their power dissipation capability or more, which implies that only about 3% of the power being controlled is lost. A small design error, unexpected thermal problem, or minor change in layout could alter this somewhat. For instance, if the loss turns out to be 4% rather than 3%, the device stresses are 33% higher, and quick failure is likely to occur. The first issue for reliability in power electronic circuits is that of managing device voltage, current, and power dissipation levels to keep them well within rating limits. This is challenging when power-handling levels are high.

The second issue for reliability is simplicity. It is well established in electronics design that the more parts there are in a system, the more likely it is to fail. Power electronic circuits tend to have few parts, especially in the main energy flow paths. Necessary operations must be carried out through shrewd use of these parts. Often, this means that sophisticated control strategies are applied to seemingly simple conversion circuits.

The third issue for reliability is integration. One way to avoid the reliability–complexity tradeoff is to integrate multiple components and functions on a single substrate. A microprocessor, for example, might contain millions of gates. All interconnections and signals flow within a single chip, and the reliability is near that of a single part. An important parallel trend in power electronic devices involves the integrated module [6]. Manufacturers seek ways to package multiple switching devices, with their interconnections and protection components, together as a unit. Control circuits for converters are also integrated as much as possible to keep the reliability high. The package itself is a factor in reliability, and one that is a subject of active research. Many semiconductor packages include small bonding wires

that can be susceptible to thermal or vibration damage. The small geometries also tend to enhance electromagnetic interference among the internal circuit components.

1.3 Trends in Power Supplies

Two distinct trends drive electronic power supplies, one of the major classes of power electronic circuits. At the high end, microprocessors, memory chips, and other advanced digital circuits require increasing power levels and increasing performance at very low voltage. It is a challenge to deliver 100 A or more efficiently at voltages that can be less than 1 V. These types of power supplies are expected to deliver precise voltages, even though the load can change by an order of magnitude in nanoseconds.

At the other end is the explosive growth of portable devices with rechargeable batteries. The power supplies for these devices and for other consumer products must be cheap and efficient. Losses in low-cost power supplies are a problem today; often, low-end power supplies and battery chargers draw energy even when their load is off. It is increasingly important to use the best possible power electronics design techniques for these supplies to save energy while minimizing costs. Efficiency standards such as the EnergyStar program place increasingly stringent requirements on a wide range of low-end power supplies.

In the past, bulky “linear” power supplies were designed with transformers and rectifiers from the ac line frequency to provide dc voltages for electronic circuits. In the late 1960s, use of dc sources in aerospace applications led to the development of power electronic dc–dc conversion circuits for power supplies. In a well-designed power electronics arrangement today, called a *switch-mode power supply*, an ac source from a wall outlet is rectified without direct transformation. The resulting high dc voltage is converted through a dc–dc converter to the 1, 3, 5, and 12 V, or other levels required. A personal computer commonly requires multiple 3.3- and 5-V supplies, 12-V supplies, additional levels, and a separate converter for 1-V delivery to the microprocessor. This does not include supplies for the video display or peripheral devices. Only a switch-mode supply can support such complex requirements with acceptable costs.

Switch-mode supplies often take advantage of MOSFET semiconductor technology. Trends toward high reliability, low cost, and miniaturization have reached the point where a 5-V power supply sold today might last more than 1,000,000 h (more than a century), provide 100 W of output in a package with volume less than 15 cm³, and sell for a price less than US\$ 0.10/W. This type of supply brings an interesting dilemma: the ac line cord to plug it in takes up more space than the power supply itself. Innovative concepts such as integrating a power supply within a connection cable will be used in the future.

Device technology for power supplies is also being driven by expanding needs in the automotive and telecommunications industries as well as in markets for portable equipment. The automotive industry is making a transition to higher voltages to handle increasing electric power needs. Power conversion for this industry must be cost effective, yet rugged enough to survive the high vibration and wide temperature range to which a passenger car is exposed. Global communication is possible only when sophisticated equipment can be used almost anywhere. This brings with it a special challenge, because electrical supplies are neither reliable nor consistent throughout much of the world. Although voltage swings in the domestic ac supply in North America are often $\pm 5\%$ around a nominal value, in many developing nations the swing can be $\pm 25\%$ – when power is available. Power converters for communications equipment must tolerate these swings and must also be able to make use of a wide range of possible backup sources. Given the enormous size of worldwide markets for mobile devices and consumer electronics, there is a clear need for flexible-source equipment. Designers are challenged to obtain maximum performance from small batteries and to create equipment with minimal energy requirements.

1.4 Conversion Examples

1.4.1 Single-Switch Circuits

Electrical energy sources take the form of dc voltage sources at various values, sinusoidal ac sources, polyphase sources, among others. A power electronic circuit might be asked to transfer energy between two different dc voltage levels, between an ac source and a dc load, or between sources at different frequencies. It might be used to adjust an output voltage or power level, drive a nonlinear load, or control a load current. In this section, a few basic converter arrangements are introduced, and energy conservation provides a tool for analysis.

EXAMPLE 1.3 Consider the circuit shown in Fig. 1.4. It contains an ac source, a switch, and a resistive load. It is a simple but complete power electronic system.

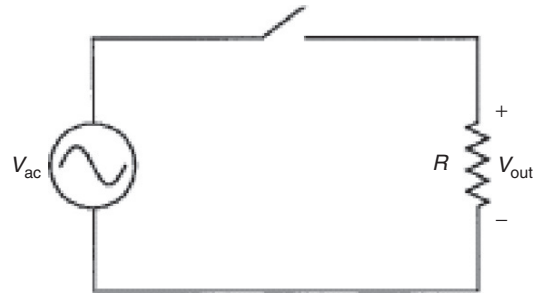


FIGURE 1.4 A simple power electronic system. (From [2], © 1998, Oxford University Press, Inc.; used by permission.)

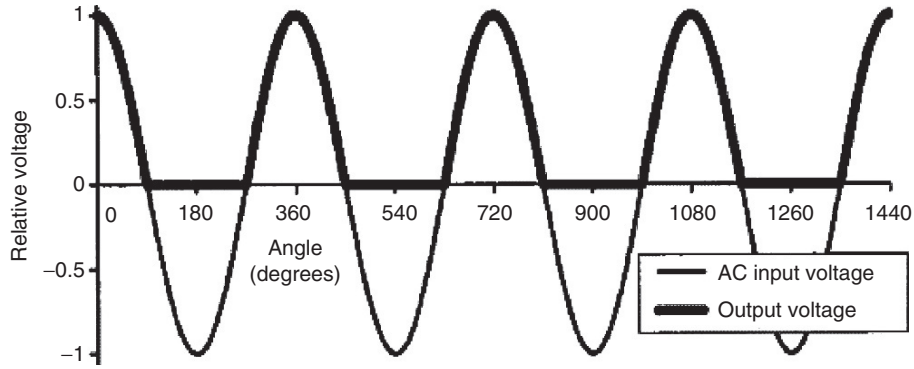


FIGURE 1.5 Input and output waveforms for Example 1.4.

Let us assign a (somewhat arbitrary) control scheme to the switch. What if the switch is turned on whenever $V_{ac} > 0$, and turned off otherwise? The input and output voltage waveforms are shown in Fig. 1.5. The input has a time average of 0, and root-mean-square (RMS) value equal to $V_{peak}/\sqrt{2}$, where V_{peak} is the maximum value of V_{ac} . The output has a nonzero average value given by

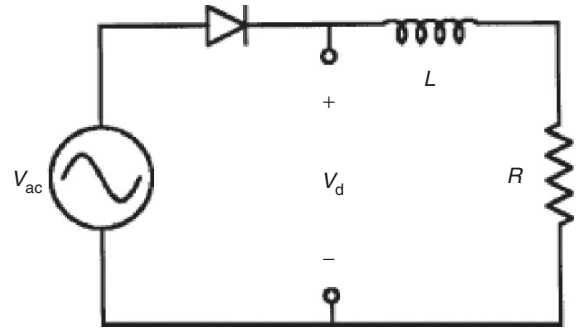
$$\begin{aligned} \langle v_{out}(t) \rangle &= \frac{1}{2\pi} \left(\int_{-\pi/2}^{\pi/2} V_{peak} \cos \theta \, d\theta + \int_{\pi/2}^{3\pi/2} 0 \, d\theta \right) \\ &= \frac{V_{peak}}{\pi} = 0.3183 V_{peak} \end{aligned} \quad (1.1)$$

and an RMS value equal to $V_{peak}/2$. Since the output has nonzero dc voltage content, the circuit can be used as an ac-dc converter. To make it more useful, a low-pass filter would be added between the output and the load to smooth out the ac portion. This filter needs to be lossless, and will be constructed from only inductors and capacitors.

The circuit in Example 1.3 acts as a half-wave rectifier with a resistive load. With the hypothesized switch action, a diode can substitute for the ideal switch. The example confirms that a simple switching circuit can perform power conversion functions. But note that a diode is not, in general, the same as an ideal switch. A diode places restrictions on the current direction, whereas a true switch would not. An ideal switch allows control over whether it is on or off, whereas a diode's operation is constrained by circuit variables.

Consider a second half-wave circuit, now with a series L - R load, shown in Fig. 1.6.

EXAMPLE 1.4 A series diode L - R circuit has ac voltage source input. This circuit operates much differently than the half-wave rectifier with resistive load. A diode will be on if forward-biased, and off if reverse-biased. In this circuit, when the diode is off, the current will be zero.

FIGURE 1.6 Half-wave rectifier with L - R load for Example 1.5.

Whenever the diode is on, the circuit is the ac source with L - R load. Let the ac voltage be $V_0 \cos(\omega t)$. From Kirchhoff's Voltage Law (KVL),

$$V_0 \cos(\omega t) = L \frac{di}{dt} + Ri.$$

Let us assume that the diode is initially off (this assumption is arbitrary, and we will check it as the example is solved). If the diode is off, the diode current is $i = 0$, and the voltage across the diode will be v_{ac} . The diode will become forward-biased when v_{ac} becomes positive. The diode will turn on when the input voltage makes a zero-crossing in the positive direction. This allows us to establish initial conditions for the circuit: $i(t_0) = 0$, $t_0 = -\pi/(2\omega)$. The differential equation can be solved in a conventional way to give

$$\begin{aligned} i(t) = V_0 \left[\frac{\omega L}{R^2 + \omega^2 L^2} \exp\left(\frac{-t}{\tau} - \frac{\pi}{2\omega\tau}\right) \right. \\ \left. + \frac{R}{R^2 + \omega^2 L^2} \cos(\omega t) \right. \\ \left. + \frac{\omega L}{R^2 + \omega^2 L^2} \sin(\omega t) \right] \end{aligned} \quad (1.2)$$

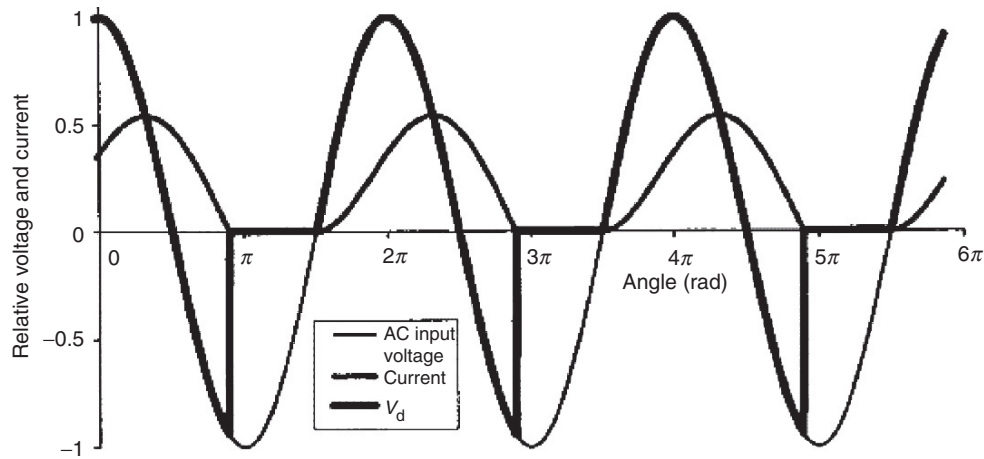


FIGURE 1.7 Input and output waveforms for Example 1.5.

where τ is the time constant L/R . What about when the diode is turned off? The first guess might be that the diode turns off when the voltage becomes negative, which is not correct. From the solution, we can note that the current is not zero when the voltage first becomes negative. If the switch attempts to turn off, it must instantly drop the inductor current to zero. The derivative of current in the inductor, di/dt , would become negative infinite. The inductor voltage $L(di/dt)$ similarly becomes negative infinite, and the devices are destroyed. What really happens is that the falling current allows the inductor to maintain forward bias on the diode. The diode will turn off only when the *current* reaches zero. A diode has definite properties that determine the circuit action, and both the voltage and current are relevant. Figure 1.7 shows the input and output waveforms for a time constant τ equal to about one-third of the ac waveform period.

1.4.2 The Method of Energy Balance

Any circuit must satisfy conservation of energy. In a lossless power electronic circuit, energy is delivered from source to load, possibly through an intermediate storage step. The energy flow must balance over time such that the energy drawn from the source matches that delivered to the load. The converter in Fig. 1.8 serves as an example of how the method of energy balance can be used to analyze circuit operation.

EXAMPLE 1.5 The switches in the circuit of Fig. 1.8 are controlled cyclically to operate in alternation: when the left switch is on, the right switch is off, and so on. What does the circuit do if each switch operates half the time? The inductor and capacitor have large values.

When the left switch is on, the source voltage V_{in} appears across the inductor. When the right switch is on,

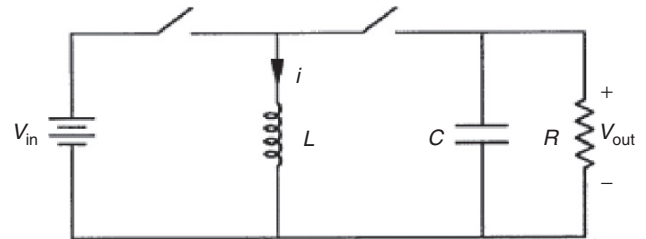


FIGURE 1.8 Energy transfer switching circuit for Example 1.5. (From [2], © 1998, Oxford University Press, Inc.; used by permission.)

the output voltage V_{out} appears across the inductor. If this circuit is to be viewed as a useful converter, the inductor should receive energy from the source and then deliver it to the load without loss. Over time, this means that energy does not build up in the inductor, but instead flows through on average. The power into the inductor, therefore, must equal the power out, at least over a cycle. Therefore, the *average* power in must equal the *average* power out of the inductor. Let us denote the inductor current as i . The input is a constant voltage source. Because L is large, this constant voltage source will not be able to change the inductor current quickly, and we can assume that the inductor current is also constant. The average power into L over the cycle period T is

$$P_{in} = \frac{1}{T} \int_0^{T/2} V_{in} i dt = \frac{V_{in} i}{2}. \quad (1.3)$$

For the average power out of L , we must be careful about current directions. The current *out* of the inductor will have a

value $-i$. The average output power is

$$P_{\text{out}} = \frac{1}{T} \int_{T/2}^T -iV_{\text{out}} dt = -\frac{V_{\text{out}} i}{2} \quad (1.4)$$

For this circuit to be viewed useful as a converter, the net energy should flow from the source to the load over time. The power conservation relationship $P_{\text{in}} = P_{\text{out}}$ requires that $V_{\text{out}} = -V_{\text{in}}$.

The method of energy balance shows that, when operated as described in the example, the circuit shown in Fig. 1.8 serves as a polarity reverser. The output voltage magnitude is the same as that of the input, but the output polarity is negative with respect to the reference node. The circuit is often used to generate a negative supply for analog circuits from a single positive input level. Other output voltage magnitudes can be achieved at the output if the switches alternate at unequal times.

If the inductor in the polarity reversal circuit is moved instead to the input, a step-up function is obtained. Consider the circuit shown in Fig. 1.9 in the following example.

EXAMPLE 1.6 The switches shown in Fig. 1.9 are controlled cyclically in alternation. The left switch is on for two-thirds of each cycle, and the right switch for the remaining one-third of each cycle. Determine the relationship between V_{in} and V_{out} . The inductor's energy should not build up when the circuit is operating normally as a converter. A power balance calculation can be used to relate the input and output voltages. Again, let i be the inductor current. When the left switch is on, power is injected into the inductor. Its average value is

$$P_{\text{in}} = \frac{1}{T} \int_0^{2T/3} V_{\text{in}} i dt = \frac{2V_{\text{in}} i}{3}. \quad (1.5)$$

Power leaves the inductor when the right switch is on. Care must be taken with respect to polarities, and the current should be set negative to represent output power.

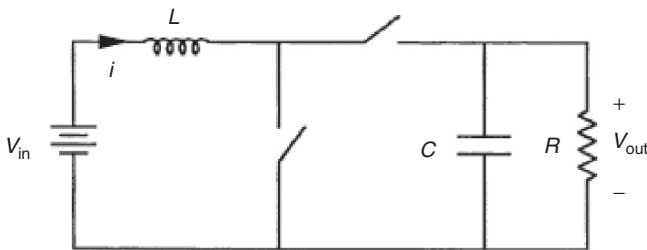


FIGURE 1.9 Switching converter Example 1.6. (From [2], © 1998, Oxford University Press, Inc.; used by permission.)

The result is

$$\begin{aligned} P_{\text{out}} &= \frac{1}{T} \int_{2T/3}^T -(V_{\text{in}} - V_{\text{out}}) i dt \\ &= -\frac{V_{\text{in}} i}{3} + \frac{V_{\text{out}} i}{3}. \end{aligned} \quad (1.6)$$

When the input and output power are equated,

$$\frac{2V_{\text{in}} i}{3} = -\frac{V_{\text{out}} i}{3} + \frac{V_{\text{out}} i}{3}, \quad \text{and} \quad 3V_{\text{in}} = V_{\text{out}} \quad (1.7)$$

and the output voltage is found to be triple the input. Many seasoned engineers find the dc-dc step-up function shown in Fig. 1.9 to be surprising. Yet, it is just one example of such action. Others (including flyback circuits related to Fig. 1.8) are used in systems ranging from controlled power supplies to spark ignitions for automobiles.

The circuits in the preceding examples have few components, provide useful conversion functions, and are efficient. If the switching devices are ideal, each circuit is lossless. Over the history of power electronics, development has tended to flow around the discovery of such circuits: a circuit with a particular conversion function is discovered, analyzed, and applied. As the circuit moves from laboratory testing to a complete commercial product, control and protection functions are added. The power portion of the circuit remains close to the original idea. The natural question arises as to whether a systematic approach to conversion is possible: can we start with a desired function and design an appropriate converter, rather than starting from the converter and working backwards toward the application? What underlying principles can be applied to design and analysis? In this chapter, a few of the key concepts are introduced. Note that, although many of the circuits look deceptively simple, all circuits are nonlinear systems with unusual behavior.

1.5 Tools for Analysis and Design

1.5.1 The Switch Matrix

The most readily apparent difference between a power electronic circuit and other types of electronic circuits is the switch action. In contrast to a digital circuit, the switches do not indicate a logic level. Control is effected by determining the times at which switches should operate. Whether there is just one switch or a large group, there is a complexity limit: if a converter has m inputs and n outputs, even the densest possible collection of switches would have a single switch between each input and output lines. The $m \times n$ switches in the circuit can be arranged

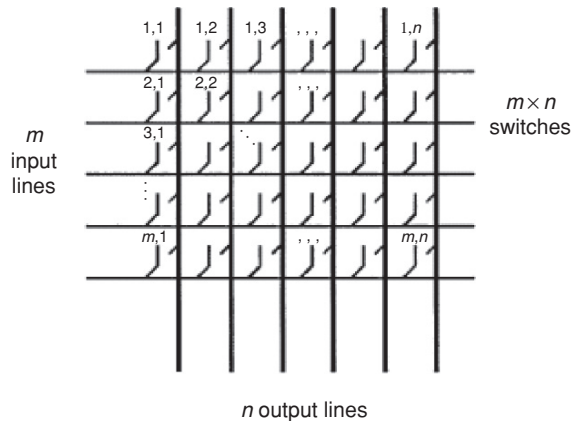


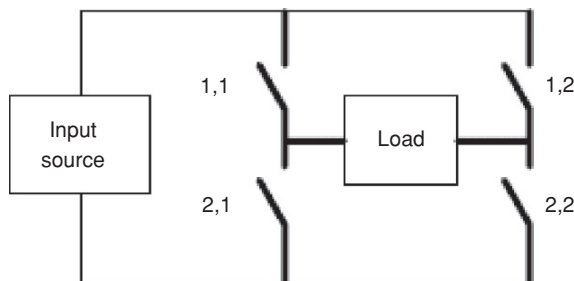
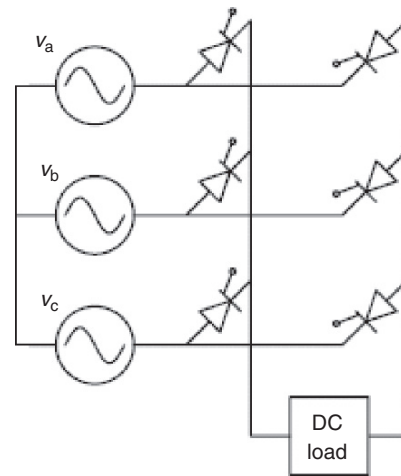
FIGURE 1.10 The general switch matrix.

according to their connections. The pattern suggests a matrix, as shown in Fig. 1.10.

