Green Energy and Technology

Sudipta Chakraborty
Marcelo G. Simões
William E. Kramer *Editors*

Power Electronics for Renewable and Distributed Energy Systems

A Sourcebook of Topologies, Control and Integration

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Foreword

Energy is one of the major challenges for the human being; maybe ranked as number three of all critical factors in order to survive. First priority is water; many areas are globally lacking on this and humans cannot live without it for many days. The second is food and the third in my opinion is energy. In a modern society, energy is necessary for almost all functions in life in order to create a sustainable society. For the moment, we are consuming fossil fuel very fast to generate energy for living. Even with the continuous increase on consumption, the fossil fuel resources are available for our life-time; but for future generations such energy resource will be a limiting factor for our society and global instability can appear very fast—maybe much faster than we can foresee today.

As engineers, we have to come up fast with solutions to solve that challenge in order to make the global energy system sustainable. It is a significant challenge, which needs to be solved by new technological innovations combined with a careful awareness about the energy we are using and what we are using it for. I think more and more people are aware of their water consumption and such awareness should also be developed for the energy consumption. In order to create energy sustainability, four important issues need to be addressed: first is to make the power production sustainable by renewable energy generation; second is to increase the electrification of the transportation sector; third is to make the energy consumption much more efficient; and fourth is to develop the necessary infrastructure to take care of the large-scale energy transport for large distances.

This book discusses many of the required energy technologies that would create a sustainable world. For renewable and distributed energy in general, power electronics is an important enabling technology which allow us to convert electrical power from one form to another very efficiently and very fast. The technology is under steady development with continuously decreasing costs and increasing reliability. It is used in electrical power production, electric transmission, distribution, and efficient consumption. In the past decade, the technology is also dramatically more utilized in the automotive sector toward electrification of vehicles.

This book is an excellent contribution to the power electronics technology as it explains different ways to generate sustainable electricity, also how to obtain efficient electrical power consumption and how to do system engineering and control of the future grid configures into a microgrid structure. It also covers the emerging areas such as smart grid and electric vehicles.

Good luck with the reading of this comprehensive book and hope this book will lead to the innovations to create a sustainable world.

Frede Blaabjerg
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Preface

Although the cost of electricity has significantly decreased since the 1930s, it is still not readily available to the disadvantaged in countries and regions of poverty. One of the single most ways to reduce poverty is to find ways to reduce the cost of energy. Renewable resources can play a significant role to reduce these costs. Electricity across our world is primarily produced from fossil fueled resources. There is significant debate about the energy sources on today's fossil-fueled power plants and the affects they may be having on climate. A primary product of combustion of fossil generation is carbon dioxide, CO_2. Many of today's computer simulations suggest that as the atmospheric concentration of CO_2 increase, the earth's average temperature will continue to increase. The earth is made up of countless ecosystems. Laboratory and field studies show that most ecosystems will collapse when subjected to fast temperature changes.

In order to reduce the production of CO_2 globally, we must focus on getting the amount of CO_2 produced per unit of energy as close to zero as possible. As researchers, scientists, and engineers, we must focus on using our energy more efficiently and finding alternative energy sources that are competitive with fossil fuel energy sources. In the near term, we must find ways to mitigate CO_2 production from our existing fossil fuel plants using technologies such as carbon capture and carbon storage. Wind, solar photovoltaic (PV), and solar thermal are becoming cost competitive but can be intermittent in nature and must be coupled through the use of power electronics to existing energy systems. As the penetration of renewable resources increase, we must effectively use renewable energy when it is produced through advanced load control strategies. Low cost, energy storage technologies will continue to develop and can be used to abate renewable energy variability. Power electronics and their respective control systems is the enabling technology that will define our future energy.

This book is an excellent reference that provides insights into the world of power electronics for renewable resources. I recommend that this book be used as a resource text together with instructor-developed exercises and laboratories at both the undergraduate and graduate level. The book provides background material for students and seasoned engineers to gain broader understanding of the application of power electronics and control systems for renewable energy applications.

William E. Kramer

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Chapter 1
Introduction

Marcelo G. Simões and Sudipta Chakraborty

Abstract In this chapter, a brief discussion on renewable energy and distributed power generation is presented followed by a discussion on characteristics of power electronics and requirement of power electronics for these energy sources. Brief summary for each of the following chapters are provided to introduce the readers to rest of this book.

1.1 Introduction

Modern societies require significant energy resources that define the way we live. The food we eat, clothes we wear, buildings we live, appliances we use, and cars we drive require different forms of energy in their production or operation. A common metric that describes economic production performance is the ratio of energy consumption per capita income divided by the energy consumed. Today, there is a 200-fold disparity in income per capita between Great Britain and Ethiopia but the ratio of income to energy consumption between these countries is only 0.30–0.32. The fact that the two ratios are nearly identical, suggests that

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Views expressed in this chapter are personal with no implied endorsement of the same by NREL/DOE.