Power electronic circuits fall into two broad classes:

1. **Direct switch matrix circuits.** In these circuits, energy storage elements are connected to the matrix only at the input and output terminals. The storage elements effectively become part of the source or the load. A rectifier with an external low-pass filter is an example of a direct switch matrix circuit. In the literature, ac-ac versions of these circuits are sometimes called *matrix converters*.
2. **Indirect switch matrix circuits,** also termed embedded converters. These circuits, like the polarity-reverser example, have energy storage elements connected *within* the matrix structure. Indirect switch matrix circuits are most commonly analyzed as a cascade connection of direct switch matrix circuits with storage in between.

The switch matrices in realistic applications are small. A 2×2 switch matrix, for example, covers all possible cases with a single-port input source and a two-terminal load. The matrix is commonly drawn as the *H-bridge* shown in Fig. 1.11. A more complicated example is the three-phase bridge rectifier shown in Fig. 1.12. There are three possible inputs, and the two terminals of the dc circuit provide outputs, which gives a 3×2

FIGURE 1.11 H-bridge configuration of a 2×2 switch matrix.FIGURE 1.12 Three-phase bridge rectifier circuit, a 3×2 switch matrix.

switch matrix. In a computer power supply with five separate dc loads, the switch matrix could be 2×10 . Very few practical converters have more than 24 switches, and most designs use fewer than 12.

A switch matrix provides a way to organize devices for a given application. It also helps us focus on three major task areas, which must be addressed individually and effectively in order to produce a useful power electronic system.

- The **“Hardware”** Task – Build a switch matrix. This involves the selection of appropriate semiconductor switches and the auxiliary elements that drive and protect them.
- The **“Software”** Task – Operate the matrix to achieve the desired conversion. All operational decisions are implemented by adjusting switch timing.
- The **“Interface”** Task – Add energy storage elements to provide the filters or intermediate storage necessary to meet the application requirements. Lossless filters with simple structures are required.

In a rectifier or other converter, we must choose the electronic parts, how to operate them, and how best to filter the output to satisfy the needs of the load.

1.5.2 Implications of Kirchhoff’s Voltage and Current Laws

A major challenge of switch circuits is their capacity to “violate” circuit laws. First, consider the simple circuits shown in Fig. 1.13. We might try the circuit shown in Fig. 1.13a for ac-dc conversion, but there is a problem. According to Kirchhoff’s Voltage Law (KVL), the “sum of voltage drops around a closed loop is zero.” However, with the switch closed, the sum of voltages around the loop is not zero. In reality, this is not a valid result. Instead, a very large current will flow

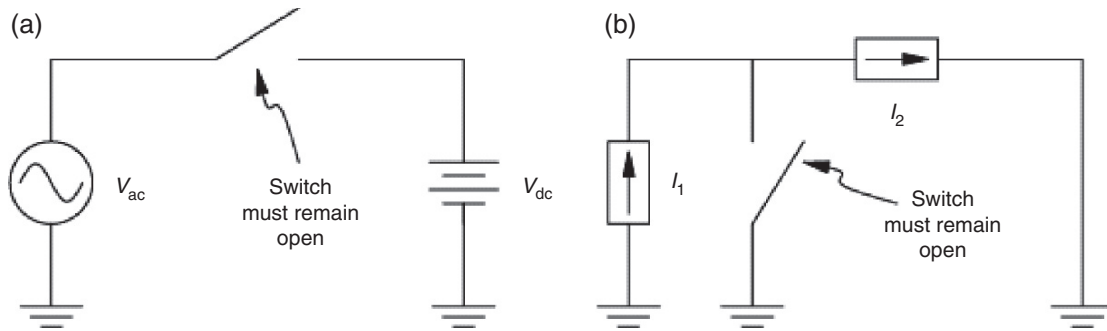


FIGURE 1.13 Hypothetical power converters: (a) possible ac–dc converter (b) possible dc–dc converter. (From [2], © 1998, Oxford University Press Inc.; used by permission.)

and cause a large $I \cdot R$ drop in the wires. KVL *will* be satisfied by the wire voltage drop, but a fire or, better yet, fuse action, might result. There is, however, nothing that would prevent an operator from trying to close the switch. KVL, then, implies a crucial restriction: a switch matrix must not attempt to interconnect unequal voltage sources directly. Notice that a wire, or dead short, can be thought of as a voltage source with $V = 0$, so KVL is a generalization of avoiding shorts across an individual voltage source.

A similar constraint holds for Kirchhoff’s Current Law (KCL) that states that “currents into a node must sum to zero.” When current sources are present in a converter, we must avoid any attempts to violate KCL. In Fig. 1.13b, if the current sources are different and if the switch is opened, the sum of the currents into the node will not be zero. In a real circuit, high voltages will build up and cause an arc to create another current path. This situation has real potential for damage, and a fuse will not help. As a result, KCL implies the restriction that a switch matrix must not attempt to interconnect unequal current sources directly. An open circuit can be thought of as a current source with $I = 0$, so KCL applies to the problem of opening an individual current source.

In contrast to conventional circuits, in which KVL and KCL are automatically satisfied, switches do not “know” KVL or KCL. If a designer forgets to check, and accidentally shorts two voltages or breaks a current source connection, some problem or damage will result. KVL and KCL place necessary constraints on the operation of a switch matrix. In the case of voltage sources, switches must not act to create short-circuit paths among unlike sources. In the case of KCL, switches must act to provide a path for currents. These constraints drastically reduce the number of valid switch-operating conditions in a switch matrix, thereby leading to manageable operating design problems.

When energy storage is included, there are interesting implications of the circuit law restrictions. Figure 1.14 shows two “circuit law problems.” In Fig. 1.14a, the voltage source will cause the inductor current to ramp up indefinitely, since $V = L di/dt$. We might consider this to be a “KVL problem”

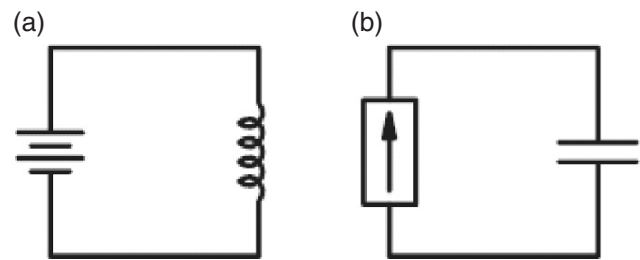


FIGURE 1.14 Short-term KVL and KCL problems in energy storage circuits: (a) an inductor cannot sustain dc voltage indefinitely; (b) a capacitor cannot sustain dc current indefinitely.

because the long-term effect is similar to shorting the source. In Fig. 1.14b, the current source will cause the capacitor voltage to ramp toward infinity. This causes a “KCL problem”; eventually, an arc will be formed to create an additional current path, just as if the current source had been opened. Of course, these connections are not problematic if they are only temporary. However, it should be evident that an inductor will not support dc voltage, and a capacitor will not support dc current. On average, over an extended time interval, the voltage across an inductor must be zero, and the current into a capacitor must be zero.

1.5.3 Resolving the Hardware Problem – Semiconductor Devices

A switch is either on or off. When on, an ideal switch will carry any current in any direction. When off, it will never carry current, no matter what voltage is applied. It is entirely lossless and changes from its on-state to its off-state instantaneously. A *real* switch can only approximate an ideal switch. The following are the aspects of real switches that differ from the ideal:

- limits on the amount and direction of on-state current;
- a nonzero on-state voltage drop (such as a diode forward voltage);

- some levels of leakage current when the device is supposed to be off;
- limitations on the voltage that can be applied when off;
- operating speed. The duration of transition between the on-states and off-states is important.

The degree to which the properties of an ideal switch must be met by a real switch depends on the application. For example, a diode can easily be used to conduct dc current; the fact that it conducts only in one direction is often an advantage, not a weakness.

Many different types of semiconductors have been applied in power electronics. In general, these fall into three groups:

1. Diodes, which are used in rectifiers, dc–dc converters, and in supporting roles.
2. Transistors, which in general are suitable for control of single-polarity circuits. Several types of transistors are applied to power converters. The IGBT type is unique to power electronics and has good characteristics for applications such as inverters.
3. Thyristors, which are multijunction semiconductor devices with latching behavior. In general, thyristors can be switched with short pulses and then maintain their state until current is removed. They act only as switches. The characteristics are especially well suited

to high-power controllable rectifiers, they have been applied to all power-conversion applications.

Some of the features of the most common power semiconductors are listed in Table 1.1. The table shows a wide variety of speeds and rating levels. As a rule, faster speeds apply to lower ratings. For each device type, cost tends to increase both for faster devices and for devices with higher power-handling capacity.

Conducting direction and blocking behavior are fundamentally tied to the device type, and these basic characteristics constrain the choice of device for a given conversion function. Consider again a diode. It carries current in only one direction and always blocks current in the other direction. Ideally, the diode exhibits no forward voltage drop or off-state leakage current. Although an ideal diode lacks the many features of an ideal switch, it is an important switching device. Other real devices operate with polarity limits on current and voltage and have corresponding ideal counterparts. It is convenient to define a special type of switch to represent this behavior: the *restricted switch*.

DEFINITION A *restricted switch* is an ideal switch with the addition of restrictions on the direction of current flow and voltage polarity. The *ideal diode* is one example of a restricted switch.

TABLE 1.1 Examples of semiconductor devices used in power electronics

Device type	Characteristics of power devices
Diode	Current ratings from under 1 A to more than 5000 A. Voltage ratings from 10 V to 10 kV or more. The fastest power devices switch in less than 10 ns, whereas the slowest require 100 μ s or more. The function of a diode applies in rectifiers and dc–dc circuits.
BJT	(Bipolar junction transistor) Conducts collector current (in one direction) when sufficient base current is applied. The function applies to dc–dc circuits. Power BJTs have mostly been supplanted by FETs and IGBTs.
FET	(Field effect transistor) Conducts drain current when sufficient gate voltage is applied. Power FETs (nearly always enhancement-mode MOSFETs) have a parallel connected reverse diode by virtue of their construction. Ratings from about 0.5 A to about 150 A and 20 V up to 1200 V. Switching times are fast, from 20 ns or less up to 200 ns. The function applies to dc–dc conversion, where the FET is in wide use, and to inverters.
IGBT	(Insulated gate bipolar transistor) A special type of transistor that has the function of a BJT with its base driven by an FET. Faster than a BJT of similar ratings, and easy to use. Ratings from 10 A to more than 600 A, with voltages of 600 to 2500 V. The IGBT is popular in inverters from about 1 to 200 kW or more. It is found almost exclusively in power electronics applications.
SCR	(Silicon-controlled rectifier) A thyristor that conducts like a diode after a gate pulse is applied. Turns off only when current becomes zero. Prevents current flow until a pulse appears. Ratings from 10 A up to more than 5000 A, and from 200 V up to 6 kV. Switching requires 1 to 200 μ s. Widely used for controlled rectifiers. The SCR is found almost exclusively in power electronics applications, and is the most common member of the thyristor family.
GTO	(Gate turn-off thyristor) An SCR that can be turned off by sending a negative pulse to its gate terminal. Can substitute for transistors in applications above 200 kW or more. The ratings approach those of SCRs, and the speeds are similar as well.
TRIAC	A semiconductor constructed to resemble two SCRs connected in reverse parallel. Ratings from 2 to 50 A and 200 to 800 V. Used in lamp dimmers, home appliances, and hand tools. Not as rugged as many other device types, but very convenient for many ac applications.
IGCT	(Integrated gate commutated thyristor) A combination device that includes a high-power thyristor and external electronics to control it. This device is a member of a larger family of combination devices, in which multiple semiconductor chips packaged together perform a single power function. The IGCT provides a high-performance GTO function for power levels above 1 MW or more.

TABLE 1.2 The types of restricted switches

Action	Device	Quadrants	Restricted switch symbol	Device symbol
Carries current in one direction, blocks in the other (forward-conducting reverse-blocking)	Diode			
Carries or blocks current in one direction (forward-conducting forward-blocking)	BJT			
Carries in one direction or blocks in both directions (forward-conducting bidirectional-blocking)	GTO			
Carries in both directions, but blocks only in one direction (bidirectional-carrying forward-blocking)	FET			
Fully bidirectional	Ideal switch			

The diode always permits current flow in one direction, while blocking flow in the other direction. It therefore represents a *forward-conducting reverse-blocking* restricted switch and operates in one quadrant on a graph of device current versus voltage. This function is automatic – the two diode terminals provide all the necessary information for switch action. Other restricted switches require a third *gate* terminal to determine their state. Consider the polarity possibilities given in Table 1.2. Additional functions such as bidirectional-conducting reverse-blocking can be obtained by reverse connection of one of the five types in the table.

The quadrant operation shown in the table indicates polarities. For example, the current in a diode will be positive when on, and the voltage will be negative when off. This means diode operation is restricted to the single quadrant comprising the upper vertical (current) axis and the left horizontal (voltage) axis. Other combinations appear in the table. Symbols for restricted switches can be built up by interpreting the diode's triangle as the current-carrying direction and the bar as the blocking direction. Five types of symbols can be drawn as shown in Table 1.2. These symbols are used infrequently, but are useful for showing the polarity behavior of switching devices. A circuit drawn with restricted switches represents an idealized power converter.

Restricted switch concepts guide the selection of devices. For example, consider an inverter intended to deliver ac load current from a dc voltage source. A switch matrix built to perform this function must be able to manipulate ac current

and dc voltage. Regardless of the physical arrangement of the matrix, we would expect bidirectional-conducting forward-blocking switches to be useful for this conversion. This is a correct result: modern inverters operating from dc voltage sources are built with FETs or with IGBTs packaged with reverse-parallel diodes. As new power devices are introduced to the market, it is straightforward to determine what types of converters will use them.

1.5.4 Resolving the Software Problem – Switching Functions

The physical $m \times n$ switch matrix can be associated with a mathematical $m \times n$ *switch state matrix*. Each element of this matrix, called a *switching function*, shows whether the corresponding physical device is on or off.

DEFINITION A *switching function*, $q(t)$, has a value of 1 when the corresponding physical switch is on and 0 when it is off. Switching functions are discrete-valued functions of time, and control of switching devices can be represented with them.

Figure 1.15 shows a typical switching function. It is periodic, with period T , representing the most likely repetitive switch action in a power converter. For convenience, it is drawn on a relative time scale that begins at 0 and draws out the square wave period by period. The actual timing is arbitrary, so the

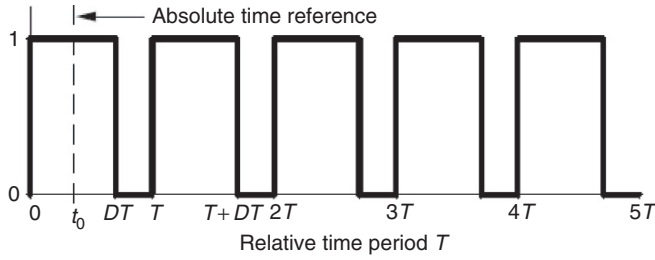


FIGURE 1.15 A generic switching function with period T , duty ratio D , and time reference t_0 .

center of the first pulse is defined as a specified time t_0 in the figure. In many converters, the switching function is generated as an actual control voltage signal that might drive the gate of either a MOSFET or some other semiconductor switching device.

The timing of switch action is the only alternative for control of a power converter. Because switch action can be represented with a discrete-valued switching function, timing can be represented within the switching function framework. On the basis of Fig. 1.15, a generic switching function can be characterized completely with three parameters:

1. The *duty ratio*, D , is the fraction of time during which the switch is on. For control purposes, the on-time interval or pulse width can be adjusted to achieve a desired result. We can term this adjustment process *pulse-width modulation* (PWM), perhaps the most important process for implementing control in power converters.
2. The frequency $f_{\text{switch}} = 1/T$ (with radian frequency $\omega = 2\pi f_{\text{switch}}$) is most often constant, although not in all applications. For control purposes, frequency can be adjusted. This strategy is sometimes used in low-power dc–dc converters to manage wide load ranges. In other converters, frequency control is unusual because the operating frequency is often dictated by the application.
3. The time delay t_0 or phase $\varphi_0 = \omega t_0$. Rectifiers often use *phase control* to provide a range of adjustment. Phase-shifted bridge circuits are common for high-power dc–dc conversion. A few specialized ac–ac converter applications use phase modulation.

With just three parameters to vary, there are relatively few possible ways to control any power electronic circuit. dc–dc converters and inverters usually rely on duty ratio adjustment (PWM) to alter their behavior. Phase control is common in controlled rectifier applications.

Switching functions are powerful tools for the general representation of converter action [7]. The most widely used control approaches derive from averages of switching functions [2, 8]. Their utility comes from their application in writing circuit equations. For example, in the boost converter shown in

Fig. 1.9, the loop and node equations change depending on which switch is acting at a given moment. The two possible circuit configurations each have distinct equations. Switching functions allow them to be combined. By assigning switching functions $q_1(t)$ and $q_2(t)$ to the left- and right-switching devices, respectively, we obtain

$$q_1 \left(V_{\text{in}} - L \frac{di_L}{dt} = 0 \right),$$

$$q_1 \left(C \frac{dv_C}{dt} + \frac{v_C}{R} = 0 \right), \text{ left switch on} \quad (1.8)$$

$$q_2 \left(V_{\text{in}} - L \frac{di_L}{dt} = v_C \right),$$

$$q_2 \left(C \frac{dv_C}{dt} + \frac{v_C}{R} = i_L \right), \text{ right switch on} \quad (1.9)$$

Because the switches alternate, and the switching functions must be 0 or 1, these sets of equations can be combined to give

$$V_{\text{in}} - L \frac{di_L}{dt} = q_2 v_C, \quad C \frac{dv_C}{dt} + \frac{v_C}{R} = q_2 i_L \quad (1.10)$$

The combined expressions are simpler and easier to analyze than the original equations.

For control purposes, the average of equations such as (1.10) often proceeds with the replacement of switching functions q with duty ratios d . The discrete time action of a switching function thus will be represented by an average duty ratio parameter. Switching functions, the advantages gained by averaging, and control approaches such as PWM are discussed at length in several chapters in this handbook.

1.5.5 Resolving the Interface Problem – Lossless Filter Design

Lossless filters for power electronic applications are sometimes called smoothing filters [9]. In applications in which dc outputs are of interest, such filters are commonly implemented as simple low-pass LC structures. The analysis is facilitated because in most cases the residual output waveform, termed ripple, has a predictable shape. Filter design for rectifiers or dc–dc converters is a question of choosing storage elements large enough to keep ripple low, but not so large that the whole circuit becomes unwieldy or expensive.

Filter design is more challenging when ac outputs are desired. In some cases, this is again an issue of low-pass filter design. However, in many applications, low-pass filters are not adequate to meet low noise requirements. In these situations, active filters can be used. In power electronics, the term active filter refers to lossless switching converters that actively inject or remove energy moment-by-moment to compensate for distortion. The circuits (discussed in Chapter 41 – Active Filters

in this handbook) are not related to the linear active filter op-amp circuits used in analog signal processing. In ac applications, there is a continuing opportunity for innovation in filter design.

1.6 Sample Applications

Although power electronics is becoming universal for electronic systems, a few emerging applications have generated wide interest. Some are discussed briefly here to introduce the breadth of activity in the field.

A hybrid electric vehicle typically has two major power electronic systems and dozens or even hundreds of smaller systems [10]. The two large units are the inverter system, which controls the electric drive motor, and a rectifier system, which manages battery charging. Smaller systems include motor controllers in electric power steering units, lighting electronics for high-intensity headlamps, controllers for the wide range of small motors that actuate everything from windshield wipers to DVD players, and power supplies for the host of microcontrollers embedded in a modern car. As plug-in hybrid and electric cars continue to develop, the efficiency and sophistication of battery chargers and drive motor controllers will increase.

In a hybrid car, a typical inverter rating is about 50 kW. Fully electric automobiles have inverter ratings to about 200 kW. Hybrid and electric drive power levels increase from there to include multimewatt inverters that power high-speed trains.

At the other power extreme, designers have been working on small power electronic systems that extract energy from various ambient sources for local purposes [11]. These energy harvesting applications will be an emerging growth area. An example application is a corrosion sensor, built into a highway bridge, that gathers energy from vibration. The vibration energy is converted and stored, then used for intermittent communication with a central monitoring computer. Typical power levels can be less than 0.001 W.

Solar, wind, and other alternative energy resources are tightly linked to power electronics. A typical solar panel produces about 30-V dc, with tolerances from 20 to 40 V or more. This randomly changing dc source must be converted to clean, tightly regulated ac voltage that synchronizes to the electricity grid and delivers energy. Solar inverter efficiency, reliability, and cost are major factors in successful energy innovation. A dual application, meaning that energy flows in the opposite direction but that many other characteristics are shared, is that of solid-state lighting [12]. In that case, flexible control of a dc current must be provided from an ac grid source.

For wind energy, a typical large-scale wind turbine can produce 2 MW of high-frequency ac power. The frequency and voltage vary rapidly according to wind speed. This power must be converted to fixed frequency and voltage for grid interconnection.

1.7 Summary

Power electronics is the study of electronic circuits for the control and conversion of electrical energy. The technology is a critical part of our energy infrastructure and is central for a wide range of uses of electricity. For power electronics design, we consider only those circuits and devices that, in principle, introduce no loss and achieve near-perfect reliability. The two key characteristics of high efficiency and high reliability are implemented with switching circuits, supplemented with energy storage. Switching circuits can be organized as switch matrices. This facilitates their analysis and design.

In a power electronic system, the three primary challenges are the hardware problem of implementing a switch matrix, the software problem of deciding how to operate that matrix, and the interface problem of removing unwanted distortion and providing the user with the desired clean power source. The hardware is implemented with a few special types of power semiconductors. These include several types of transistors, especially MOSFETs and IGBTs, and several types of thyristors, especially SCRs and GTOs. The software problem can be represented in terms of switching functions. The frequency, duty ratio, and phase of switching functions are available for operational purposes. The interface problem is addressed by means of lossless filter circuits. Most often, these are lossless LC passive filters to smooth out ripple or reduce harmonics. Active filter circuits also have been applied to make dynamic corrections in power conversion waveforms.

Improvements in devices and advances in control concepts have led to steady improvements in power electronic circuits and systems. This is driving tremendous expansion of applications. Personal computers, for example, would be unwieldy and inefficient without power electronic dc supplies. Mobile devices and laptop computers would be impractical. High-efficiency lighting, motor controls, and a wide range of industrial controls depend on power electronics. Strong growth is occurring in automotive applications, in lighting, in dc power supplies for portable devices, in high-end converters for advanced microprocessors, and in alternative and renewable energy. During the next generation, we will reach a time when almost all electrical energy is processed through power electronics somewhere in the path from generation to end use.

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Section I

Power Electronics Devices

Power Electronics for Renewable Energy Sources

**C. V. Nayar, S. M. Islam,
H. Dehbonei, and K. Tan**

*Department of Electrical and
Computer Engineering, Curtin
University of Technology, GPO
Box U1987, Perth, Western
Australia 6845, Australia*

H. Sharma

*Research Institute for Sustainable
Energy, Murdoch University,
Perth, Western Australia,
Australia*

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28.1 Introduction

The Kyoto agreement on global reduction of greenhouse gas emissions has prompted renewed interest in renewable energy systems worldwide. Many renewable energy technologies today are well developed, reliable, and cost competitive with the conventional fuel generators. The cost of renewable energy technologies is on a falling trend and is expected to fall further as demand and production increases. There are many renewable energy sources (RES) such as biomass, solar, wind, mini hydro and tidal power. However, solar and wind energy systems make use of advanced power electronics technologies and, therefore the focus in this chapter will be on solar photovoltaic and wind power.

One of the advantages offered by (RES) is their potential to provide sustainable electricity in areas not served by the conventional power grid. The growing market for renewable energy technologies has resulted in a rapid growth in the need of power electronics. Most of the renewable energy technologies produce DC power and hence power electronics and control equipment are required to convert the DC into AC power.

Inverters are used to convert DC to AC. There are two types of inverters: (a) stand-alone or (b) grid-connected. Both types have several similarities but are different in terms of control functions. A stand-alone inverter is used in off-grid

applications with battery storage. With back-up diesel generators (such as photovoltaic (PV)/diesel/hybrid power systems), the inverters may have additional control functions such as operating in parallel with diesel generators and bi-directional operation (battery charging and inverting). Grid interactive inverters must follow the voltage and frequency characteristics of the utility generated power presented on the distribution line. For both types of inverters, the conversion efficiency is a very important consideration. Details of stand-alone and grid-connected inverters for PV and wind applications are discussed in this chapter.

Section 28.2 covers stand-alone PV system applications such as battery charging and water pumping for remote areas. This section also discusses power electronic converters suitable for PV-diesel hybrid systems and grid-connected PV for rooftop and large-scale applications. Of all the renewable energy options, the wind turbine technology is maturing very fast. A marked rise in installed wind power capacity has been noticed worldwide in the last decade. Per unit generation cost of wind power is now quite comparable with the conventional generation. Wind turbine generators are used in stand-alone battery charging applications, in combination with fossil fuel generators as part of hybrid systems and as grid-connected systems. As a result of advancements in blade design, generators, power electronics, and control systems, it has been possible to increase dramatically the availability of large-scale wind power.

Many wind generators now incorporate speed control mechanisms like blade pitch control or use converters/inverters to regulate power output from variable speed wind turbines. In Section 28.3, electrical and power conditioning aspects of wind energy conversion systems were included.

28.2 Power Electronics for Photovoltaic Power Systems

28.2.1 Basics of Photovoltaics

The density of power radiated from the sun (referred as “solar energy constant”) at the outer atmosphere is 1.373 kW/m^2 . Part of this energy is absorbed and scattered by the earth’s atmosphere. The final incident sunlight on earth’s surface has a peak density of 1 kW/m^2 at noon in the tropics. The technology of photovoltaics (PV) is essentially concerned with the conversion of this energy into usable electrical form. Basic element of a PV system is the solar cell. Solar cells can convert the energy of sunlight directly into electricity. Consumer appliances used to provide services such as lighting, water pumping, refrigeration, telecommunication, television, etc. can be run from PV electricity. Solar cells rely on a quantum-mechanical process known as the “photovoltaic effect” to produce electricity. A typical solar cell consists of a p–n junction formed in a semiconductor material similar to a diode. Figure 28.1 shows a schematic diagram of the cross section through a crystalline solar cell [1]. It consists of a 0.2–0.3 mm thick monocrystalline or polycrystalline silicon wafer having two layers with different electrical properties formed by “doping” it with other impurities (e.g. boron and phosphorous). An electric field is established at the junction between the negatively doped (using phosphorous atoms) and the positively doped (using boron atoms) silicon layers. If light is incident on the solar cell, the energy from the light (photons) creates free charge carriers, which are separated by the electrical field. An electrical voltage is generated at the external contacts, so that current can

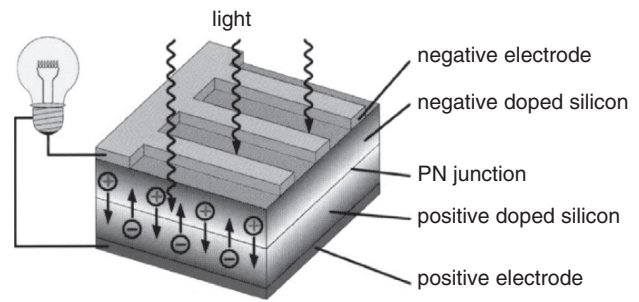


FIGURE 28.1 Principle of the operation of a solar cell [2].

flow when a load is connected. The photocurrent (I_{ph}), which is internally generated in the solar cell, is proportional to the radiation intensity.

A simplified equivalent circuit of a solar cell consists of a current source in parallel with a diode as shown in Fig. 28.2a. A variable resistor is connected to the solar cell generator as a load. When the terminals are short-circuited, the output voltage and also the voltage across the diode is zero. The entire photocurrent (I_{ph}) generated by the solar radiation then flows to the output. The solar cell current has its maximum (I_{sc}). If the load resistance is increased, which results in an increasing voltage across the p–n junction of the diode, a portion of the current flows through the diode and the output current decreases by the same amount. When the load resistor is open-circuited, the output current is zero and the entire photocurrent flows through the diode. The relationship between current and voltage may be determined from the diode characteristic equation

$$I = I_{ph} - I_0(e^{qV/kT} - 1) = I_{ph} - I_d \quad (28.1)$$

where q is the electron charge, k is the Boltzmann constant, I_{ph} is photocurrent, I_0 is the reverse saturation current, I_d is diode current, and T is the solar cell operating temperature ($^{\circ}\text{K}$). The current vs voltage (I – V) of a solar cell is thus equivalent to an “inverted” diode characteristic curve shown in Fig. 28.2b.

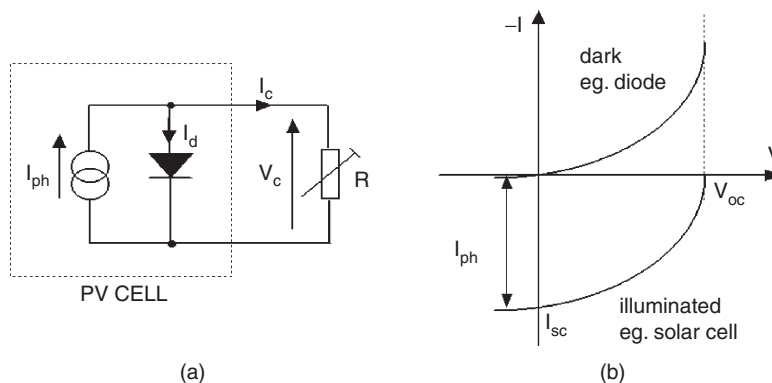


FIGURE 28.2 Simplified equivalent circuit for a solar cell.

A number of semiconductor materials are suitable for the manufacturing of solar cells. The most common types using silicon semiconductor material (Si) are:

- Monocrystalline Si cells.
- Polycrystalline Si cells.
- Amorphous Si cells.

A solar cell can be operated at any point along its characteristic current–voltage curve, as shown in Fig. 28.3. Two important points on this curve are the open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}). The open-circuit voltage is the maximum voltage at zero current, while short-circuit current is the maximum current at zero voltage. For a silicon solar cell under standard test conditions, V_{oc} is typically 0.6–0.7 V, and I_{sc} is typically 20–40 mA for every square centimeter of the cell area. To a good approximation, I_{sc} is proportional to the illumination level, whereas V_{oc} is proportional to the logarithm of the illumination level.

A plot of power (P) against voltage (V) for this device (Fig. 28.3) shows that there is a unique point on the I – V curve at which the solar cell will generate maximum power. This is known as the maximum power point (V_{mp} , I_{mp}). To maximize the power output, steps are usually taken during fabrication, the three basic cell parameters: open-circuit voltage, short-circuit current, and fill factor (FF) – a term describing how

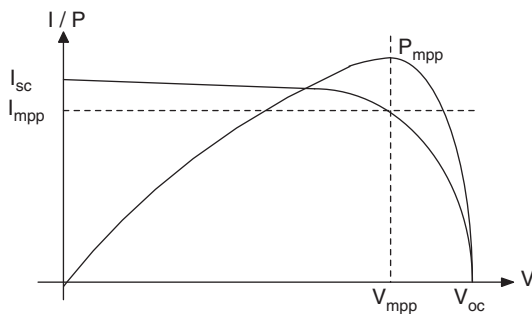


FIGURE 28.3 Current vs voltage (I – V) and current power (P – V) characteristics for a solar cell.

“square” the I – V curve is, given by

$$\text{Fill Factor} = (V_{mp} \times I_{mp}) / (V_{oc} \times I_{sc}) \quad (28.2)$$

For a silicon solar cell, FF is typically 0.6–0.8. Because silicon solar cells typically produce only about 0.5 V, a number of cells are connected in series in a PV module. A panel is a collection of modules physically and electrically grouped together on a support structure. An array is a collection of panels (see Fig. 28.4).

The effect of temperature on the performance of silicon solar module is illustrated in Fig. 28.5. Note that I_{sc} slightly increases linearly with temperature, but, V_{oc} and the maximum power, P_m decrease with temperature [1].

Figure 28.6 shows the variation of PV current and voltages at different insolation levels. From Figs. 28.5 and 28.6, it can be seen that the I – V characteristics of solar cells at a given insolation and temperature consist of a constant voltage segment

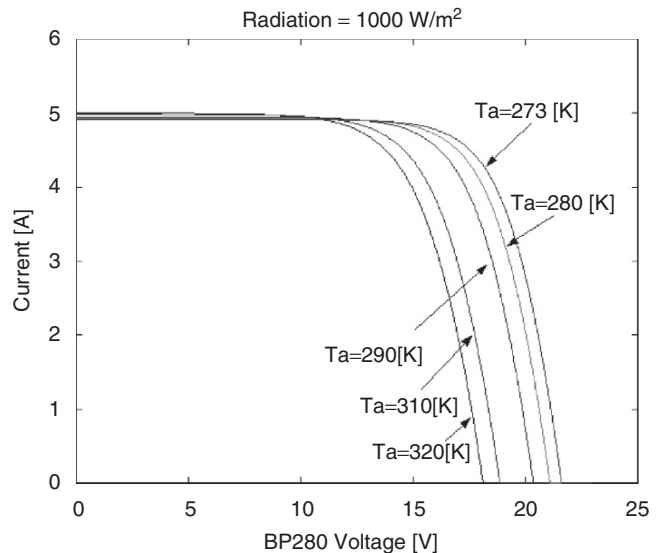


FIGURE 28.5 Effects of temperature on silicon solar cells.

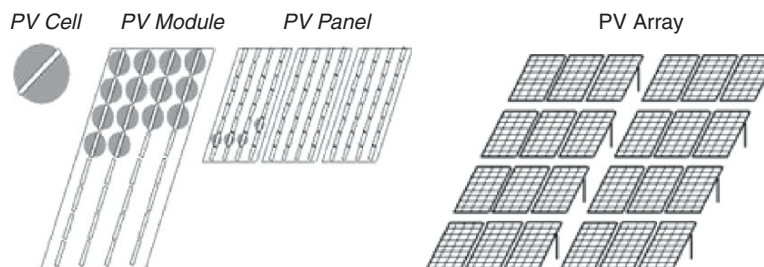


FIGURE 28.4 PV generator terms.

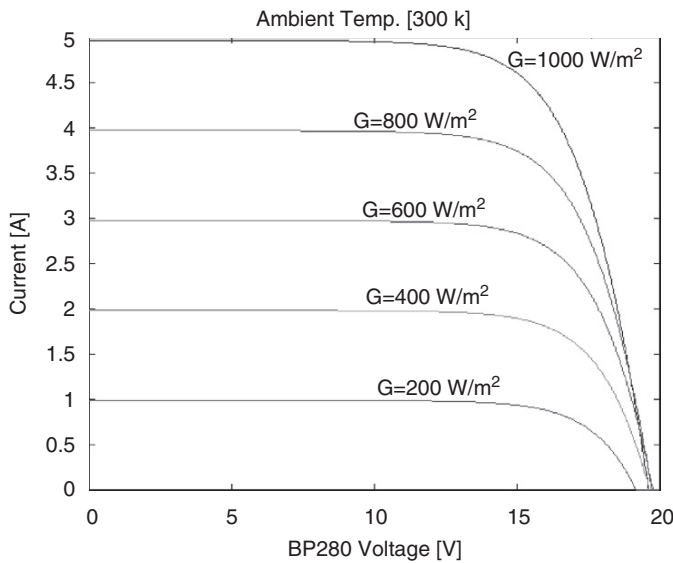


FIGURE 28.6 Typical current/voltage (I - V) characteristic curves for different insolation.

and a constant current segment [3]. The current is limited, as the cell is short-circuited. The maximum power condition occurs at the knee of the characteristic curve where the two segments meet.

28.2.2 Types of PV Power Systems

Photovoltaic power systems can be classified as:

- Stand-alone PV systems.
- Hybrid PV systems.
- Grid-connected PV systems.

Stand-alone PV systems, shown in Fig. 28.7, are used in remote areas with no access to a utility grid. Conventional power systems used in remote areas often based on manually controlled diesel generators operating continuously or for a few hours. Extended operation of diesel generators at

low load levels significantly increases maintenance costs and reduces their useful life. Renewable energy sources such as PV can be added to remote area power systems using diesel and other fossil fuel powered generators to provide 24-hour power economically and efficiently. Such systems are called “hybrid energy systems.” Figure 28.8 shows a schematic of a PV-diesel hybrid system. In grid-connected PV systems shown in Fig. 28.9, PV panels are connected to a grid through inverters without battery storage. These systems can be classified as small systems like the residential rooftop systems or large grid-connected systems. The grid-interactive inverters must be synchronized with the grid in terms of voltage and frequency.

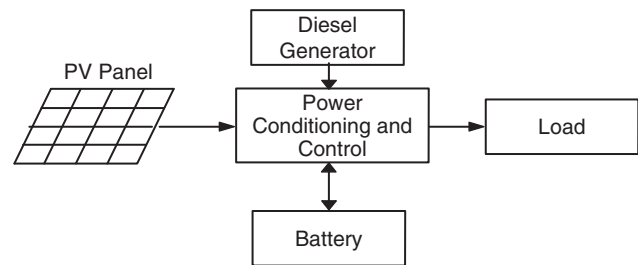


FIGURE 28.8 PV-diesel hybrid system.

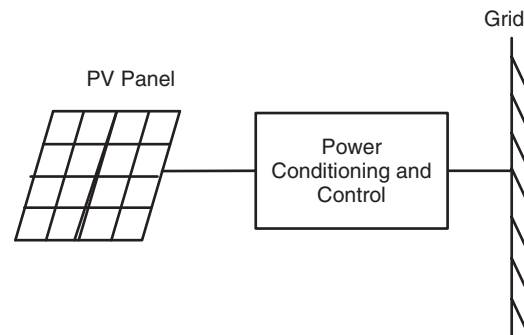


FIGURE 28.9 Grid-connected PV system.

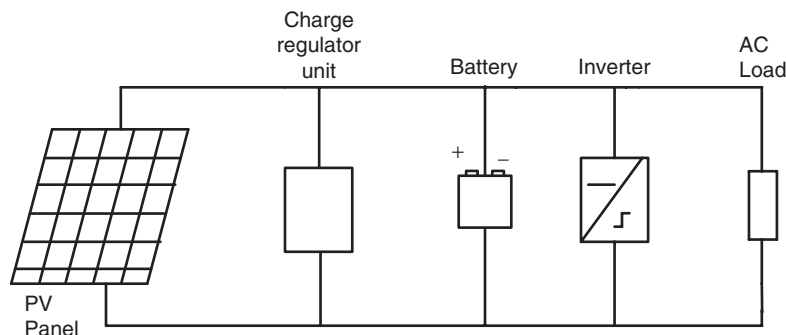


FIGURE 28.7 Stand-alone PV system.

28.2.3 Stand-alone PV Systems

The two main stand-alone PV applications are:

- Battery charging.
- Solar water pumping.

28.2.3.1 Battery Charging

28.2.3.1.1 Batteries for PV Systems Stand-alone PV energy system requires storage to meet the energy demand during periods of low solar irradiation and nighttime. Several types of batteries are available such as the lead acid, nickel–cadmium, lithium, zinc bromide, zinc chloride, sodium sulfur, nickel–hydrogen, redox, and vanadium batteries. The provision of cost-effective electrical energy storage remains one of the major challenges for the development of improved PV power systems. Typically, lead-acid batteries are used to guarantee several hours to a few days of energy storage. Their reasonable cost and general availability has resulted in the widespread application of lead-acid batteries for remote area power supplies despite their limited lifetime compared to other system components. Lead-acid batteries can be deep or shallow cycling gelled batteries, batteries with captive or liquid electrolyte, sealed and non-sealed batteries etc. [4]. Sealed batteries are valve regulated to permit evolution of excess hydrogen gas (although catalytic converters are used to convert as much evolved hydrogen and oxygen back to water as possible). Sealed batteries need less maintenance. The following factors are considered in the selection of batteries for PV applications [1]:

- Deep discharge (70–80% depth of discharge).
- Low charging/discharging current.
- Long duration charge (slow) and discharge (long duty cycle).
- Irregular and varying charge/discharge.
- Low self discharge.
- Long life time.
- Less maintenance requirement.
- High energy storage efficiency.
- Low cost.