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increased standards of living will require increased energy in order to maintain such a ratio. Over the past 200 years, developed countries consumed more energy per capita than all the other previous societies throughout the history. Since fossil-fuel resources are limited, a drive toward more energy sustainability leads to renewable energy-based power generation. The costs of renewable resources such as solar, and wind have decreased in recent years due to technology and material production advances. Different forms of renewable energy are available in every country across the globe. For the developed world, a new paradigm of distributed power generation that is less dependent on fossil-fuel resources must be developed, in order to maintain the standard of living and sustainable growth. Developing countries growth and prosperity should increase as they begin to access to electric power through locally occurring natural energy sources providing them a new way of life through energy solutions that are sustainable.

The technology of power electronics is fundamental for renewable energy systems. Many renewable resources are intermittent and, without power electronics, we could not regulate voltage, frequency, and power output characteristics. Depending on the available renewable sources, DC–AC inverters, AC–DC rectifiers, and DC–DC converters are required. A rectifier might be a frontend for an electric grid connected to a load or an inverter can be the interface with local generation. There are other converters for intermediate stages, necessary for adapting the energy produced by the source in such a way that both the energy source and the power conversion operate at their highest efficiencies. Rotating machines are typically used to produce power from sources such as hydro and wind; and storage systems can be used to compensate for intermittency. Resources such as sunlight, hydrogen, and sometimes natural gas require DC–DC conversion, followed by the DC–AC inverter to integrate to the AC grid. In the past 20 years, new energy storage technologies such as ultracapacitors and electrochemical storage have been developed. The output of these devices tends to be DC. A Power electronic converter is needed to convert the power from DC to AC during discharge and AC back to DC during energy storage charging. Energy storage systems can be used to help regulate intermittent renewable energy systems by providing power when the output power is low or by absorbing power when excess power is available.

Power converters for renewable energy integration present a higher complexity when compared with those used in industrial or stand-alone systems because they have to efficiently manage power flow and stay synchronized with the grid. Power electronics for renewable and alternative energy systems require the following attributes:

- High efficiency: A negligible part of the power should be lost during conversion. This requirement is affected by input and output energy fluctuations and by conversion efficiency, changing with the quantity of energy at input/output terminals. The converter has to operate in continuous tracking of the input/output quantities and a subsequent real-time adjustment of the converter operation ensuring the highest energy transfer. This requires two or more power conversion stages (typically AC–DC and/or DC–DC and/or DC–AC).

- Optimal energy transfer: All renewable sources are energy constrained and as such, they need control algorithms to achieve a maximum power point operation. For example, PV arrays must be interconnected with maximum power point tracking (MPPT) in order to optimize their energy transfer.
- Bidirectional power flow: In some cases, the power converter has to be able to supply either the local load and/or the grid.
- High reliability: The continuity of service is a major issue when delivering energy.
- Synchronization capabilities: All power sources connected with the grid have to be fully synchronized and operate in a safe manner thus ensuring high efficiency and reliability, plus conforming to electrical requirements such as the IEEE 1547 interconnection standard for utility grid applications.
- Electromagnetic interference (EMI) filtering: The quality of the energy injected on the grid must respect electromagnetic compatibility (EMC) standards.
- Smart metering: The converter between the local source/load and the grid must be capable of tracking the energy consumed by load or injected on the grid. Real-time information can be passed to an automatic billing system capable of taking into account parameters as the buy/sell energy in real time at the best economic conditions and informing the owner of the installation of all required pricing parameter decisions.
- Communication: Intelligent functioning of power electronics depends on their capability to support communications at the same time that power flows in the systems. Such functions are fundamental for overall system optimization and for implementing sophisticated dispatching strategies.
- Fault tolerance: A key issue for a modern grid is the built-in ability of avoiding propagation of failures among the nodes and to recover from local failures. This capability should be managed by the power converter, which should incorporate monitoring, communication systems, and reconfiguration systems.
- Additional functions capable of making the interface user-friendly and accessible anywhere through Internet-based communications.

Different aspects of these attributes are covered in the 14 chapters written by well-known educators, engineers, and scientists who have developed products and prototypes in their respective areas of expertise and with a focus on renewable and distributed energy applications. The book provides background knowledge for the reader to understand how to enable efficient interconnection and economical operation of dispersed installations to the utility grid. Achieving one of the tenets of the smart grid initiative—enabling active participation of consumers in the demand response using timely information and control options.

Chapter 2 gives a description and overview of power electronic technologies including a description of the fundamental systems that are the building blocks of power electronic systems. Technologies that are described include: power semiconductor switching devices, converter circuits that process energy from one DC level to another DC level, converters that produce variable frequency from DC sources, principles of rectifying AC input voltage in uncontrolled DC output voltage and their extension to controlled rectifiers, converters that convert to AC from DC (inverters) or from AC with fixed, or variable output frequency (AC controllers, DC–DC–AC converters, matrix converters, or cycloconverters). The chapter also covers pulse width modulation control techniques in detail.

Chapter 3 discusses photovoltaic systems and describes how semiconductor devices can directly convert solar energy into direct current. PV cell technology is explained and a description of how, incident light spectrum, panel tilt, cell temperature, panel design, surface deposits, shadows, and materials on the solar cell can influence performance. In order to have modules or arrays for higher voltage or current, the cells must be associated, and control algorithms must be implemented in order to make the system operate with high efficiency. Descriptions of power electronics, digital controls, sun tracking, and remote monitoring are provided as the basis for the modern PV energy systems.

Chapter 4 presents wind energy systems, with coverage on the basic energy conversion from wind, wind turbines, and their aerodynamic and control issues. The chapter continues with a discussion on how wind energy systems can be isolated or grid-connected and the difference between onshore and offshore applications. Specific power electronics for wind turbine applications include: partially rated power electronics, full scale power electronics, FACTS, and advanced topologies. The chapter concludes in how wind turbines can be controlled and integrated.

Chapter 5 gives examples and applications of small hydropower systems. A small hydropower can be used as stand-alone cost-effective solution to provide remote power or enhance grid connected power systems. This chapter provides a discussion of basic principles of hydropower resources, how to find the best places to site hydropower in rivers. Power turbine system technologies that can be used for small-hydro applications are also discussed. Systems such as fixed-speed with induction generator, variable-speed with a cage-bar induction generator or synchronous generator, variable-speed with a multiple-pole synchronous generator or multiple-pole permanent magnet synchronous generator; and variable-speed with a doubly-fed induction generator are described.

Chapter 6 introduces fuel cell systems and their associated power electronic converter topologies. The introduction includes a description of different fuel cell technologies and the physics behind the characteristic polarization curve and dynamic behavior. Two models for control applications are discussed, one for a proton exchange membrane fuel cell (PEMFC) and another for the solid oxide fuel cell (SOFC) with detailed equations. The chapter presents specific power converter topologies used for fuel cell systems highlighting their advantages and drawbacks.

Chapter 7 explains how variable (adjustable) speed generation systems provide reduction of fuel consumption and improve electrical power generation systems. Two basic topologies are presented; one is based on the application of permanent magnet generator and another one on slip-ring induction machines. A description of how power is controlled from engine driven generators is described. A variable-speed power generation with the slip-ring induction machine system is introduced that utilizes a control method based on space vector theory. In the chapter, discussions were provided showing how the reference stator voltage vector, rotor current amplitude, frequency, and phase are controlled to provide a stable sinusoidal three-phase stator voltage.

Chapter 8 provides the basics of micro turbines operation and integration techniques. Microturbines are a relatively new technology for generation of electric power, and are commercially available in ratings from 30 kW up to 1 MW or more. This chapter describes how microturbines perform, and how they differ from other more traditional forms of electric power generation. Emphasis is placed on the power electronics and control features of typical microturbines.

Chapter 9 provides a discussion on the various technical components that are used for battery energy storage systems for utility-scale energy storage and how these technical components are interrelated. A basic description of how battery energy storage systems work is provided with several examples to illustrate how battery energy storage can be used in large-scale applications. An overview of how the storage system's power electronics work is given in the chapter followed by a more detailed description of possible power electronic topologies and power electronic controls that are used to ensure that the system can be properly integrated with the generation source and, if necessary, the load. Battery management and monitoring through the power electronic controls are discussed and a detailed example of battery energy storage system integration is provided.

Chapter 10 introduces the concept of fast response energy storage systems that have the ability to provide or to absorb a high amount of electrical energy in a short period of time without diminishing the lifetime of the storage device. Major technologies discussed in this chapter are: electric double layer capacitors (EDLC) that store energy in the electrical field of a capacitor; Flywheels that utilize kinetic energy, and superconducting magnets (SME) where energy is kept in the magnetic field of a lossless inductor. Fast storage technologies show promise to allow increasing penetration of renewable energy sources and support Smart Grid. In this chapter, the power converters that are used to manage power delivered and stored for these fast response energy storage systems are provided along with descriptions of how to integrate these technologies for renewable energy system applications.

Chapter 11 covers application of modular power electronics for renewable and distributed energy applications. The chapter starts with basics of modular power electronics such as power electronics building block (PEBB) and integrated power electronics module (IPEM). A description of common power electronics topologies for different renewable and distributed energy applications are given showing that generalized power electronic topologies can be formalized to design building block modular power electronics interfaces. The chapter concludes by giving examples suggesting that such modular power electronics can eventually improve the overall life-cycle cost and reliability for renewable and distributed energy systems.

Chapter 12 provides a fundamental description of microgrids. The current and future capability of microgrids for aggregating multiple resources is described. Concepts such as plug-and-play technologies need to be developed to accommodate the addition or removal of different sources and loads without a need to develop complex interconnection, load flow, and dispatch studies. Dynamic microgrid interactions between different aggregated resources and their power electronic controllers are discussed.

Chapter 13 focuses on the role that power electronics will have in future smartgrids. The operation of future electricity grids will be multi-disciplinary in nature with merging of energy and communication infrastructures, and interaction of state-of-the-art technologies such as power electronics, computational intelligence, signal processing, or smart metering. The chapter provides good background information of emerging distribution systems, evolutionary changes, and enabling the technologies that will be needed. Power electronic-based interface systems with smart topologies and controls are explained. Three examples of smart interface control systems are described including smart inverters, smart power router, and the concept of the virtual synchronous generator.

Chapter 14 explains practical issues for commercialization of current and future plug-in hybrid electric vehicles and focuses primarily on power electronics-based solutions for both current as well as future electric vehicle technologies. New plug-in hybrid vehicle power system architectures are discussed in detail together with key battery technologies that are used for transportation applications. Advanced power electronics battery management techniques and charging infrastructures for electric vehicles and plug-in hybrid electric vehicles are also described in this chapter.