Battery manufacturers specify the nominal number of complete charge and discharge cycles as a function of the depth-of-discharge (DOD), as shown in Fig. 28.10. While this information can be used reliably to predict the lifetime of lead-acid batteries in conventional applications, such as uninterruptible power supplies or electric vehicles, it usually results in an overestimation of the useful life of the battery bank in renewable energy systems.

Two of the main factors that have been identified as limiting criteria for the cycle life of batteries in PV power systems are incomplete charging and prolonged operation at a low state-of-charge (SOC). The objective of improved battery control strategies is to extend the lifetime of lead-acid batteries to achieve a typical number of cycles shown in Fig. 28.10. If

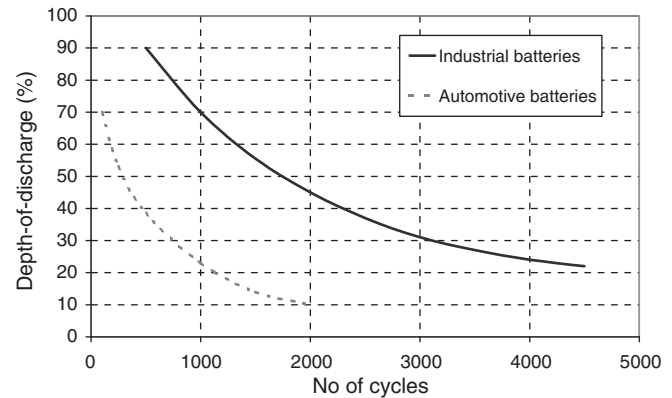


FIGURE 28.10 Nominal number of battery cycles vs DOD.

this is achieved, an optimum solution for the required storage capacity and the maximum DOD of the battery can be found by referring to manufacturer's information. Increasing the capacity will reduce the typical DOD and therefore prolong the battery lifetime. Conversely, it may be more economic to replace a smaller battery bank more frequently.

28.2.3.1.2 PV Charge Controllers Blocking diodes in series with PV modules are used to prevent the batteries from being discharged through the PV cells at night when there is no sun available to generate energy. These blocking diodes also protect the battery from short circuits. In a solar power system consisting of more than one string connected in parallel, if a short circuit occurs in one of the strings, the blocking diode prevents the other PV strings to discharge through the short-circuited string.

The battery storage in a PV system should be properly controlled to avoid catastrophic operating conditions like overcharging or frequent deep discharging. Storage batteries account for most PV system failures and contribute significantly to both the initial and the eventual replacement costs. Charge controllers regulate the charge transfer and prevent the battery from being excessively charged and discharged. Three types of charge controllers are commonly used:

- Series charge regulators.
- Shunt charge regulators.
- DC–DC converters.

A. A Series Charge Regulators

The basic circuit for the series regulators is given in Fig. 28.11. In the series charge controller, the switch S_1 disconnects the PV generator when a predefined battery voltage is achieved. When the voltage reduces below the discharge limit, the load is disconnected from the battery to avoid deep discharge beyond the limit. The main problem associated with this type of controller is the losses associated with the switches. This extra power loss

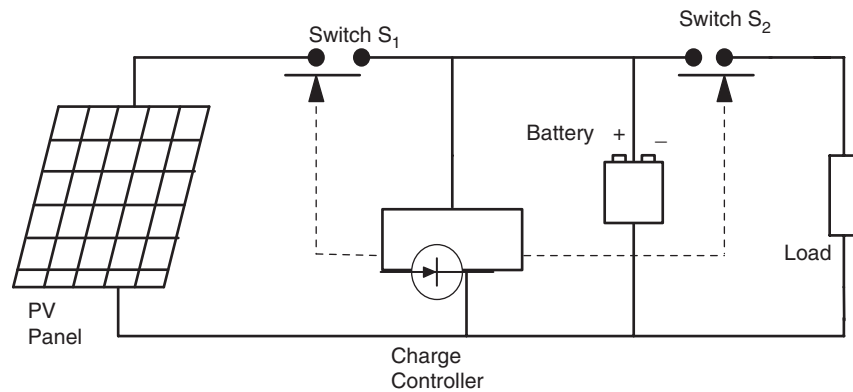


FIGURE 28.11 Series charge regulator.

has to come from the PV power and this can be quite significant. Bipolar transistors, metal oxide semi conductor field effect transistors (MOSFETs), or relays are used as the switches.

B. Shunt Charge Regulators

In this type, as illustrated in Fig. 28.12, when the battery is fully charged the PV generator is short-circuited using an electronic switch (S_1). Unlike series controllers, this method works more efficiently even when the battery is completely discharged as the short-circuit switch need not be activated until the battery is fully discharged [1].

The blocking diode prevents short-circuiting of the battery. Shunt-charge regulators are used for the small PV applications (less than 20 A).

Deep discharge protection is used to protect the battery against the deep discharge. When the battery voltage reaches below the minimum set point for deep discharge limit, switch S_2 disconnects the load. Simple series and shunt regulators allow only relatively coarse adjustment of the current flow and seldom meet the exact requirements of PV systems.

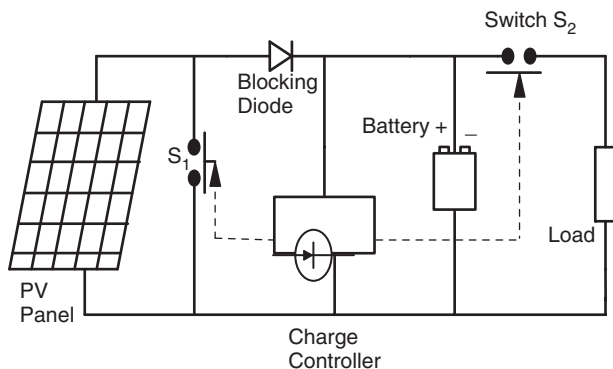


FIGURE 28.12 Shunt charge regulator.

C. DC–DC Converter Type Charge Regulators

Switch mode DC-to-DC converters are used to match the output of a PV generator to a variable load. There are various types of DC–DC converters such as:

- Buck (step-down) converter.
- Boost (step-up) converter.
- Buck–boost (step-down/up) converter.

Figures 28.13–28.15 show simplified diagrams of these three basic types converters. The basic concepts are an electronic switch, an inductor to store energy, and a “flywheel” diode, which carries the current during that part of switching cycle

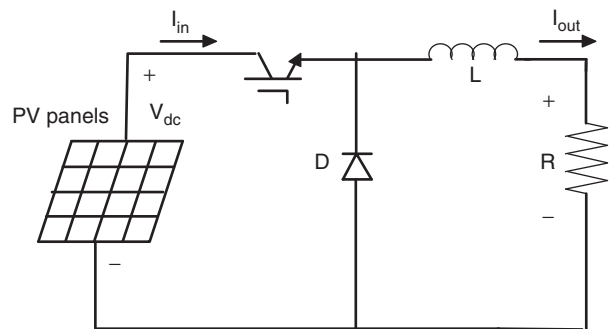


FIGURE 28.13 Buck converter.

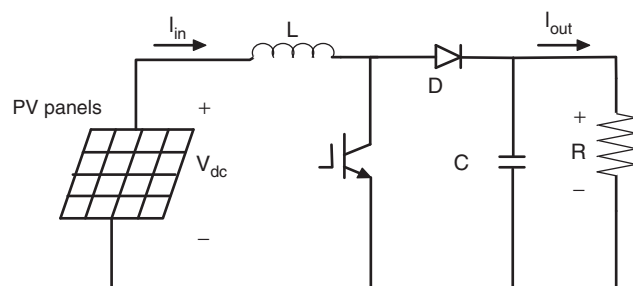


FIGURE 28.14 Boost converter.

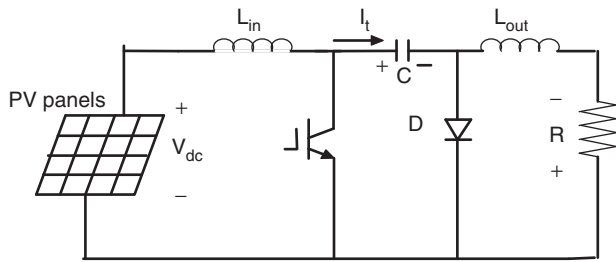


FIGURE 28.15 Boost-buck converter.

when the switch is off. The DC–DC converters allow the charge current to be reduced continuously in such a way that the resulting battery voltage is maintained at a specified value.

28.2.3.1.3 Maximum Power Point Tracking (MPPT) A controller that tracks the maximum power point locus of the PV array is known as the MPPT. In Fig. 28.16, the PV power output is plotted against the voltage for insolation levels from 200 to 1000 W/m² [5]. The points of maximum array power form a curve termed as the maximum power locus. Due to high cost of solar cells, it is necessary to operate the PV array at its maximum power point (MPP). For overall optimal operation of the system, the load line must match the PV array's MPP locus.

Referring to Fig. 28.17, the load characteristics can be either curve OA or curve OB depending upon the nature of the load and its current and voltage requirements. If load OA is considered and the load is directly coupled to the solar array, the array will operate at point A1, delivering only power P1. The maximum array power available at the given insolation is P2. In order to use PV array power P2, a power conditioner coupled between array and the load is needed.

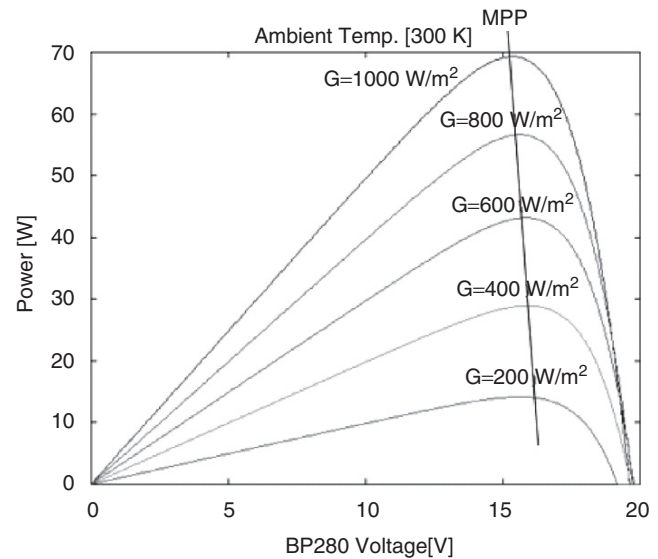


FIGURE 28.16 Typical power/voltage characteristics for increased insolation.

There are generally two ways of operating PV modules at maximum power point. These ways take advantage of analog and/or digital hardware control to track the MPP of PV arrays.

28.2.3.1.4 Analog Control There are many analog control mechanisms proposed in different articles. For instance, fractional short-circuit current (I_{SC}) [6–9], fractional open-circuit voltage (V_{OP}) [6, 7, 10–13], and ripple correlation control (RCC) [14–17].

Fractional open-circuit voltage (V_{OP}) is one of the simple analogue control method. It is based on the assumption that the maximum power point voltage, V_{MPP} , is a linear function

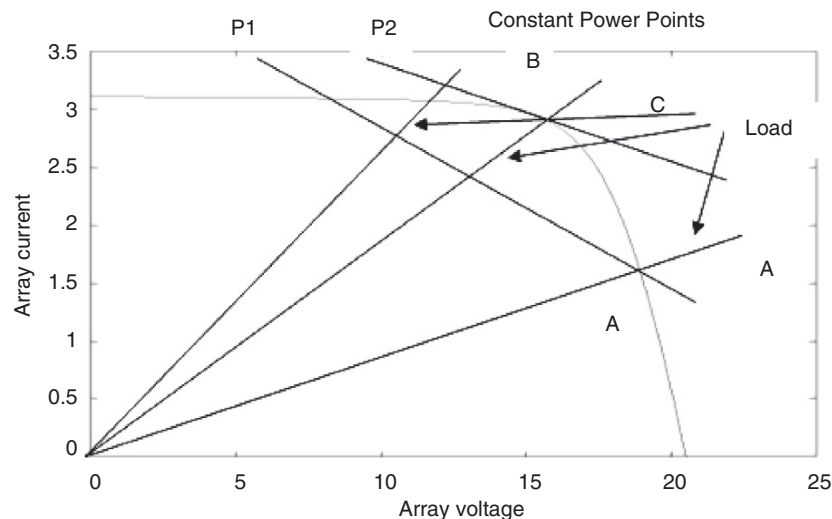


FIGURE 28.17 PV array and load characteristics.

of the open-circuit voltage, V_{OC} . For example $V_{MPP} = kV_{OC}$ where $k \approx 0.76$. This assumption is reasonably accurate even for large variations in the cell short-circuit current and temperature. This type of MPPT is probably the most common type. A variation to this method involves periodically open-circuiting the cell string and measuring the open-circuit voltage. The appropriate value of V_{MPP} can then be obtained with a simple voltage divider.

28.2.3.1.5 Digital Control There are many digital control mechanisms that were proposed in different articles. For instance, perturbation and observation (P&O) or hill climbing [18–23], fuzzy logic [24–28], neural network [18, 29–31], and incremental conductance (IncCond) [32–35].

The P&O or hill climbing control involves around varying the input voltage around the optimum value by giving it a small increment or decrement alternately. The effect on the output power is then assessed and a further small correction is made to the input voltage. Therefore, this type of control is called a hill climbing control. The power output of the PV array is sampled at an every definite sampling period and compared with the previous value. In the event, when power is increased then the solar array voltage is stepped in the same direction as the previous sample time, but if the power is reduced then the array voltage is stepped in the opposite way and try to operate the PV array at its optimum/maximum power point.

To operate the PV array at the MPP, perturb and adjust method can be used at regular intervals. Current drawn is sampled every few seconds and the resulting power output of the solar cells is monitored at regular intervals. When an increased current results in a higher power, it is further increased until power output starts to reduce. But if the increased PV current results in lesser amount of power than in the previous sample, then the current is reduced until the MPP is reached.

28.2.3.2 Inverters for Stand-alone PV Systems

Inverters convert power from DC to AC while rectifiers convert it from AC to DC. Many inverters are bi-directional, i.e. they are able to operate in both inverting and rectifying modes. In many stand-alone PV installations, alternating current is needed to operate 230 V (or 110 V), 50 Hz (or 60 Hz) appliances. Generally stand-alone inverters operate at 12, 24, 48, 96, 120, or 240 V DC depending upon the power level. Ideally, an inverter for a stand-alone PV system should have the following features:

- Sinusoidal output voltage.
- Voltage and frequency within the allowable limits.
- Cable to handle large variation in input voltage.
- Output voltage regulation.
- High efficiency at light loads.

- Less harmonic generation by the inverter to avoid damage to electronic appliances like television, additional losses, and heating of appliances.
- Photovoltaic inverters must be able to withstand overloading for short term to take care of higher starting currents from pumps, refrigerators, etc.
- Adequate protection arrangement for over/under-voltage and frequency, short circuit etc.
- Surge capacity.
- Low idling and no load losses.
- Low battery voltage disconnect.
- Low audio and radio frequency (RF) noise.

Several different semiconductor devices such as metal oxide semiconductor field effect transistor (MOSFETs) and insulated gate bipolar transistors (IGBTs) are used in the power stage of inverters. Typically MOSFETs are used in units up to 5 kVA and 96 V DC. They have the advantage of low switching losses at higher frequencies. Because the on-state voltage drop is 2 V DC, IGBTs are generally used only above 96 V DC systems.

Voltage source inverters are usually used in stand-alone applications. They can be single phase or three phase. There are three switching techniques commonly used: square wave, quasi-square wave, and pulse width modulation. Square-wave or modified square-wave inverters can supply power tools, resistive heaters, or incandescent lights, which do not require a high quality sine wave for reliable and efficient operation. However, many household appliances require low distortion sinusoidal waveforms. The use of true sine-wave inverters is recommended for remote area power systems. Pulse width modulated (PWM) switching is generally used for obtaining sinusoidal output from the inverters.

A general layout of a single-phase system, both half bridge and full bridge, is shown in Fig. 28.18. In Fig. 28.18a, single-phase half bridge is with two switches, S_1 and S_2 , the capacitors C_1 and C_2 are connected in series across the DC source. The junction between the capacitors is at the mid-potential. Voltage across each capacitor is $V_{dc}/2$. Switches S_1 and S_2 can be switched on/off periodically to produce AC voltage. Filter (L_f and C_f) is used to reduce high-switch frequency components and to produce sinusoidal output from the inverter. The output of inverter is connected to load through a transformer. Figure 28.18b shows the similar arrangement for full-bridge configuration with four switches. For the same input source voltage, the full-bridge output is twice and the switches carry less current for the same load power.

The power circuit of a three phase four-wire inverter is shown in Fig. 28.19. The output of the inverter is connected to load via three-phase transformer (delta/Y). The star point of the transformer secondary gives the neutral connection. Three phase or single phase can be connected to this system. Alternatively, a center tap DC source can be used to supply the converter and the mid-point can be used as the neutral.

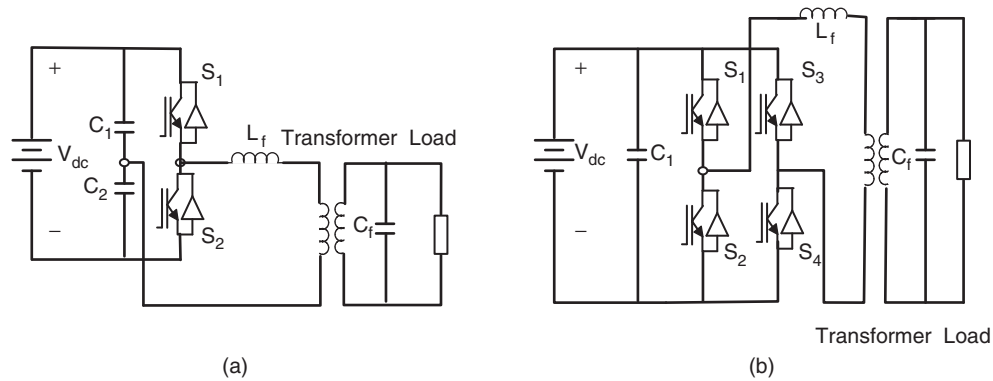


FIGURE 28.18 Single-phase inverter: (a) half bridge and (b) full bridge.

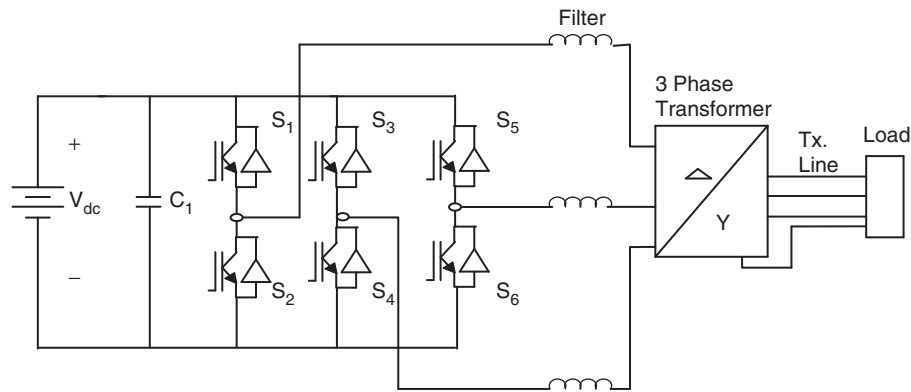


FIGURE 28.19 A stand-alone three-phase four wire inverter.

Figure 28.20 shows the inverter efficiency for a typical inverter used in remote area power systems. It is important to consider that the system load is typically well below the nominal inverter capacity P_{nom} , which results in low conversion efficiencies at loads below 10% of the rated inverter output power. Optimum overall system operation is achieved if the total energy dissipated in the inverter is minimized. The high conversion efficiency at low power levels of recently developed inverters for grid-connected PV systems shows that there is a significant potential for further improvements in efficiency.