Chapter 15 introduces a new distributed control paradigm for power system control, called multi-agent systems (MAS). The development of advanced communication infrastructures can provide power electronics interfaces with the ability to control complex power systems in efficient and scalable ways and in real-time. Multi-agent systems (MAS) are based on distributing information and computing algorithms for complex networks, and are an excellent technological solution for power electronics applications. This chapter focuses on applications of MAS in power systems and provides applications how MAS can be used with other artificial intelligence techniques in order to make the grid smarter and more flexible.

Chapter 2
Fundamentals of Power Electronics

Edison R. C. da Silva and Malik E. Elbuluk

Abstract This chapter gives a description and overview of power electronic technologies including a description of the fundamental systems that are the building blocks of power electronic systems. Technologies that are described include: power semiconductor switching devices, converter circuits that process energy from one DC level to another DC level, converters that produce variable frequency from DC sources, principles of rectifying AC input voltage in uncontrolled DC output voltage and their extension to controlled rectifiers, converters that convert to AC from DC (inverters) or from AC with fixed or variable output frequency (AC controllers, DC–DC–AC converters, matrix converters, or cycloconverters). The chapter also covers control of power converters with focus on pulse width modulation (PWM) control techniques.

2.1 Definition, History, Applications and Trends of Power Electronics

Power electronics (PE) experienced tremendous growth after the introduction of the first solid-state power switch, the silicon controlled rectifier (SCR) in 1957. Today, almost all of the technologies that require control of power control utilize PE technology. This chapter will give the reader an overview on the field of PE including:

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- A description of the fundamentals of the power semiconductor switching devices.
- Converter circuits that process energy from one DC level to another DC level.
- Converters that produce variable frequency from DC sources.
- Principles of rectifying AC input voltage in uncontrolled DC output voltage and their extension to controlled rectifiers.
- Converters that convert to AC from DC (inverters) or from AC with fixed or variable output frequency.
- AC controllers.
- DC–DC–AC converters.
- Matrix converters or cycloconverters.
- Detailed description of pulse width modulations control techniques.

Power electronic circuits are used to control the power conversion from one or more AC or DC sources to one or more AC or DC loads, and sometimes with bidirectional capabilities. In most power electronics systems, this conversion is accomplished with two functional modules called the control stage and the power stage. Figure 2.1 shows the topology for a single source and single load converter application that includes a power processor (the power stage) and a controller (the control stage). The converter, handles the power transfer from the input to output, or vice versa, and is constituted of power semiconductor devices acting as switches, plus passive devices (inductor and capacitor). The controller is responsible for operating the switches according to specific algorithms monitoring physical quantities (usually voltages and currents) measured at the system input and or output.

The modern PE era began in 1957. It was during that year the first commercial thyristor, or Silicon Controlled Rectifier (SCR), was introduced by General Electric Company. The SCR, started replacing the mercury arc rectifiers, invented in 1902, and the later developed thyratron (invented in 1923) and ignitron (invented in 1931), allowed the commercialization of several industrial circuits conceived during the 1920s and 1940s (like the cycloconverter, the chopper, and the parallel inverter) as well as the Graetz bridge conceived in 1897.

The SCR was the only available power device for more than 25 years after its invention (and still is very useful for extremely high power applications). Since it is very difficult to impose turn-off conditions for SCR's, faster devices, with higher voltage and current capabilities, with better controllability were developed,

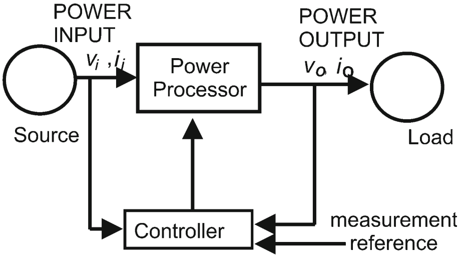


Fig. 2.1 A general power electronic system

including the bipolar junction transistor (BJT) invented in 1970. The BJT was used in applications from low to medium power and frequency and now is considered obsolete. The metal oxide semiconductor field effect transistor (MOSFET) was invented in 1978 and is used for power electronic switching applications of low power and high frequencies. The gate turn-off thyristor (GTO), is used in applications from medium to high power and from low to medium frequencies. The insulated gate bipolar transistor (IGBT) developed in 1983 is used in applications from low to medium power and frequency. The integrated gate commutated thyristor (IGCT) invented in 1997 is used in applications from medium to high power and from low to medium frequencies.

Through the use of this switching technology power electronics systems can operate in the range from few watts up to GW, with frequency range from some 100 Hz up to some 100 kHz, depending on the power handled [1]. The advent of microelectronics and computer control made it possible to apply modern control theory to PE and at same the time made possible very complex circuit functions. Therefore, the area of PE, became interdisciplinary, as indicated in Fig. 2.2. At the high power level, PE deals with static and rotating equipment for generation, transmission, and distribution handling large amount of power. For consumer electronic applications power converters and circuits are important for information processing, employing analog and digital circuits, or microprocessors including microcontrollers, digital signal processors (DSP), and field programmable gate arrays (FPGA). In the area of control, PE deals with stability and response characteristics in systems with feedback loops, based on classical or modern control. With the development of very large system integration (VLSI), ultra large system integration (ULSI), and other sophisticated computer-assisted designs; advanced control systems could be used to develop new power electronic topologies.

The development of devices and equipment able to individually or in combination convert efficiently electric energy from AC to DC, DC to DC, DC to AC, and AC to AC together with the changes that occurred in electrical power engineering has resulted in wide spread of PE in a large spectrum of applications.

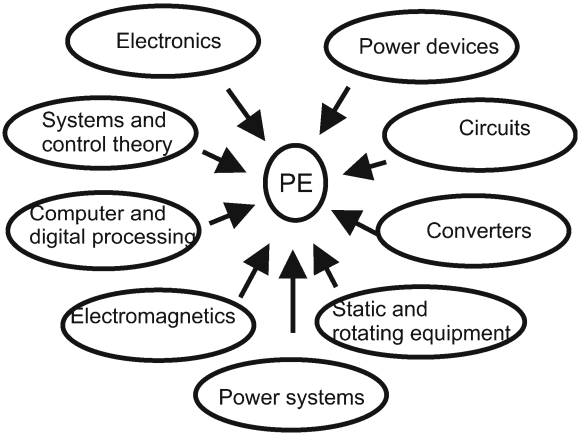


Fig. 2.2 Power electronics and related topics

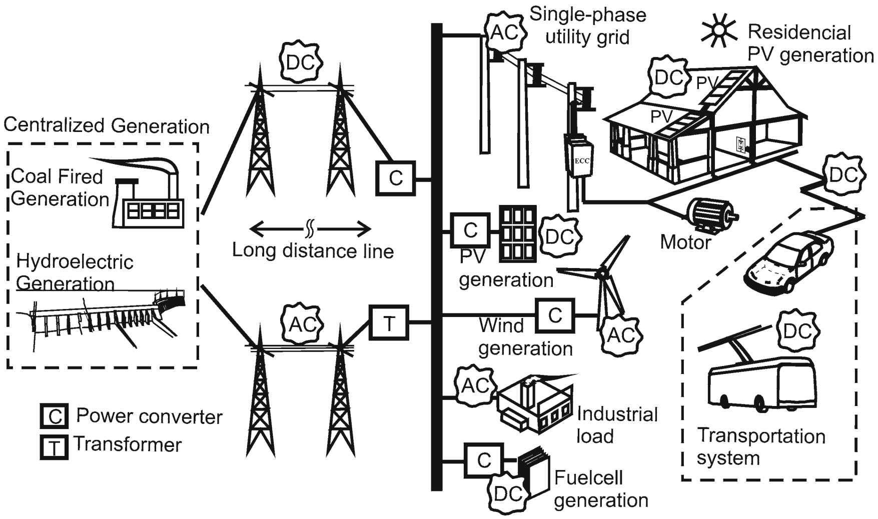


Fig. 2.3 Power electronics and electrical energy generation transmission, storage, and distribution

Figure 2.3 shows how electrical energy generation is distributed for the end-user, showing transmission, distribution, storage, renewable energy sources and users. In fact, nowadays PE is a key technology for all those sub-systems, and has spread in many applications, examples including:

- Residential: heaters, home appliances, electronic lighting, equipment sources;
- Commercial: heaters, fans, elevators Uninterruptible Power Supply (UPS), AC and DC breakers, battery chargers;
- Industrial: pumps, blowers, robots, inductive heaters, welding, machine drive, portable sources;
- Transportation: electrical and hybrid vehicles, battery chargers, railroad electric system;
- Utility systems: high voltage direct current, generators, reactive compensators, interface for photovoltaic, wind, fuel cells systems, Flexible AC Transmission System (FACTS) equipment;
- Aerospace: sources for spacecrafts, satellites, planes;
- Communication: sources, RF amplifiers, audio-amplifiers.

Power electronics will continue to be an enabling technology to address our future electricity needs. It is expected that new power devices for higher power, higher frequency, and lower losses will continue to be invented. Global energy concerns will provoke a large interest in the increase of the conversion efficiency and more application of PE in power quality, distributed generation, energy conservation, and smart grids. The integration of power and control circuitry into functional modules will result in systems solutions that are highly integrated into packaged products that will be both more reliable and affordable.

2.2 Power Semiconductor Devices

Electronic switches capable of handling high voltage and current operations at high frequency (HF) are the most important devices needed in the design of energy conversion systems that use PE. For the purposes of this discussion we will define the concept of an ideal switch. An ideal power electronic switch can be represented as a three terminals device as shown in Fig. 2.4. The input, the output, and a control terminal that imposes ON/OFF conditions on the switch. A switch is considered "ideal" when it is open, it has zero-current through it and can handle infinite voltage. When the switch is closed it has zero-voltage across it and can carry infinite current. Also, an ideal switch changes condition instantly, which means that it takes zero-time to switch from ON-to-OFF or OFF-to-ON. Additional characteristics of an ideal switch include that it exhibits zero-power dissipation, carries bidirectional current, and can support bidirectional voltage. If we plot the switch current (i) with respect to its voltage (v) we define four quadrants that are often referred to as the v-i plane and are shown in Fig. 2.5. By definition, an ideal switch can operate in all four quadrants.