Bi-directional inverters convert DC power to AC power (inverter) or AC power to DC power (rectifier) and are becoming very popular in remote area power systems [4, 5]. The principle of a stand-alone single-phase bi-directional inverter used in a PV/battery/diesel hybrid system can be explained by referring Fig. 28.21. A charge controller is used to interface the PV array and the battery. The inverter has a full-bridge configuration realized using four power electronic switches (MOSFET or IGBTs) S_1 – S_4 . In this scheme, the diagonally opposite switches (S_1 , S_4) and (S_2 , S_3) are switched using a sinusoidally PWM gate pulses. The inverter produces sinusoidal output voltage. The inductors X_1 , X_2 , and the AC output capacitor C_2 filter out the high-switch frequency components

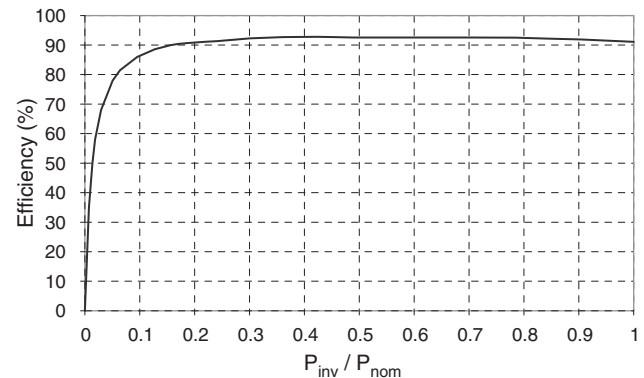


FIGURE 28.20 Typical inverter efficiency curve.

from the output waveform. Most inverter topologies use a low frequency (50 or 60 Hz) transformer to step up the inverter output voltage. In this scheme, the diesel generator and the converter are connected in parallel to supply the load. The voltage sources, diesel and inverter, are separated by the link inductor X_m . The bi-directional power flow between inverter and the diesel generator can be established.

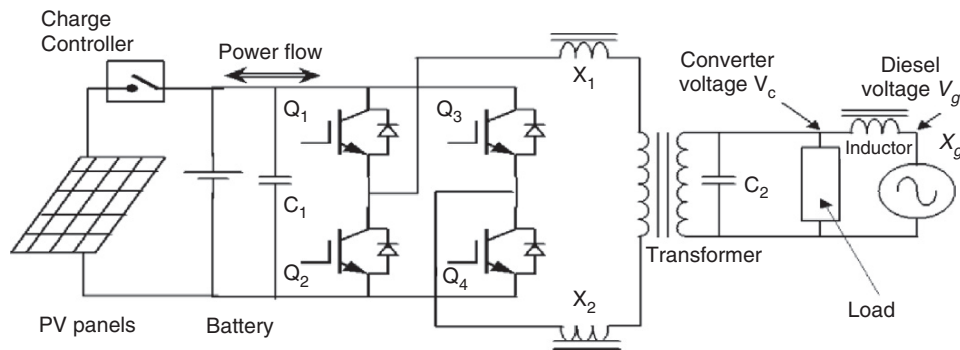


FIGURE 28.21 Bi-directional inverter system.

The power flow through the link inductor, X_m , is

$$S_m = V_m I_m^* \quad (28.3)$$

$$P_m = (V_m V_c \sin \delta) / X_m \quad (28.4)$$

$$Q_m = (V_m / X_m) (V_m - V_c \cos \delta) \quad (28.5)$$

$$\delta = \sin^{-1} [(X_m P_m) / (V_m V_c)] \quad (28.6)$$

where δ is the phase angle between the two voltages. From Eq. (28.4), it can be seen that the power supplied by the inverter from the batteries (inverter mode) or supplied to the batteries (charging mode) can be controlled by controlling the phase angle δ . The PWM pulses separately control the amplitude of the converter voltage, V_c , while the phase angle with respect to the diesel voltage is varied for power flow.

28.2.3.3 Solar Water Pumping

In many remote and rural areas, hand pumps or diesel driven pumps are used for water supply. Diesel pumps consume fossil fuel, affects environment, needs more maintenance, and are less reliable. Photovoltaic powered water pumps have received considerable attention recently due to major developments in the field of solar cell materials and power electronic systems technology.

28.2.3.3.1 Types of Pumps Two types of pumps are commonly used for the water pumping applications: positive and centrifugal displacement. Both centrifugal and positive displacement pumps can be further classified into those with motors that are (a) surface mounted and those which are (b) submerged into the water ("submersible").

Displacement pumps have water output directly proportional to the speed of the pump, but, almost independent of head. These pumps are used for solar water pumping from deep wells or bores. They may be piston type pumps, or use

diaphragm driven by a cam, rotary screw type, or use progressive cavity system. The pumping rate of these pumps is directly related to the speed and hence constant torque is desired.

Centrifugal pumps are used for low-head applications especially if they are directly interfaced with the solar panels. Centrifugal pumps are designed for fixed-head applications and the pressure difference generated increases in relation to the speed of pump. These pumps are rotating impeller type, which throws the water radially against a casing, so shaped that the momentum of the water is converted into useful pressure for lifting [4]. The centrifugal pumps have relatively high efficiency but it reduces at lower speeds, which can be a problem for the solar water pumping system at the time of low light levels. The single-stage centrifugal pump has just one impeller whereas most borehole pumps are multistage types where the outlet from one impeller goes into the center of another and each one keeps increasing the pressure difference.

From Fig. 28.22, it is quite obvious that the load line is located relatively faraway from P_{max} line. It has been reported that the daily utilization efficiency for a DC motor drive is 87% for a centrifugal pump compared to 57% for a constant torque characteristics load. Hence, centrifugal pumps are more compatible with PV arrays. The system operating point is

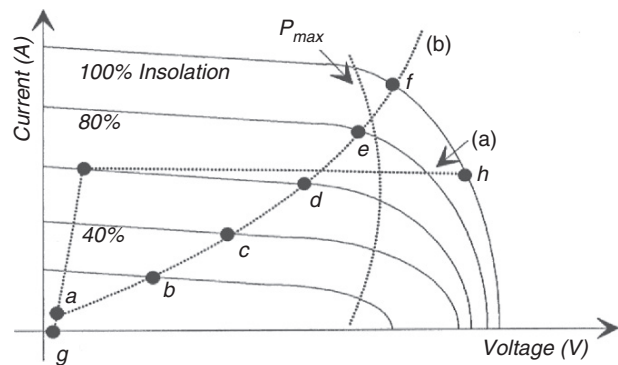


FIGURE 28.22 I-V characteristics of a PV array and two mechanical loads: (a) constant torque and (b) centrifugal pump.

determined by the intersection of the I - V characteristics of the PV array and the motor as shown in Fig. 28.22. The torque-speed slope is normally large due to the armature resistance being small. At the instant of starting, the speed and the back emf are zero. Hence the motor starting current is approximately the short-circuit current of the PV array. By matching the load to the PV source through MPPT, the starting torque increases.

The matching of a DC motor depends upon the type of load being used. For instance, a centrifugal pump is characterized by having the load torque proportional to the square of speed. The operating characteristics of the system (i.e. PV source, permanent magnet (PM) DC motor and load) are at the intersection of the motor and load characteristics as shown in Fig. 28.23 (i.e. points a, b, c, d, e, and f for centrifugal pump). From Fig. 28.23, the system utilizing the centrifugal pump as its load tends to start at low solar irradiation (point a) level. However, for the systems with an almost constant torque characteristics in Fig. 28.22, the start is at almost 50% of one sun (full insolation) which results in short period of operation.

28.2.3.3.2 Types of Motors There are various types of motors available for the PV water pumping applications:

- DC motors.
- AC motors.

DC motors are preferred where direct coupling to PV panels is desired whereas AC motors are coupled to the solar panels through inverters. AC motors in general are cheaper than the DC motors and are more reliable but the DC motors are more

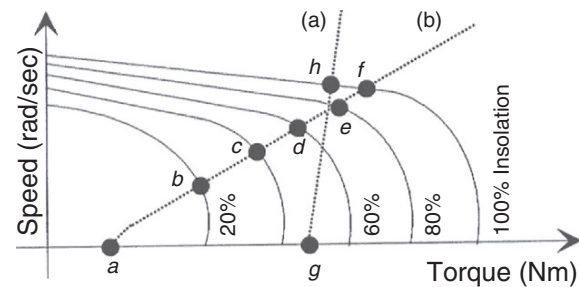


FIGURE 28.23 Speed torque characteristics of a DC motor and two mechanical loads: (a) helical rotor and (b) centrifugal pump.

efficient. The DC motors used for solar pumping applications are:

- Permanent magnet DC motors with brushes.
- Permanent DC magnet motors without brushes.

In DC motors with the brushes, the brushes are used to deliver power to the commutator and need frequent replacement due to wear and tear. These motors are not suitable for submersible applications unless long transmission shafts are used. Brush-less DC permanent magnet motors have been developed for submersible applications.

The AC motors are of the induction motor type, which is cheaper than DC motors and available, worldwide. However, they need inverters to change DC input from PV to AC power. A comparison of the different types of motors used for PV water pumping is given in Table 28.1.

TABLE 28.1 Comparison of the different types of motor used for PV water pumping

Types of motor	Advantages	Disadvantages	Main features
Brushed DC	Simple and efficient for PV applications. No complex control circuits is required as the motor starts without high current surge. These motors will run slowly but do not overheat with reduced voltage.	Brushes need to be replaced periodically (typical replacement interval is 2000–4000 hr or 2 years).	Requires MPPT for optimum performance. Available only in small motor sizes. Increasing current (by paralleling PV modules) increases the torque. Increasing voltage (by series PV modules) increases the speed.
Brush-less DC	Efficient. Less maintenance is required.	Electronic computation adds to extra cost, complexity, and increased risk of failure/malfunction. In most cases, oil cooled, can't be submerged as deep as water cooled AC units.	Growing trend among PV pump manufacturers to use brush-less DC motors, primarily for centrifugal type submersible pumps.
AC induction motors	No brushes to replace. Can use existing AC motor/pump technology which is cheaper and easily available worldwide. These motors can handle larger pumping requirements.	Needs an inverter to convert DC output from PV to AC adding additional cost and complexity. Less efficient than DC motor-pump units. Prone to overheating if current is not adequate to start the motor or if the voltage is too low.	Available for single or three supply. Inverters are designed to regulate frequency to maximize power to the motor in response to changing insolation levels.

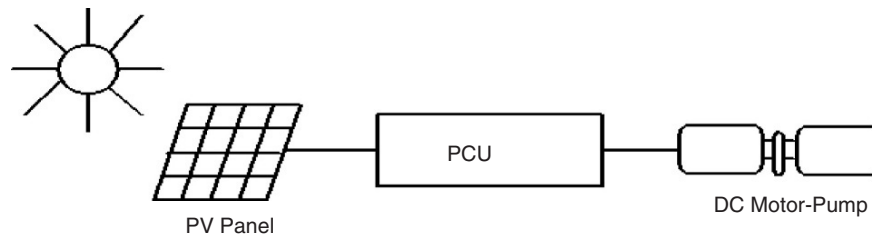


FIGURE 28.24 Block diagram for DC motor driven pumping scheme.

28.2.3.3.3 Power Conditioning Units for PV Water Pumping

Most PV pump manufacturers include power conditioning units (PCU) which are used for operating the PV panels close to their MPP over a range of load conditions and varying insolation levels and also for power conversion. DC or AC motor-pump units can be used for PV water pumping. In its simplest form, a solar water pumping system comprises of PV array, PCU, and DC water-pump unit as shown in Fig. 28.24.

In case of lower light levels, high currents can be generated through power conditioning to help in starting the motor-pump units especially for reciprocating positive displacement type pumps with constant torque characteristics, requiring constant current throughout the operating region. In positive displacement type pumps, the torque generated by the pumps depends on the pumping head, friction, and pipe diameter etc. and needs certain level of current to produce the necessary torque. Some systems use electronic controllers to assist starting and operation of the motor under low solar radiation. This is particularly important when using positive displacement pumps. The solar panels generate DC voltage and current. The solar water pumping systems usually has DC or AC pumps. For DC pumps, the PV output can be directly connected to the pump through MPPT or a DC–DC converter can also be used for interfacing for controlled DC output from PV panels. To feed the AC motors, a suitable interfacing is required for the power conditioning. These PV inverters for the stand-alone applications are very expensive. The aim of power conditioning equipment is to supply the controlled voltage/current output from the converters/inverters to the motor-pump unit.

These power-conditioning units are also used for operating the PV panels close to their maximum efficiency for fluctuating solar conditions. The speed of the pump is governed by the available driving voltage. Current lower than the acceptable limit will stop the pumping. When the light level increases, the operating point will shift from the MPP leading to the reduction of efficiency. For centrifugal pumps, there is an increase in current at increased speed and the matching of I – V characteristics is closer for wide range of light intensity levels. For centrifugal pumps, the torque is proportional to the square of speed and the torque produced by the motors is proportional to the current. Due to decrease in PV current output,

the torque from the motor and consequently the speed of the pump is reduced resulting in decrease in back emf and the required voltage of the motor. Maximum power point tracker can be used for controlling the voltage/current outputs from the PV inverters to operate the PV close to maximum operating point for the smooth operation of motor-pump units. The DC–DC converter can be used for keeping the PV panels output voltage constant and help in operating the solar arrays close to MPP. In the beginning, high starting current is required to produce high starting torque. The PV panels cannot supply this high starting current without adequate power conditioning equipment like DC–DC converter or by using a starting capacitor. The DC–DC converter can generate the high starting currents by regulating the excess PV array voltage. DC–DC converter can be boost or buck converter.

Brush-less DC motor (BDCM) and helical rotor pumps can also be used for PV water pumping [36]. Brush-less DC motors are a self synchronous type of motor characteristics by trapezoidal waveforms for back emf and air flux density. They can operate off a low voltage DC supply which is switched through an inverter to create a rotating stator field. The current generation of BDCMs use rare earth magnets on the rotor to give high air gap flux densities and are well suited to solar application. The block diagram of such an arrangement is shown in Fig. 28.25 which consists of PV panels, DC–DC converter, MPPT, and BDCM.

The PV inverters are used to convert the DC output of the solar arrays to the AC quantity so as to run the AC motors driven pumps. These PV inverters can be variable frequency type, which can be controlled to operate the motors over wide range of loads. The PV inverters may involve impedance matching to match the electrical characteristics of the load and array. The motor-pump unit and PV panels operate at their maximum efficiencies. Maximum power point tracker is also used in the power conditioning. To keep the voltage stable for the inverters, the DC–DC converter can be used. The inverter/converter has a capability of injecting high-switch frequency components, which can lead to the overheating and the losses. So care shall be taken for this. The PV arrays are usually connected in series, parallel, or a combination of series parallel, configurations. The function of power electronic interface, as mentioned before, is to convert the DC power from the array to the required voltage and frequency to drive the AC motors.

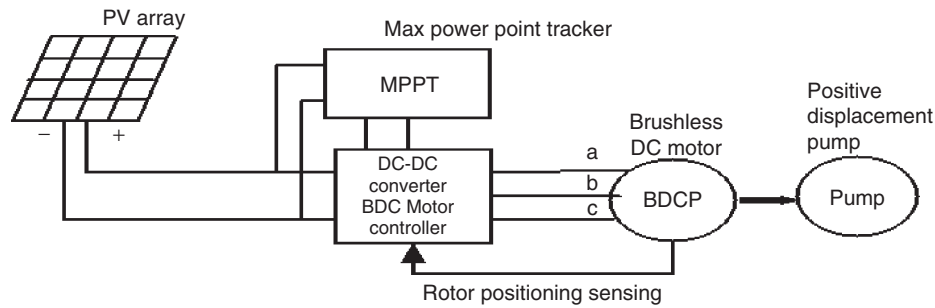


FIGURE 28.25 Block diagram for BDCM for PV application.

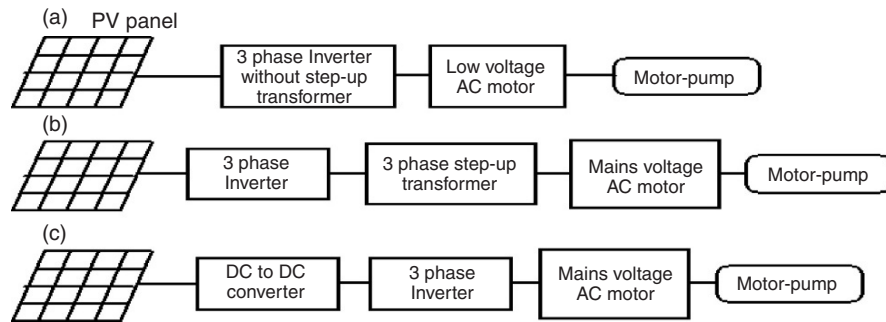


FIGURE 28.26 Block diagrams for various AC motor driven pumping schemes.

The motor-pump system load should be such that the array operates close to its MPP at all solar insolation levels. There are mainly three types solar powered water pumping systems as shown in Fig. 28.26.

The first system shown in Fig. 28.26a is an imported commercially available unit, which uses a specially wound low voltage induction motor driven submersible pump. Such a low voltage motor permits the PV array voltage to be converted to AC without using a step-up transformer. The second system, shown in Fig. 28.26b makes use of a conventional “off-the-shelf” 415 V, 50 Hz, induction motor [6]. This scheme needs a step-up transformer to raise inverter output voltage to high voltage. Third scheme as shown in Fig. 28.26c comprises of a DC–DC converter, an inverter that switches at high frequency, and a mains voltage motor driven pump. To get the optimum discharge (Q), at a given insolation level, the efficiency of the DC–DC converter and the inverter should be high. So the purpose should be to optimize the output from PV array, motor, and the pump. The principle used here is to vary the duty cycle of a DC–DC converter so that the output voltage is maximum. The DC–DC converter is used to boost the solar array voltage to eliminate the need for a step-up transformer and operate the array at the MPP. The three-phase inverter used in the interface is designed to operate in a variable frequency mode over the range of 20–50 Hz, which is the practical limit for most 50 Hz induction motor applications. Block diagram for frequency control is given in Fig. 28.27.

This inverter would be suitable for driving permanent magnet motors by incorporating additional circuitry for position sensing of the motor’s shaft. Also the inverter could be modified, if required, to produce higher output frequencies for high-speed permanent magnet motors. The inverter has a three-phase full-bridge configuration implemented by MOSFET power transistors.

28.2.4 Hybrid Energy Systems

The combination of RES, such as PV arrays or wind turbines, with engine-driven generators and battery storage, is widely recognized as a viable alternative to conventional remote area power supplies (RAPS). These systems are generally classified as hybrid energy systems (HES). They are used increasingly for electrification in remote areas where the cost of grid extension is prohibitive and the price for fuel increases drastically with the remoteness of the location. For many applications, the combination of renewable and conventional energy sources compares favorably with fossil fuel-based RAPS systems, both in regard to their cost and technical performance. Because these systems employ two or more different sources of energy, they enjoy a very high degree of reliability as compared to single-source systems such as a stand-alone diesel generator or a stand-alone PV or wind system. Applications of hybrid energy systems range from small power supplies for remote

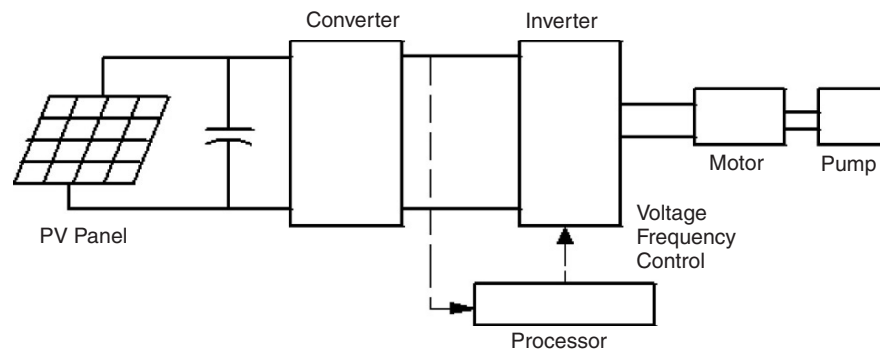


FIGURE 28.27 Block diagram for voltage/frequency control.

households, providing electricity for lighting and other essential electrical appliances, to village electrification for remote communities has been reported [37].

Hybrid energy systems generate AC electricity by combining RES such as PV array with an inverter, which can operate alternately or in parallel with a conventional engine-driven generator. They can be classified according to their configuration as [38]:

- Series hybrid energy systems.
- Switched hybrid energy systems.
- Parallel hybrid energy systems.

The parallel hybrid systems can be further divided to DC or AC coupling. An overview of the three most common system topologies is presented by Bower [39]. In the following comparison of typical PV-diesel system configurations are described.

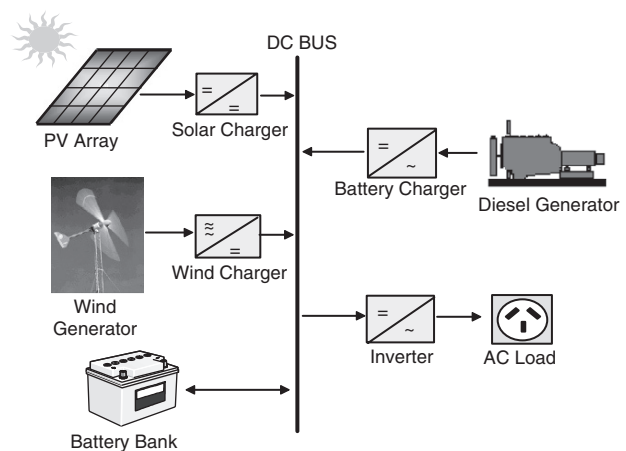


FIGURE 28.28 Series hybrid energy system.

28.2.4.1 Series Configuration

In the conventional series hybrid systems shown in Fig. 28.28, all power generators feed DC power into a battery. Each component has therefore to be equipped with an individual charge controller and in the case of a diesel generator with a rectifier.

To ensure reliable operation of series hybrid energy systems both the diesel generator and the inverter have to be sized to meet peak loads. This results in a typical system operation where a large fraction of the generated energy is passed through the battery bank, therefore resulting in increased cycling of the battery bank and reduced system efficiency. AC power delivered to the load is converted from DC to regulated AC by an inverter or a motor generator unit. The power generated by the diesel generator is first rectified and subsequently converted back to AC before being supplied to the load, which incurs significant conversion losses.

The actual load demand determines the amount of electrical power delivered by the PV array, wind generator, the battery bank, or the diesel generator. The solar and wind charger prevents overcharging of the battery bank from the PV generator

when the PV power exceeds the load demand and the batteries are fully charged. It may include MPPT to improve the utilization of the available PV energy, although the energy gain is marginal for a well-sized system. The system can be operated in manual or automatic mode, with the addition of appropriate battery voltage sensing and start/stop control of the engine-driven generator.

Advantages:

- The engine-driven generator can be sized to be optimally loaded while supplying the load and charging the battery bank, until a battery SOC of 70–80% is reached.
- No switching of AC power between the different energy sources is required, which simplifies the electrical output interface.
- The power supplied to the load is not interrupted when the diesel generator is started.
- The inverter can generate a sine-wave, modified square-wave, or square-wave depending on the application.

Disadvantages:

- The inverter cannot operate in parallel with the engine-driven generator, therefore the inverter must be sized to supply the peak load of the system.
- The battery bank is cycled frequently, which shortens its lifetime.
- The cycling profile requires a large battery bank to limit the depth-of-discharge (DOD).
- The overall system efficiency is low, since the diesel cannot supply power directly to the load.
- Inverter failure results in complete loss of power to the load, unless the load can be supplied directly from the diesel generator for emergency purposes.

28.2.4.2 Switched Configuration

Despite its operational limitations, the switched configuration remains one of the most common installations in some developing countries. It allows operation with either the engine-driven generator or the inverter as the AC source, yet no parallel operation of the main generation sources is possible. The diesel generator and the RES can charge the battery bank. The main advantage compared with the series system is that the load can be supplied directly by the engine-driven generator, which results in a higher overall conversion efficiency. Typically, the diesel generator power will exceed the load demand, with excess energy being used to recharge the battery bank. During periods of low electricity demand the diesel generator is switched off and the load is supplied from the PV array together with stored energy. Switched hybrid energy systems can be operated in manual mode, although the increased complexity of the system makes it highly desirable to include an automatic controller, which can be implemented with the addition of appropriate battery voltage sensing and start/stop control of the engine-driven generator (Fig. 28.29).

Advantages:

- The inverter can generate a sine-wave, modified square-wave, or square-wave, depending on the particular application.
- The diesel generator can supply the load directly, therefore improving the system efficiency and reducing the fuel consumption.

Disadvantages:

- Power to the load is interrupted momentarily when the AC power sources are transferred.
- The engine-driven alternator and inverter are typically designed to supply the peak load, which reduces their efficiency at part load operation.

28.2.4.3 Parallel Configuration

The parallel hybrid system can be further classified as DC and AC couplings as shown in Fig. 28.30. In both schemes, a bi-directional inverter is used to link between the battery and an AC source (typically the output of a diesel generator). The bi-directional inverter can charge the battery bank (rectifier operation) when excess energy is available from the diesel generator or by the renewable sources, as well as act as a DC–AC converter (inverter operation). The bi-directional inverter may also provide “peak shaving” as part of a control strategy when the diesel engine is overloaded. In Fig. 28.30a, the renewable energy sources (RES) such as photovoltaic and wind are coupled on the DC side. DC integration of RES results in “custom” system solutions for individual supply cases requiring high costs for engineering, hardware, repair, and maintenance. Furthermore, power system expandability for covering needs of growing energy and power demand is also difficult. A better approach would be to integrate the RES on the AC side rather than on the DC side as shown in Fig. 28.30b.

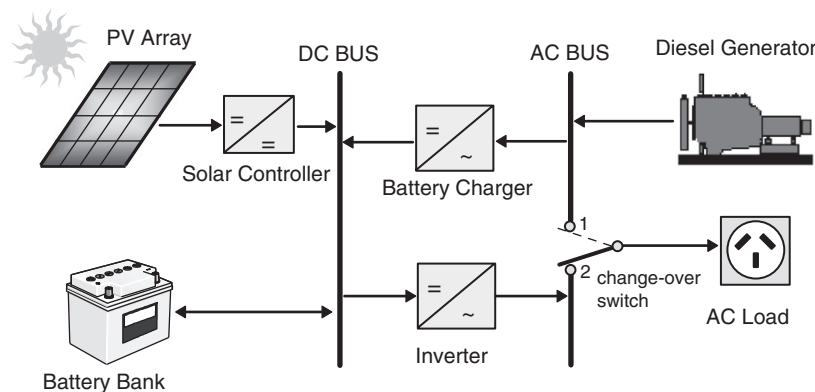


FIGURE 28.29 Switched PV-diesel hybrid energy system.

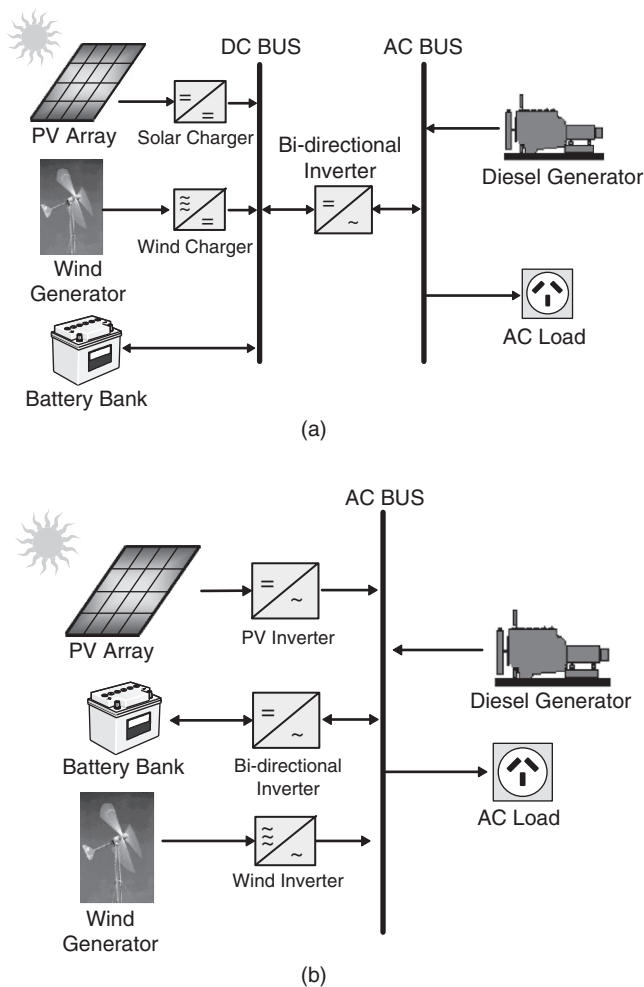


FIGURE 28.30 Parallel PV-diesel hybrid energy system: (a) DC decoupling and (b) AC coupling.

Parallel hybrid energy systems are characterized by two significant improvements over the series and switched system configuration.

The inverter plus the diesel generator capacity rather than their individual component ratings limit the maximum load that can be supplied. Typically, this will lead to a doubling of the system capacity. The capability to synchronize the inverter with the diesel generator allows greater flexibility to optimize the operation of the system. Future systems should be sized with a reduced peak capacity of the diesel generator, which results in a higher fraction of directly used energy and hence higher system efficiencies.

By using the same power electronic devices for both inverter and rectifier operation, the number of system components is minimized. Additionally, wiring and system installation costs are reduced through the integration of all power-conditioning devices in one central power unit. This highly integrated system concept has advantages over a more modular approach to

system design, but it may prevent convenient system upgrades when the load demand increases.

The parallel configuration offers a number of potential advantages over other system configurations. These objectives can only be met if the interactive operation of the individual components is controlled by an “intelligent” hybrid energy management system. Although today’s generation of parallel systems include system controllers of varying complexity and sophistication, they do not optimize the performance of the complete system. Typically, both the diesel generator and the inverter are sized to supply anticipated peak loads. As a result most parallel hybrid energy systems do not utilize their capability of parallel, synchronized operation of multiple power sources.

Advantages:

- The system load can be met in an optimal way.
- Diesel generator efficiency can be maximized.
- Diesel generator maintenance can be minimized.
- A reduction in the rated capacities of the diesel generator, battery bank, inverter, and renewable resources is feasible, while also meeting the peak loads.

Disadvantages:

- Automatic control is essential for the reliable operation of the system.
- The inverter has to be a true sine-wave inverter with the ability to synchronize with a secondary AC source.
- System operation is less transparent to the untrained user of the system.

28.2.4.4 Control of Hybrid Energy Systems

The design process of hybrid energy systems requires the selection of the most suitable combination of energy sources, power-conditioning devices, and energy storage system together with the implementation of an efficient energy dispatch strategy. System simulation software is an essential tool to analyze and compare possible system combinations. The objective of the control strategy is to achieve optimal operational performance at the system level. Inefficient operation of the diesel generator and “dumping” of excess energy is common for many RAPS, operating in the field. Component maintenance and replacement contributes significantly to the lifecycle cost of systems. These aspects of system operation are clearly related to the selected control strategy and have to be considered in the system design phase.

Advanced system control strategies seek to reduce the number of cycles and the DOD for the battery bank, run the diesel generator in its most efficient operating range, maximize the utilization of the renewable resource, and ensure high reliability of the system. Due to the varying nature of the load demand, the fluctuating power supplied by the photovoltaic generator, and the resulting variation of battery SOC, the hybrid energy system controller has to respond to continuously

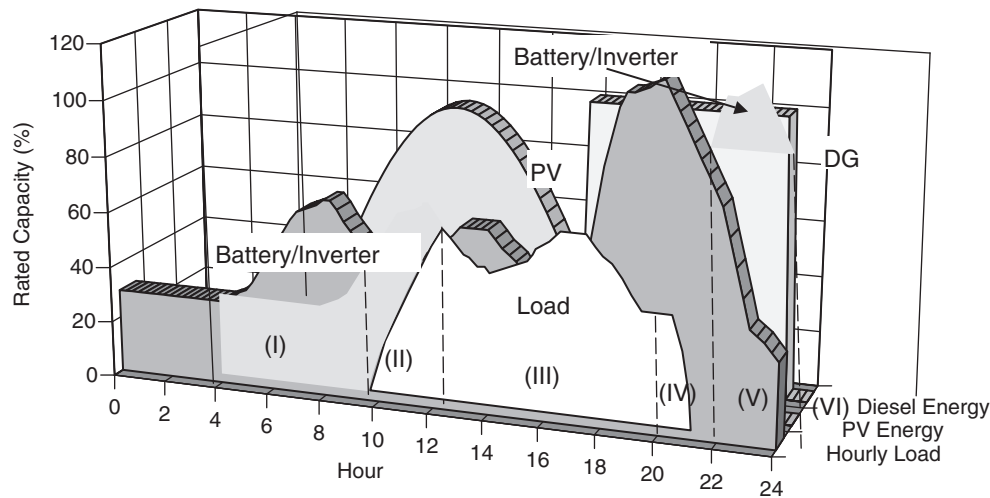


FIGURE 28.31 Operating modes for a PV single-diesel hybrid energy system.

changing operating conditions. Figure 28.31 shows different operating modes for a PV single-diesel system using a typical diesel dispatch strategy.

- Mode (I): The base load, which is typically experienced at nighttime and during the early morning hours, is supplied by energy stored in the batteries. Photovoltaic power is not available and the diesel generator is not started.
- Mode (II): PV power is supplemented by stored energy to meet the medium load demand.
- Mode (III): Excess energy is available from the PV generator, which is stored in the battery. The medium load demand is supplied from the PV generator.
- Mode (IV): The diesel generator is started and operated at its nominal power to meet the high evening load. Excess energy available from the diesel generator is used to recharge the batteries.
- Mode (V): The diesel generator power is insufficient to meet the peak load demand. Additional power is supplied from the batteries by synchronizing the inverter AC output voltage with the alternator waveform.
- Mode (VI): The diesel generator power exceeds the load demand, but it is kept operational until the batteries are recharged to a high SOC level.

In principle, most efficient operation is achieved if the generated power is supplied directly to the load from all energy sources, which also reduces cycling of the battery bank. However, since diesel generator operation at light loads is inherently inefficient, it is common practice to operate the engine-driven generator at its nominal power rating and to recharge the batteries from the excess energy. The selection of the most efficient control strategy depends on fuel, maintenance and component replacement cost, the system configuration, environmental conditions, as well as constraints imposed on the operation of the hybrid energy system.

28.2.5 Grid-connected PV Systems

The utility interactive inverters not only conditions the power output of the PV arrays but ensures that the PV system output is fully synchronized with the utility power. These systems can be battery less or with battery backup. Systems with battery storage (or flywheel) provide additional power supply reliability. The grid connection of PV systems is gathering momentum because of various rebate and incentive schemes. This system allows the consumer to feed its own load utilizing the available solar energy and the surplus energy can be injected into the grid under the energy by back scheme to reduce the payback period. Grid-connected PV systems can become a part of the utility system. The contribution of solar power depends upon the size of system and the load curve of the house. When the PV system is integrated with the utility grid, a two-way power flow is established. The utility grid will absorb excess PV power and will feed the house during nighttime and at instants while the PV power is inadequate. The utility companies are encouraging this scheme in many parts of the world. The grid-connected system can be classified as:

- Rooftop application of grid-connected PV system.
- Utility scale large system.

For small household PV applications, a roof mounted PV array can be the best option. Solar cells provide an environmentally clean way of producing electricity, and rooftops have always been the ideal place to put them. With a PV array on the rooftop, the solar generated power can supply residential load. The rooftop PV systems can help in reducing the peak summer load to the benefit of utility companies by feeding the household lighting, cooling, and other domestic loads. The battery storage can further improve the reliability of the system at the time of low insolation level, nighttime,

or cloudy days. But the battery storage has some inherent problems like maintenance and higher cost.

For roof-integrated applications, the solar arrays can be either mounted on the roof or directly integrated into the roof. If the roof integration does not allow for an air channel behind the PV modules for ventilation purpose, then it can increase the cell temperature during the operation consequently leading to some energy losses. The disadvantage with the rooftop application is that the PV array orientation is dictated by the roof. In case, when the roof orientation differs from the optimal orientation required for the cells, then efficiency of the entire system would be suboptimal.

Utility interest in PV has centered on the large grid-connected PV systems. In Germany, USA, Spain, and in several other parts of the world, some large PV scale plants have been installed. The utilities are more inclined with large scale, centralized power supply. The PV systems can be centralized or distributed systems.

Grid-connected PV systems must observe the islanding situation, when the utility supply fails. In case of islanding, the PV generators should be disconnected from mains. PV generators can continue to meet only the local load, if the PV output matches the load. If the grid is re-connected during islanding, transient overcurrents can flow through the PV system inverters and the protective equipments like circuit breakers may be damaged. The islanding control can be achieved through inverters or via the distribution network. Inverter controls can be designed on the basis of detection of grid voltage, measurement of impedance, frequency variation, or increase in harmonics. Protection shall be designed for the islanding, short circuits, over/under-voltages/currents, grounding, and lightning, etc.

The importance of the power generated by the PV system depends upon the time of the day specially when the utility is experiencing the peak load. The PV plants are well suited to summer peaking but it depends upon the climatic condition of the site. PV systems being investigated for use as peaking stations would be competitive for load management. The PV users can defer their load by adopting load management to get the maximum benefit out of the grid-connected PV plants and feeding more power into the grid at the time of peak load.

The assigned capacity credit is based on the statistical probability with which the grid can meet peak demand [4]. The capacity factor during the peaks is very similar to that of conventional plants and similar capacity credit can be given for the PV generation except at the times when the PV plants are generating very less power unless adequate storage is provided. With the installation of PV plants, the need of extra transmission lines, transformers can be delayed or avoided. The distributed PV plants can also contribute in providing reactive power support to the grid and reduce burden on VAR compensators.

28.2.5.1 Inverters for Grid-connected Applications

Power conditioner is the key link between the PV array and mains in the grid-connected PV system. It acts as an interface that converts DC current produced by the solar cells into utility grade AC current. The PV system behavior relies heavily on the power-conditioning unit. The inverters shall produce good quality sine-wave output. The inverter must follow the frequency and voltage of the grid and the inverter has to extract maximum power from the solar cells with the help of MPPT and the inverter input stage varies the input voltage until the MPP on the I - V curve is found. The inverter shall monitor all the phases of the grid. The inverter output shall be controlled in terms of voltage and frequency variation. A typical grid-connected inverter may use a PWM scheme and operates in the range of 2–20 kHz.

28.2.5.2 Inverter Classifications

The inverters used for the grid interfacing are broadly classified as:

- Voltage source inverters (VSI).
- Current source inverters (CSI).

Whereas the inverters based on the control schemes can be classified as:

- Current controlled (CC).
- Voltage controlled (VC).

The source is not necessarily characterized by the energy source for the system. It is a characteristic of the topology of the inverter. It is possible to change from one source type to another source type by the addition of passive components. In the voltage source inverter (VSI), the DC side is made to appear to the inverter as a voltage source. The VSIs have a capacitor in parallel across the input whereas the CSIs have an inductor in series with the DC input. In the CSI, the DC source appears as a current source to the inverter. Solar arrays are fairly good approximation to a current source. Most PV inverters are voltage source even though the PV is a current source. Current source inverters are generally used for large motor drives though there have been some PV inverters built using a current source topology. The VSI is more popular with the PWM VSI dominating the sine-wave inverter topologies.

Figure 28.32a shows a single-phase full-bridge bi-directional VSI with (a) voltage control and phase-shift (δ) control – voltage-controlled voltage source inverter (VCVSI). The active power transfer from the PV panels is accomplished by controlling the phase angle δ between the converter voltage and the grid voltage. The converter voltage follows the grid voltage. Figure 28.32b shows the same VSI operated as a current controlled (CCVSI). The objective of this scheme is to control active and reactive components of the current fed into the grid using PWM techniques.

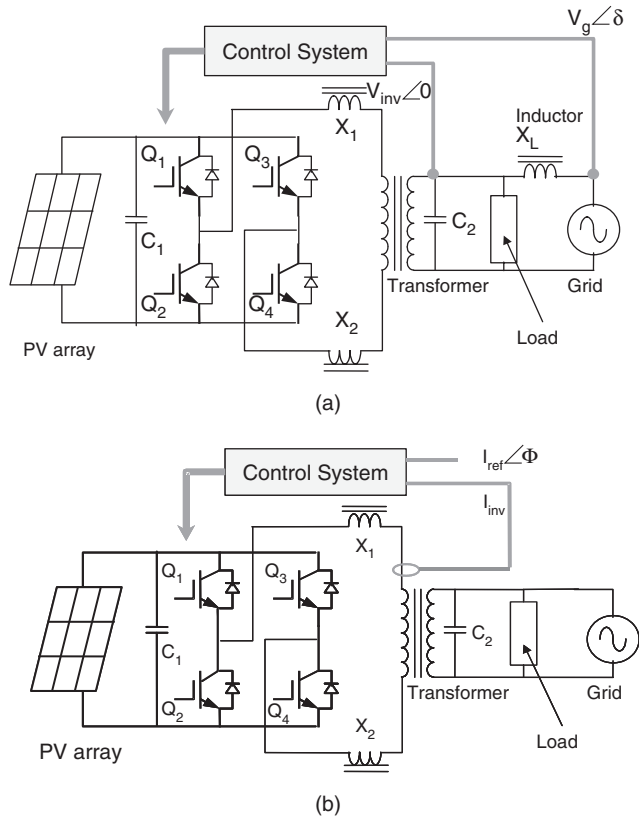


FIGURE 28.32 Voltage source inverter: (a) voltage control and (b) current control.