Practical or real switches do have their limitations in all of the characteristics explained in an ideal switch. For example, when a switch is on, it has some voltage across it, known as the on-voltage and it carries a finite current. During the off stage, it may carry a small current known as the leakage current while supporting a finite voltage. The switching from ON-to-OFF and vice versa does not happen instantaneously. Of course, all actual switching devices take times to switch and we define these characteristics as the delay, rise, storage, and fall times. As a consequence of the above two non-ideal cases, there is voltage and current across the switch at all times, which will result in two types of losses. The first loss occurs during the on and off-states and is defined as the "conduction loss". The second loss is defined as the "switching loss" which occurs just as the switch changes state as either opening or closing. The switch losses result in raising the overall

Fig. 2.4 Ideal switch

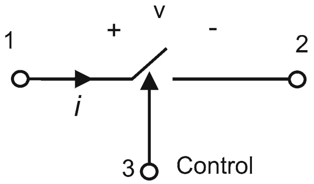
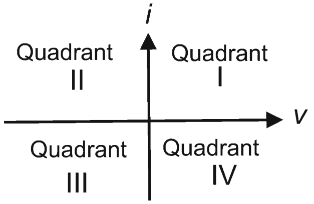


Fig. 2.5 *4-quadrant* switch *v-i* characteristics



switch temperature. Further, the ON/OFF-state of the power switch must be controlled though an external signal.

2.2.1 Classifications of Power Switches

The concept of the ideal switch is important when evaluating circuit topologies. Assumptions of zero-voltage drop, zero-leakage current, and instantaneous transitions make it easier to simulate and model the behavior of various electrical designs. Using the characteristics of an ideal switch, there are three classes of power switches:

1. *Uncontrolled switch*: The switch has no control terminal. The state of the switch is determined by the external voltage or current conditions of the circuit in which the switch is connected. A diode is an example of such switch.
2. *Semi-controlled switch*: In this case the circuit designer has limited control over the switch. For example, the switch can be turned-on from the control terminal. However, once ON, it cannot be turned-off from the control signal. The switch can be switched off by the operation of the circuit or by an auxiliary circuit that is added to force the switch to turn-off. A thyristor or a SCR is an example of this switch type.
3. *Fully controlled switch*: The switch can be turned-on and off via the control terminal. Examples of this switch are the BJT, the MOSFET, the IGBT, the GTO thyristor, and the MOS-controlled thyristor (MCT).

2.2.1.1 Uncontrolled Switches

A diode, also known as rectifier, is an *uncontrolled switch*. It is a two terminal device with a symbol depicted in Fig. 2.6a. The terminals are known as Anode (A) and cathode (K). In the ideal case, the diode current (i_d) is unidirectional and current can only flow from the anode to the cathode. The diode voltage (v_d) is measured as being positive from the anode to the cathode.

The v-i characteristics for a real (non-ideal) diode are shown in Fig. 2.6b. In quadrant I, the diode is in the ON-state, and is known as the forward-biased region. When it is ON the diode carries a positive current while supporting a small voltage. The diode current varies exponentially with the diode voltage. The diode is reversed-biased in quadrant III, which is the OFF-state. When it is OFF, the diode supports a negative voltage and carries a negligible current (leakage current). When the negative voltage exceeds a certain limit, known as the breakdown voltage, the leakage current increases rapidly while the voltage remains at the breaking value, which potentially damages the device. Therefore, operation that exceeds the breakdown voltage must be avoided.

The ideal diode characteristics are shown in Fig. 2.6c. During the ON-state, the diode has zero-voltage across it and carries a positive current. During the OFF-state, the diode carries zero-current and supports a negative voltage.

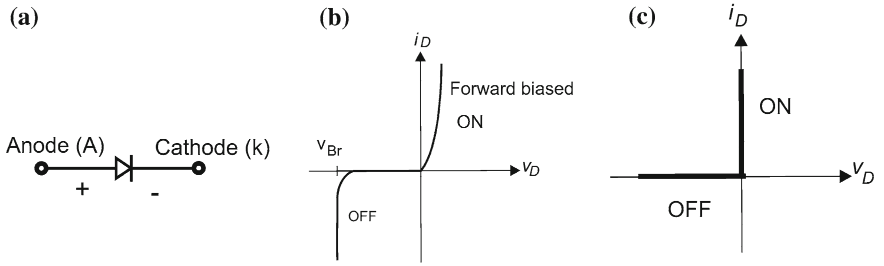


Fig. 2.6 Diode: **a** symbol, **b** *i-v* characteristics, and **c** idealized characteristics