28.2.5.3 Inverter Types

Different types are being in use for the grid-connected PV applications such as:

- Line-commutated inverter.
- Self-commutated inverter.
- Inverter with high-frequency transformer.

28.2.5.3.1 Line-commutated Inverter The line-commutated inverters are generally used for the electric motor applications. The power stage is equipped with thyristors. The maximum

power tracking control is required in the control algorithm for solar application. The basic diagram for a single-phase line-commutated inverter is shown in the Fig. 28.33 [3].

The driver circuit has to be changed to shift the firing angle from the rectifier operation ($0 < \phi < 90$) to inverter operation ($90 < \phi < 180$). Six-pulse or 12-pulse inverter are used for the grid interfacing but 12-pulse inverters produce less harmonics. The thyristor type inverters require a low impedance grid interface connection for commutation purpose. If the maximum power available from the grid connection is less than twice the rated PV inverter power, then the line-commutated inverter should not be used [3]. The line-commutated inverters are cheaper but inhibits poor power quality. The harmonics injected into the grid can be large unless taken care of by employing adequate filters. These line-commutated inverters also have poor power factor, poor power quality, and need additional control to improve the power factor. Transformer can be used to provide the electrical isolation. To suppress the harmonics generated by these inverters, tuned filters are employed and reactive power compensation is required to improve the lagging power factor.

28.2.5.3.2 Self-commutated Inverter A switch mode inverter using pulse width modulated (PWM) switching control, can be used for the grid connection of PV systems. The basic block diagram for this type of inverter is shown in the Fig. 28.34. The inverter bridges may consist of bipolar transistors, MOSFET transistors, IGBT's, or gate turn-off thyristor's (GTO's), depending upon the type of application. GTO's are used for the higher power applications, whereas IGBT's can be switched at higher frequencies i.e. 16 kHz, and are generally used for many grid-connected PV applications. Most of the present day inverters are self-commutated sine-wave inverters.

Based on the switching control, the voltage source inverters can be further classified based on the switching control as:

- PWM (pulse width modulated) inverters.
- Square-wave inverters.
- Single-phase inverters with voltage cancellations.
- Programmed harmonic elimination switching.
- Current controlled modulation.

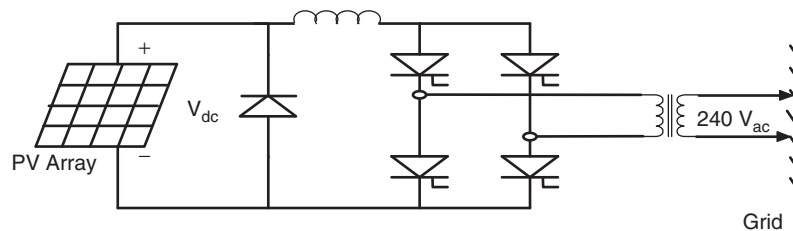


FIGURE 28.33 Line-commutated single-phase inverter.

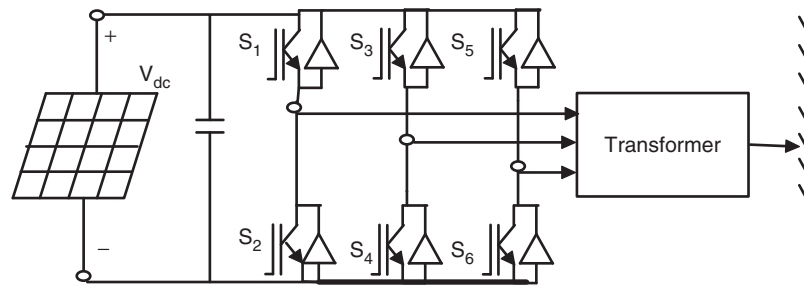


FIGURE 28.34 Self-commutated inverter with PWM switching.

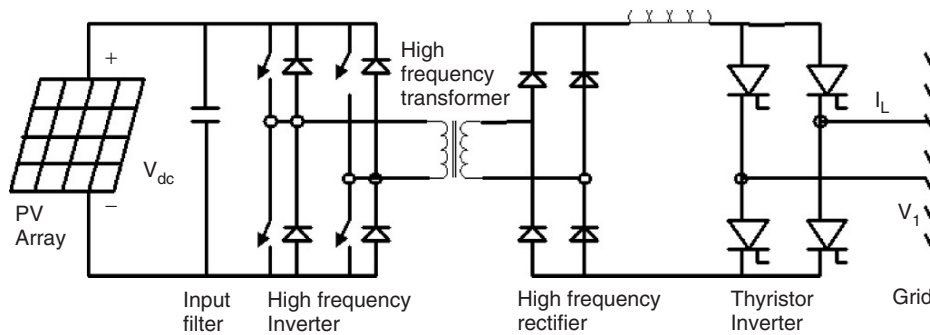


FIGURE 28.35 PV inverter with high frequency transformer.

28.2.5.3.3 Inverter with High-frequency Transformer The 50 Hz transformer for a standard PV inverter with PWM switching scheme can be very heavy and costly. While using frequencies more than 20 kHz, a ferrite core transformer can be a better option [3]. A circuit diagram of a grid-connected PV system using high frequency transformer is shown in the Fig. 28.35.

The capacitor on the input side of high frequency inverter acts as the filter. The high frequency inverter with PWM is used to produce a high frequency AC across the primary winding of the high frequency transformer. The secondary voltage of this transformer is rectified using high frequency rectifier. The DC voltage is interfaced with a thyristor inverter through low-pass inductor filter and hence connected to the grid. The line current is required to be sinusoidal and in phase with the line voltage. To achieve this, the line voltage (V_1) is measured to establish the reference waveform for the line current I_L^* . This reference current I_L^* multiplied by the transformer ratio gives the reference current at the output of high frequency inverter. The inverter output can be controlled using current control technique [40]. These inverters can be with low frequency transformer isolation or high frequency transformer isolation. The low frequency (50/60 Hz) transformer of a standard inverter with PWM is a very heavy and bulky component. For residential grid interactive rooftop inverters below 3 kW rating, high frequency transformer isolation is often preferred.

28.2.5.3.4 Other PV Inverter Topologies In this section, some of the inverter topologies discussed in various research papers have been discussed.

A. Multilevel Converters

Multilevel converters can be used with large PV systems where multiple PV panels can be configured to create voltage steps. These multilevel voltage-source converters can synthesize the AC output terminal voltage from different level of DC voltages and can produce staircase waveforms. This scheme involves less complexity, and needs less filtering. One of the schemes (half-bridge diode-clamped three level inverter [41]) is given in Fig. 28.36. There is no transformer in this topology. Multilevel converters can be beneficial for large systems in terms of cost and efficiency. Problems associated with shading and malfunction of PV units need to be addressed.

B. Non-insulated Voltage Source

In this scheme [42], string of low voltage PV panels or one high-voltage unit can be coupled with the grid through DC to DC converter and voltage-source inverter. This topology is shown in Fig. 28.37. PWM-switching scheme can be used to generate AC output. Filter has been used to reject the switching components.

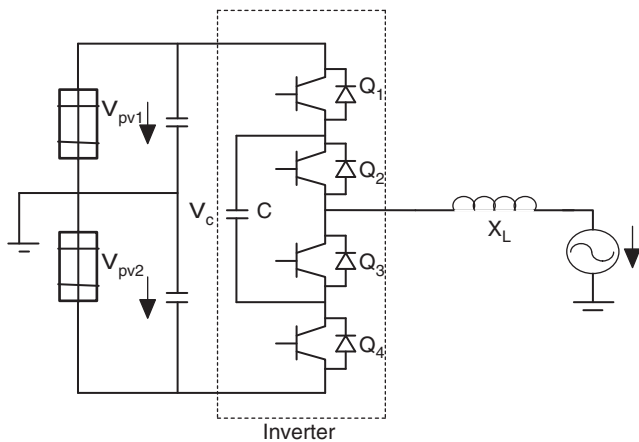


FIGURE 28.36 Half-bridge diode-clamped three-level inverter.

C. Non-insulated Current Source

This type of configuration is shown in Fig. 28.38. Non-insulated current-source inverters [42] can be used to interface the PV panels with the grid. This topology involves low cost which can provide better efficiency. Appropriate controller can be used to reduce current harmonics.

D. Buck Converter with Half-bridge Transformer Link

PV panels are connected to grid via buck converter and half bridge as shown in Fig. 28.39. In this, high-frequency PWM switching has been used at the low-voltage PV side to generate an attenuated rectified 100 Hz sine-wave current waveform [43]. Half-wave bridge is utilized to convert this output to 50 Hz signal suitable for grid interconnection. To step up the voltage, transformer has also been connected before the grid connection point.

E. Flyback Converter

This converter topology steps up the PV voltage to DC bus voltage. Pulse width modulation operated converter has been used for grid connection of PV system (Fig. 28.40).

This scheme is less complex and has less number of switches. Flyback converters can be beneficial for remote areas due to less complex power conditioning components.

F. Interface Using Paralleled PV Panels

Low voltage AC bus scheme [44] can be comparatively efficient and cheaper option. One of the schemes is shown in Fig. 28.41. A number of smaller PV units can be paralleled together and then connected to combine single low-frequency transformer. In this scheme, the PV panels are connected in parallel rather than series to avoid problems associated with shading or malfunction of one of the panels in series connection.

28.2.5.4 Power Control through PV Inverters

The system shown in Fig. 28.42 shows control of power flow on to the grid [45]. This control can be an analog or a microprocessor system. This control system generates the waveforms and regulates the waveform amplitude and phase to control the power flow between the inverter and the grid. The grid-interfaced PV inverters, voltage-controlled VSI (VCVSI), or current-controlled VSI (CCVSI) have the potential of bi-directional power flow. They cannot only feed the local load but also can export the excess active and reactive power to the utility grid. An appropriate controller is required in order to avoid any error in power export due to errors in synchronization, which can overload the inverter.

There are advantages and limitations associated with each control mechanism. For instance, VCVSIs provide voltage support to the load (here the VSI operates as a voltage source), while CCVSIs provide current support (here the VSI operates as a current source). The CCVSI is faster in response compared to the VCVSI, as its power flow is controlled by the switching instant, whereas in the VCVSI the power flow is controlled by adjusting the voltage across the decoupling inductor. Active and reactive power are controlled independently in the CCVSI, but are coupled in the VCVSI. Generally, the advantages of one type of VSI are considered as a limitation of the other type [46].

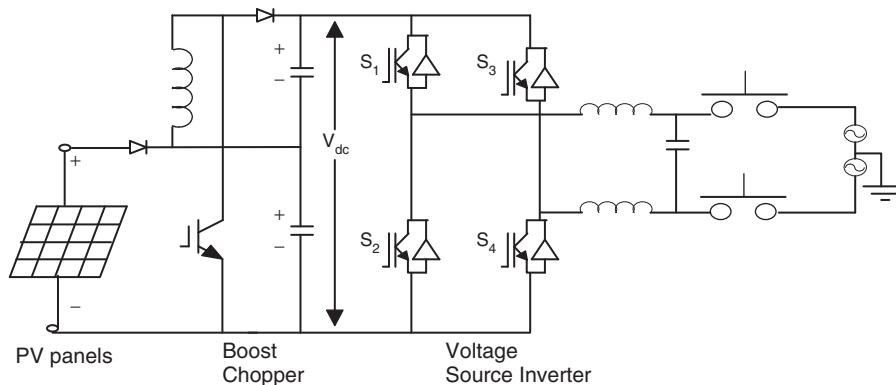


FIGURE 28.37 Non-insulated voltage source.

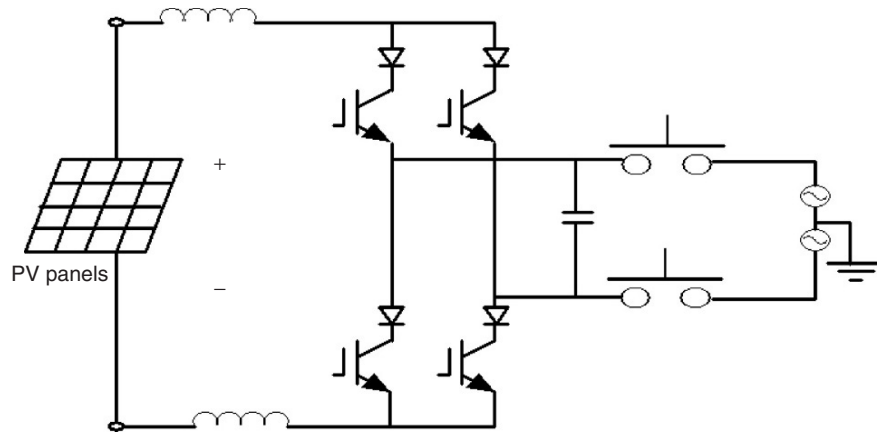


FIGURE 28.38 Non-insulated current source.

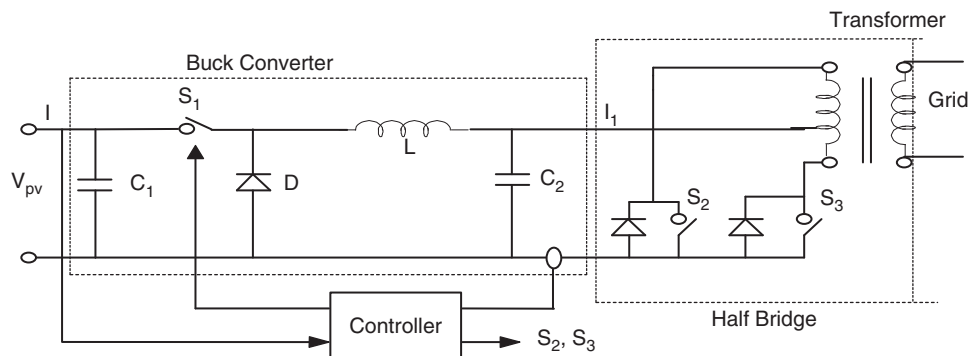


FIGURE 28.39 Buck converter with half-bridge transformer link.

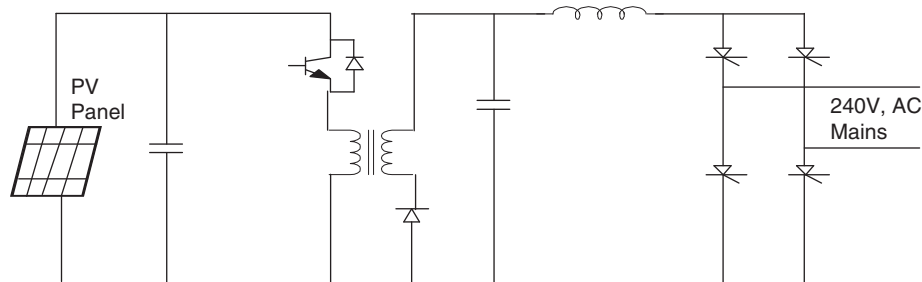


FIGURE 28.40 Flyback converter.

Figure 28.43 shows the simplified/equivalent schematic diagram of a VCVSI. For the following analysis it is assumed that the output low-pass filters (L_f and C_f) of VSIs will filter out high-order harmonics generated by PWMs. The decoupling inductor (X_m) is an essential part of any VCVSI as it makes the power flow control possible. In a VCVSI, the power flow of the distributed generation system (DGS) is controlled by adjusting the amplitude and phase (power angle (δ)) of the inverter output voltage with respect to the grid voltage. Hence, it is important to consider the proper sizing of the decoupling inductor and the maximum power angle to provide the required power flow when designing VCVSIs. The phasor

diagram of a simple grid-inverter interface with a first-order filter are shown in Fig. 28.44.

Referring to Fig. 28.43, the fundamental grid current (I_g) can be expressed by Eq. (28.7):

$$I_g = \frac{V_g \angle 0 - V_c \angle \delta}{jX_m} = -\frac{V_c \sin \delta}{X_m} - j \frac{V_g - V_c \cos \delta}{X_m} \quad (28.7)$$

where V_g and V_c are respectively the grid and the VCVSI's fundamental voltages, and X_m is the decoupling inductor impedance. Using per unit values ($S_{base} = V_{base}^2/Z_{base}$,

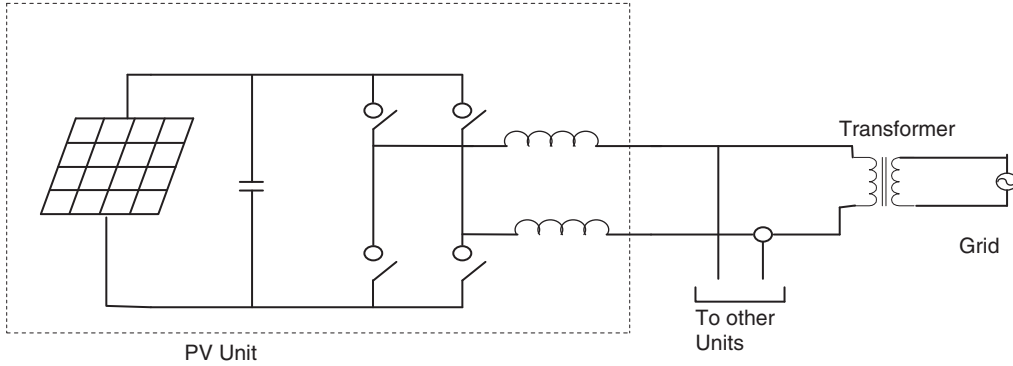


FIGURE 28.41 Converter using parallel PV units.

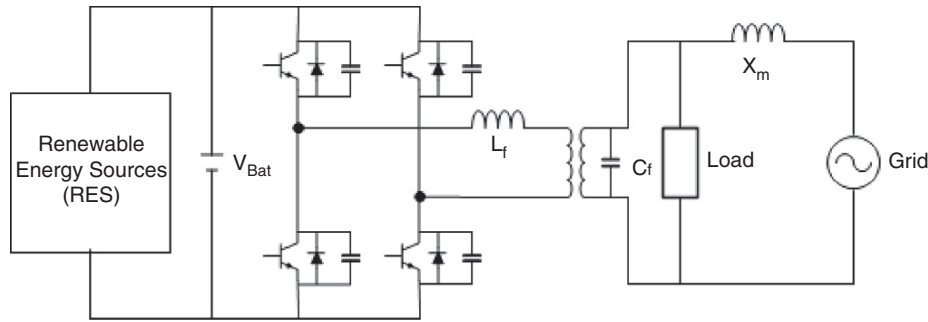


FIGURE 28.42 Schematic diagram of a parallel processing DGS.

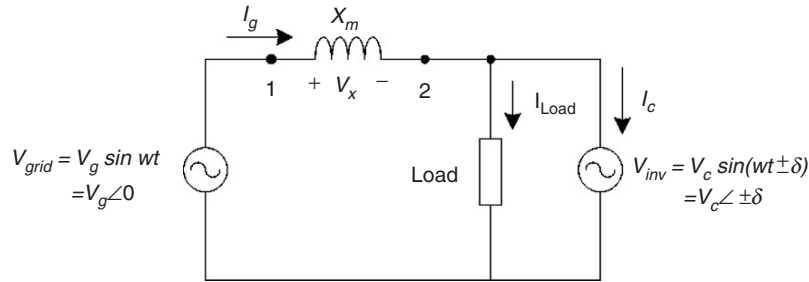


FIGURE 28.43 The equivalent circuit diagram of a VCVSI.

$V_{base} = V_c$, and $Z_{base} = X_m$) where V_{base} , Z_{base} , and S_{base} are the base voltage, impedance and complex power values respectively. The grid apparent power can be expressed as Eq. (28.8).

$$S_{gpu} = -V_{gpu} \sin \delta + j(V_{gpu}^2 - V_{gpu} \cos \delta) \quad (28.8)$$

Using per unit values, the complex power of the VCVSI and decoupling inductor are

$$S_{cpu} = -V_{gpu} \sin \delta + j(V_{gpu} \cos \delta - 1) \quad (28.9)$$

$$S_{xpu} = j(V_{gpu}^2 - 2V_{gpu} \cos \delta + 1) \quad (28.10)$$

where S_{gpu} , S_{cpu} , and S_{xpu} are per unit values of the grid, VCVSI, and decoupling inductor apparent power respectively, and V_{gpu} is the per unit value of the grid voltage.

Figure 28.45 shows the equivalent schematic diagram of a CCSI. As a CCSI controls the current flow using the VSI switching instants, it can be modeled as a current source and there is no need for a decoupling inductor (Fig. 28.45). As the current generated from the CCSI can be controlled independently from the AC voltage, the active and reactive power controls are decoupled. Hence, unity power factor operation is possible for the whole range of the load. This is one of the main advantages of CCSI.

As the CCSI is connected in parallel to the DGS, it follows the grid voltage. Figure 28.46 shows the phasor diagram of a

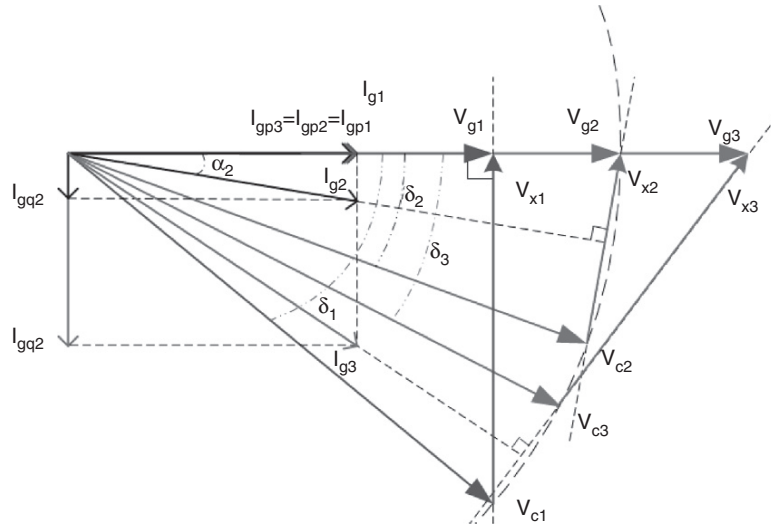


FIGURE 28.44 Phasor diagram of a VCVSI with resistive load and assuming the grid is responsible for supplying the active power [46].

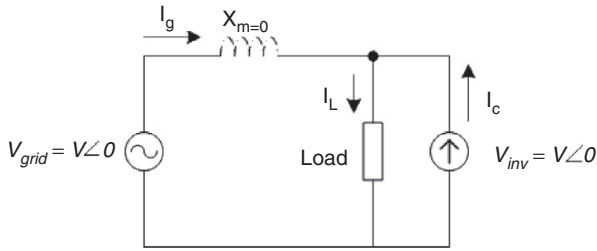


FIGURE 28.45 The equivalent circuit of a CCVSI.

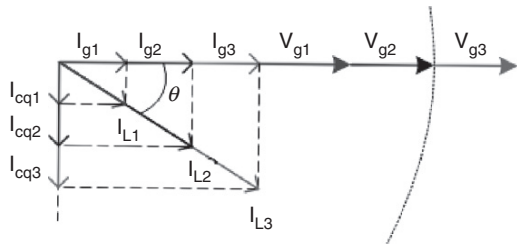


FIGURE 28.46 Phasor diagram of a CCVSI with inductive load and assuming grid is responsible for supplying the active power [46].

CCVSI based DGS in the presence of an inductive load (considering the same assumption as VCVSI section). Figure 28.49 shows that when the grid voltage increases, the load's active power consumption, which supplied by the grid increases and the CCVSI compensates the increase in the load reactive power demand. In this case, the CCVSI maintains grid supply at unity power factor, keeping the current phase delay with respect to the grid voltage at a fixed value (θ). Therefore, the CCVSI cannot maintain the load voltage in the presence of a DGS without

utilizing extra hardware and control mechanisms. This limitation on load voltage stabilization is one of the main drawbacks of CCVSI based DGS.

Assuming the load active current demand is supplied by the grid (reactive power support function), the required grid current can be rewritten as follows

$$I_g^* = \text{Re}[I_L] = \text{Re}\left[\frac{S_L}{V_g}\right] \quad (28.11)$$

where, S_L is the demanded load apparent power. For grid power conditioning, it is preferred that the load operate at unity power factor. Therefore, the CCVSI must provide the remainder of the required current Eq. (28.12)

$$I_c = I_L - I_g^* \quad (28.12)$$

For demand side management (DSM), it is desirable to supply the active power by the RES, where excess energy from the RES is injected into the DGS. The remaining load reactive power will be supplied by the CCVSI. Hence Eq. (28.12) can be rewritten as Eq. (28.13).

$$I_g^* = \text{Re}[I_L] - \text{Re}[I_c] = \text{Re}\left[\frac{S_L - P_{RES}}{V_g}\right] \quad (28.13)$$

When using a voltage controller for grid-connected PV inverter, it has been observed that a slight error in the phase of synchronizing waveform can grossly overload the inverter whereas a current controller is much less susceptible to voltage phase shifts [45]. Due to this reason, the current controllers are better suited for the control of power export from the PV inverters to the utility grid since they are less sensitive to errors in synchronizing sinusoidal voltage waveforms.

A prototype current-controlled type power conditioning system has been developed by the first author and tested on a weak rural feeder line at Kalbarri in Western Australia [47]. The choice may be between additional conventional generating capacity at a centralized location or adding smaller distributed generating capacities using RES like PV. The latter option can have a number of advantages like:

- The additional capacity is added wherever it is required without adding additional power distribution infrastructure. This is a critical consideration where the power lines and transformers are already at or close to their maximum ratings.
- The power conditioning system can be designed to provide much more than just a source of real power, for minimal extra cost. A converter providing real power needs only a slight increase in ratings to handle significant amounts of reactive or even harmonic power. The same converter that converts DC PV power to AC power can simultaneously provide the reactive power support to the weak utility grid.

The block diagram of the power conditioning system used in the Kalbarri project has been shown in the Fig. 28.47. This CCVSI operates with a relatively narrow switching frequency band near 10 kHz. The control diagram indicates the basic operation of the power conditioning system. The two outer control loops operate to independently control the real and reactive power flow from the PV inverter. The real power is controlled by an outer MPPT algorithm with an inner DC link voltage control loop providing the real current magnitude request I_p^* and hence the real power export through PV converter is controlled through the DC link voltage regulation. The DC link voltage is maintained at a reference value by a PI control loop, which gives the real current reference magnitude as its output. At regular intervals, the DC link voltage is scanned over the entire voltage range to check that the algorithm is operating on the absolute MPP and is not stuck around a local MPP. During the night, the converter can still be

used to regulate reactive power of the grid-connected system although it cannot provide active power. During this time, the PI controller maintain a minimum DC link voltage to allow the power conditioning system to continue to operate, providing the necessary reactive power.

The AC line voltage regulation is provided by a separate reactive power control, which provides the reactive current magnitude reference I_Q^* . The control system has a simple transfer function, which varies the reactive power command in response to the AC voltage fluctuations. Common to the outer real and reactive power control loops is an inner higher bandwidth zero average current error (ZACE) current control loop. I_p^* is in phase with the line voltages, and I_Q^* is at 90° to the line voltage. These are added together to give one (per phase) sinusoidal converter current reference waveform (I_{ac}^*). The CCVSI control consists of analog and digital circuitry which acts as a ZACE transconductance amplifier in converting I_{ac}^* into AC power currents [48].

28.2.5.5 System Configurations

The utility compatible inverters are used for power conditioning and synchronization of PV output with the utility power. In general, four types of battery-less grid-connected PV system configurations have been identified:

- Central plant inverter.
- Multiple string DC/DC converter with single output inverter.
- Multiple string inverter.
- Module integrated inverter.

28.2.5.5.1 Central Plant Inverter In the central plant inverter, usually a large inverter is used to convert DC power output of PV arrays to AC power. In this system, the PV modules are serially stringed to form a panel (or string) and several such panels are connected in parallel to a single DC bus. The block diagram of such a scheme is shown in Fig. 28.48.

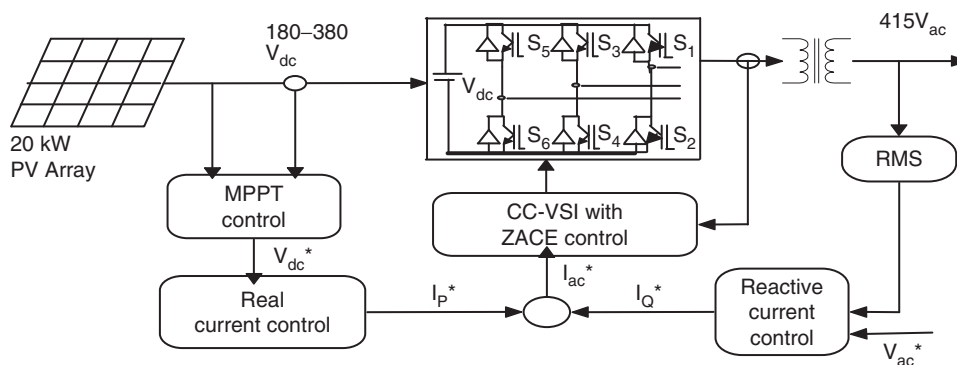


FIGURE 28.47 Block diagram of Kalbarri power conditioning system.

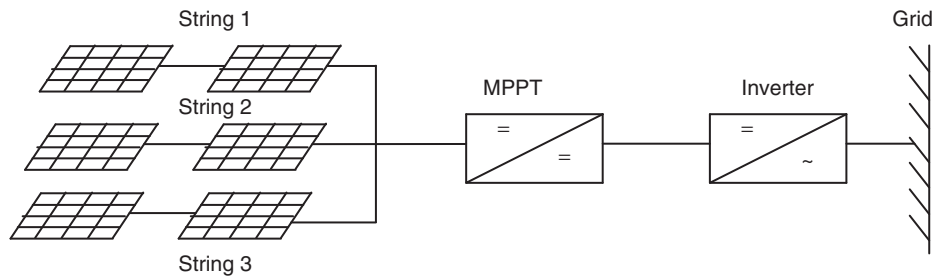


FIGURE 28.48 Central plant inverter.

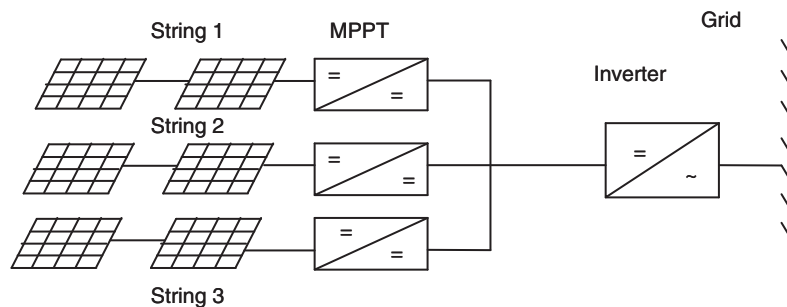


FIGURE 28.49 Multiple string DC/DC converter.

28.2.5.5.2 Multiple String DC/DC Converter In multiple string DC/DC converter, as shown in Fig. 28.49, each string will have a boost DC/DC converter with transformer isolation. There will be a common DC link, which feeds a transformer-less inverter.

28.2.5.5.3 Multiple String Inverters Figure 28.50 shows the block diagram of multiple string inverter system. In this scheme, several modules are connected in series on the DC side to form a string. The output from each string is converted to AC through a smaller individual inverter. Many such inverters are connected in parallel on the AC side. This arrangement is not badly affected by the shading of the panels. It is also not seriously affected by inverter failure.

28.2.5.5.4 Module Integrated Inverter In the module integrated inverter system (Fig. 28.51), each module (typically 50–300 W) will have a small inverter. No cabling is required. It is expected that high volume of small inverters will bring down the cost.

28.2.5.6 Grid-compatible Inverters Characteristics

The characteristics of the grid-compatible inverters are:

- Response time.
- Power factor.
- Frequency control.
- Harmonic output.
- Synchronization.
- Fault current contribution.

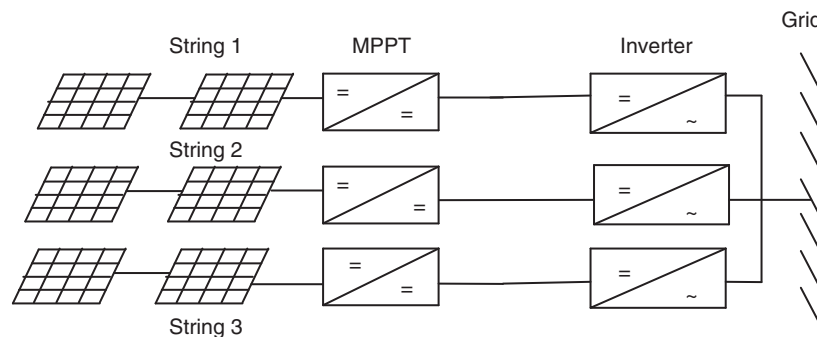


FIGURE 28.50 Multiple string inverter.

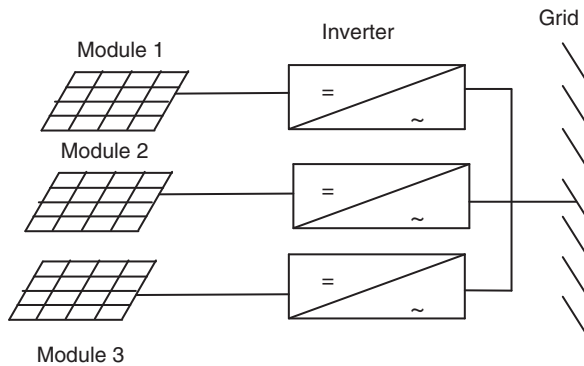


FIGURE 28.51 Module integrated inverter.

- DC current injection.
- Protection.

The response time of the inverters shall be extremely fast and governed by the bandwidth of the control system. Absence of rotating mass and use of semiconductor switches allow inverters to respond in millisecond time frame. The power factor of the inverters is traditionally poor due to displacement power factor and the harmonics. But with the latest development in the inverter technology, it is possible to maintain the power factor close to unity. The converters/inverters have the capability of creating large voltage fluctuation by drawing reactive power from the utility rather than supplying [49]. With proper control, inverters can provide voltage support by importing/exporting reactive power to push/pull towards a desired set point. This function would be of more use to the utilities as it can assist in the regulation of the grid system at the domestic consumer level.

Frequency of the inverter output waveshape is locked to the grid. Frequency bias is where the inverter frequency is deliberately made to run at 53 Hz. When the grid is present, this will be pulled down to the nominal 50 Hz. If the grid fails, it will drift upwards towards 53 Hz and trip on over frequency. This can help in preventing islanding.

Harmonics output from the inverters have been very poor traditionally. Old thyristor-based inverters are operated with slow switching speeds and could not be pulse width modulated. This resulted in inverters known as six-pulse or twelve-pulse inverters. The harmonics so produced from the inverters can be injected into the grid, resulting in losses, heating of appliances, tripping of protection equipments, and poor power quality. The number of pulses being the number of steps in a sine-wave cycle. With the present advent in the power electronics technology, the inverter controls can be made very good. Pulse width modulated inverters produce high quality sine waves. The harmonic levels are very low, and can be lower than the common domestic appliances. If the harmonics are present in the grid voltage waveform, harmonic currents can

be induced in the inverter. These harmonic currents, particularly those generated by a voltage-controlled inverter, will in fact help in supporting the grid. These are good harmonic currents. This is the reason that the harmonic current output of inverters must be measured onto a clean grid source so that the only harmonics being produced by the inverters are measured.

Synchronization of inverter with the grid is performed automatically and typically uses zero crossing detection on the voltage waveform. An inverter has no rotating mass and hence has no inertia. Synchronization does not involve the acceleration of a rotating machine. Consequently the reference waveforms in the inverter can be jumped to any point required within a sampling period. If phase-locked loops are used, it could take up a few seconds. Phase-locked loops are used to increase the immunity to noise. This allows the synchronization to be based on several cycles of zero crossing information. The response time for this type of locking will be slower.

Photovoltaic panels produce a current that is proportional to the amount of light falling on them. The panels are normally rated to produce 1000 W/m^2 at 25°C . Under these conditions, the short-circuit current possible from these panels is typically only 20% higher than the nominal current whereas it is extremely variable for wind. If the solar radiation is low then the maximum current possible under short-circuit is going to be less than the nominal full load current. Consequently PV systems cannot provide the short-circuit capacity to the grid. If a battery is present, the fault current contribution is limited by the inverter. With the battery storage, it is possible for the battery to provide the energy. However, inverters are typically limited between 100 and 200% of nominal rating under current limit conditions. The inverter needs to protect itself against the short circuits because the power electronic components will typically be destroyed before a protection device like circuit breaker trips.

In case of inverter malfunction, inverters have the capability to inject the DC components into the grid. Most utilities have guidelines for this purpose. A transformer shall be installed at the point of connection on the AC side to prevent DC from being entering into the utility network. The transformer can be omitted when a DC detection device is installed at the point of connection on the AC side in the inverter. The DC injection is essentially caused by the reference or power electronics device producing a positive half cycle that is different from the negative half cycle resulting in the DC component in the output. If the DC component can be measured, it can then be added into the feedback path to eliminate the DC quantity.

28.2.5.6.1 Protection Requirements A minimum requirement to facilitate the prevention of islanding is that the inverter energy system protection operates and isolates the inverter energy system from the grid if:

- Over voltage.
- Under voltage.

- Over frequency.
- Under frequency exists.

These limits may be either factory set or site programmable. The protection voltage operating points may be set in a narrower band if required, e.g. 220–260 V. In addition to the passive protection detailed above, and to prevent the situation where islanding may occur because multiple inverters provide a frequency reference for one another, inverters must have an accepted active method of islanding prevention following grid failure, e.g. frequency drift, impedance measurement, etc. Inverter controls for islanding can be designed on the basis of detection of grid voltage, measurement of impedance, frequency variation, or increase in harmonics. This function must operate to force the inverter output outside the protection tolerances specified previously, thereby resulting in isolation of the inverter energy system from the grid. The maximum combined operation time of both passive and active protections should be 2 s after grid failure under all local load conditions. If frequency shift is used, it is recommended that the direction of shift be down. The inverter energy system must remain disconnected from the grid until the reconnection conditions are met. Some inverters produce high voltage spikes, especially at light load, which can be dangerous for the electronic equipment. IEEE P929 gives some idea about the permitted voltage limits.

If the inverter energy system does not have the above frequency features, the inverter must incorporate an alternate anti-islanding protection feature that is acceptable to the relevant electricity distributor. If the protection function above is to be incorporated in the inverter it must be type tested for compliance with these requirements and accepted by the relevant electricity distributor. Otherwise other forms of external protection relaying are required which have been type tested for compliance with these requirements and approved by the relevant electricity distributor. The inverter shall have adequate protection against short circuit, other faults, and overheating of inverter components.

28.3 Power Electronics for Wind Power Systems

In rural USA, the first wind mill was commissioned in 1890 to generate electricity. Today, large wind generators are competing with utilities in supplying clean power economically. The average wind turbine size has been 300–600 kW until recently. The new wind generators of 1–3 MW have been developed and are being installed worldwide, and prototype of even higher capacity is under development. Improved wind turbine designs and plant utilization have resulted in significant reduction in wind energy generation cost from 35 cents per kWh in 1980 to less than 5 cents per kWh in 1999, in locations where wind regime is favorable. At this generation cost, wind energy has become

one of the least cost power sources. Main factors that have contributed to the wind power technology development are:

- High strength fiber composites for manufacturing large low-cost blades.
- Variable speed operation of wind generators to capture maximum energy.
- Advancement in power electronics and associated cost.
- Improved plant operation and efficiency.
- Economy of scale due to availability of large wind generation plants.
- Accumulated field experience improving the capacity factor.
- Computer prototyping by accurate system modeling and simulation.

The Table 28.2 is for wind sites with average annual wind speed of 7 m/s at 30 m hub height. Since 1980s, wind technology capital costs have reduced by 80% worldwide. Operation and maintenance costs have declined by 80% and the availability factor of grid-connected wind plants has increased to 95%. At present, the capital cost of wind generator plants has dropped to about \$600 per kW and the electricity generation cost has reduced to 6 cents per kWh. It is expected to reduce the generation cost below 4 cents per kWh. Keeping this in view, the wind generation is going to be highly competitive with the conventional power plants. In Europe, USA, and Asia the wind power generation is increasing rapidly and this trend is going to continue due to economic viability of wind power generation.

TABLE 28.2 Wind power technology developments

	1980	1999	Future
Cost per kWh	\$0.35–0.40	\$0.05–0.07	<\$0.04
Capital cost per kW	\$2000–3000	\$500–700	<\$400
Operating life	5–7 Years	20 Years	30 Years
Capacity factor (average)	15%	25–30%	>30%
Availability	50–65%	95%	>95%
Wind turbine unit size range	50–150 kW	300–1000 kW	500–2000 kW

The technical advancement in power electronics is playing an important part in the development of wind power technology. The contribution of power electronics in control of fixed speed/variable speed wind turbines and interfacing to the grid is of extreme importance. Because of the fluctuating nature of wind speed, the power quality and reliability of the wind based power system needs to be evaluated in detail. Appropriate control schemes require power conditioning.