2.2.1.2 Semi-controlled Switches

The thyristor or SCR is a power semiconductor switch whose turn-on can be activated from the control terminal Gate but once it turns ON, the control terminal becomes ineffective and the thyristor behaves similar to a diode. Therefore, the thyristor is considered a *semi-controlled switch*. The name, controlled rectifier, is an indication that a thyristor is a device that can be considered as a diode whose turn-on can be commanded externally. Figure 2.7a shows the circuit symbol for a thyristor. Although there are similarities between the diode and the thyristor circuit symbols, their operation is very different. The thyristor current, I_A, flows from the anode (A) to the cathode (K) and the voltage V_{Ak}, across the thyristor is positive when the anode is at higher voltage than the cathode. Figure 2.7b shows the *v-i* characteristics of a real or non-ideal thyristor. In quadrant I, in the absence of a gate current, the device is OFF in the forward blocking region and supports a positive voltage. If a gate current is applied, the device switches to the on-state region and the device has a *v-i* characteristic similar to that of a diode. In quadrant III, the device is OFF and the region is known as the reverse blocking region. Again the characteristics are similar to those of a diode. Comparing the switching characteristics of a diode and a thyristor, it appears that when the thyristor is OFF, it can block large positive or negative voltage, which is a fundamental feature that is important in circuit applications, such as AC/AC converters. This can be clearly seen in the ideal characteristics of the thyristor as shown in Fig. 2.7c. In the ON-state, the thyristor has zero-voltage across it and carries a positive current. In the

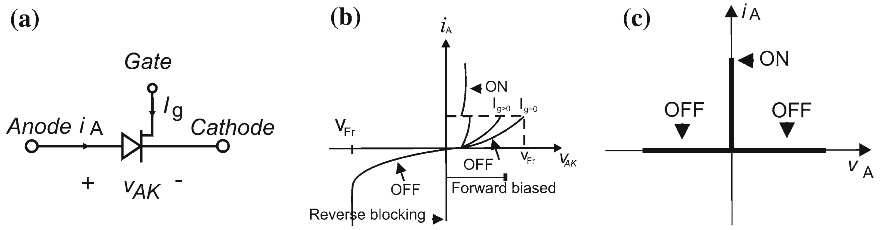


Fig. 2.7 Thyristor: **a** symbol, **b** *i-v* characteristics, and **c** idealized characteristics

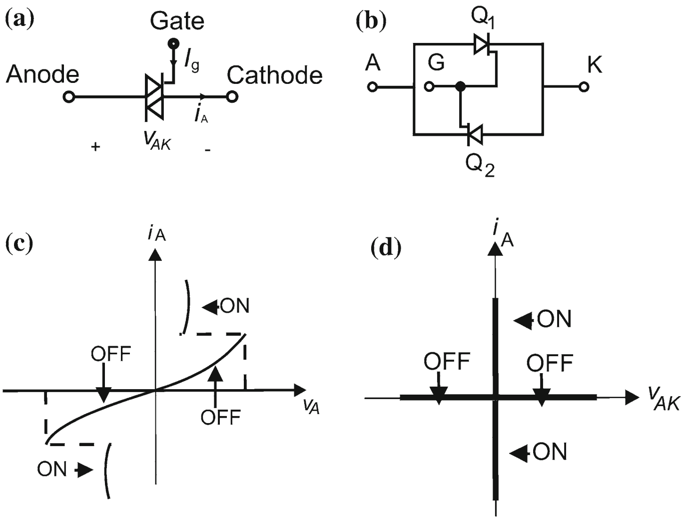


Fig. 2.8 The triac: **a** symbol, **b** two-thyristor-representation, **c** *i*-*v* characteristics, and **d** idealized characteristics

OFF-state, the thyristor can support a positive voltage in the forward blocking region or a negative voltage, similar to a diode, in the reverse blocking region. Therefore, the thyristor can be considered to carry an unidirectional current and supports a bidirectional voltage.

The triac, shown in Fig. 2.8a, is also a semi-controlled switch. A triac can be modeled as two thyristors connected back-to-back as shown in Fig. 2.8b. Triacs are considered as bidirectional voltage and bidirectional current devices, as shown by the *v*-*i* characteristics in Fig. 2.8c. The ideal characteristics are in Fig. 2.8d. As a low-cost bidirectional switch, the triac is the primary switch that is used for low power electronic commercial circuits such as light dimmers and control circuits for single-phase motors used in home appliances.

2.2.1.3 Fully Controlled Switches

In a *fully controlled switch* the ON- and OFF-states can be activated externally through a control terminal. A number of power switches fall into the category of controlled switches; some of them are transistor-based devices and others are thyristor-based devices. A brief description of each device is given in the following sections:

A. *The Bipolar Junction Transistor*

Figure 2.9a shows the circuit symbol for an npn-type BJT. The base (*B*) is the control terminal, where the power terminals are the collector (*C*) and the emitter (*E*). The *v*-*i* characteristics of the device are shown in Fig. 2.9b. The device

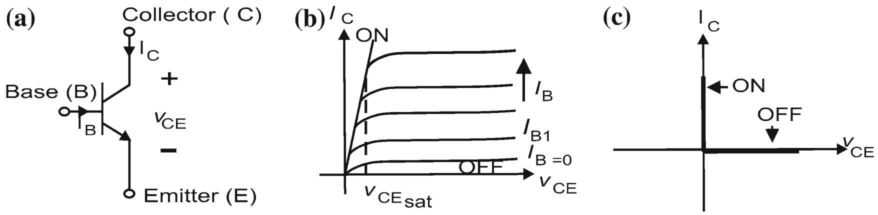


Fig. 2.9 The BJT: **a** symbol, **b** *i*-*v* characteristics, and **c** idealized characteristics

operates in quadrant I and is characterized by the plot of the collector current (I_C) versus the collector to emitter voltage (v_{CE}). The device has three regions two of them where the device operates as a switch and the third is where the device operates as a linear amplifier. The device is OFF in the region below $i_B = 0$ and is ON in the region where v_{CE} is less than $v_{CE(\text{Sat})}$. Neglecting the middle region, the idealized device characteristics as a switch are shown in Fig. 2.9c. During the ON-state the device carries a collector current $I_C > 0$ with $v_{CE} = 0$. In the OFF-state, the device supports positive $v_{CE} > 0$ with $I_C = 0$. Therefore, the BJT is unidirectional current and voltage device. The BJT has historical importance, but today most of its function are covered by devices like the IGBT.

B. *The Metal Oxide Semiconductor Field Effect Transistor*

Figure 2.10a shows the circuit symbol for an n-channel, enhancement mode MOSFET. Similar to the BJT, it has a control terminal known as the gate (*G*) and the power terminals are the drain (*D*) and source (*S*). The device is controlled by supplying a voltage (v_{GS}) between the gate and the source. This makes it a voltage-controlled device compared to the BJT, which is a current-controlled device. The real *v*-*i* characteristics of device are shown in Fig. 2.10b. Similar to the BJT, the MOSFET operates within three operating regions. Two of the regions are used when the device is operated as a switch, and the third is when the device is used as an amplifier. To maintain the MOSFET in the off-state, v_{GS} must be less than a threshold voltage known as v_T, which is the region below the line marked OFF. And when the device is ON it act as resistance determined by the slope of the line marked ON. The idealized characteristics of a MOSFET switch are shown in Fig. 2.10c. When the device is ON, it has zero v_{DS} and carriers a current $I_D > 0$ and when the device is OFF it supports a positive v_{DS} and has zero drain current $(I_D = 0)$.

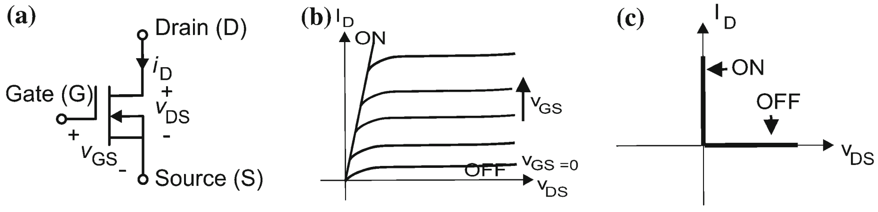


Fig. 2.10 The MOSFET: **a** symbol, **b** *i*-*v* characteristics, and **c** idealized characteristics

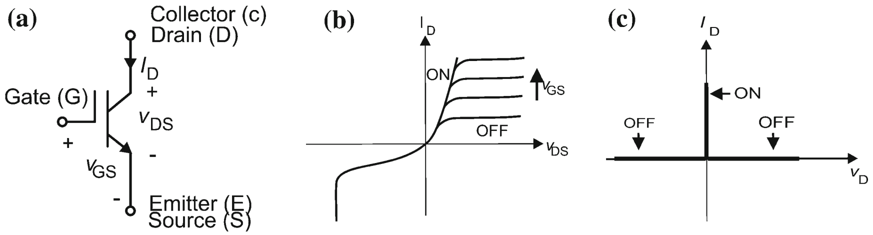


Fig. 2.11 The IGBT: **a** symbol, **b** *i-v* characteristics, and **c** idealized characteristics

Three other MOSFET configurations include: n-channel depletion mode and p-channel enhancement and depletion modes.

C. *The Insulated Gate Bipolar Transistor (IGBT)*

The IGBT is a hybrid or also known as double mechanism device. Its control port resembles a MOSFET and its output or power port resembles a BJT. Therefore, an IGBT combines the fast switching of a MOSFET and the low power conduction loss of a BJT. Figure 2.11a shows a circuit symbol that is used for an IGBT, which is slightly different from the MOSFET with similar terminal labels. The control terminal is labeled as gate (*G*) and the power terminals are labeled as collector (*C*) and emitter (*E*). The *i-v* characteristics of a real IGBT are shown in Fig. 2.11b, which shows that the device operates in quadrants I and III. The ideal characteristics of the device are shown in Fig. 2.11c. The device can block bidirectional voltage and conduct unidirectional current. An IGBT can change to the ON-state very fast but is slower than a MOSFET device. Discharging the gate capacitance completes control of the IGBT to the OFF-state. IGBT's are typically used for high power switching applications such as motor controls and for medium power PV and wind PE.

D. *The Gate Turn-Off Thyristor*

The GTO thyristor is a device that operates similar to a normal thyristor except the device physics, design and manufacturing features allow it to be turned-off by a negative gate current which is accomplished through the use of a bipolar transistor. The circuit symbol for a GTO is shown in Fig. 2.12a. The *v-i* characteristics and the ideal switch characteristics are shown in Fig. 2.12 b, c. Although the device has been in existence since the late 1960s, and it has been successfully used in high power drives, IGBTs have reached price and rating party and are expected to replace GTO's in new power electronic designs.

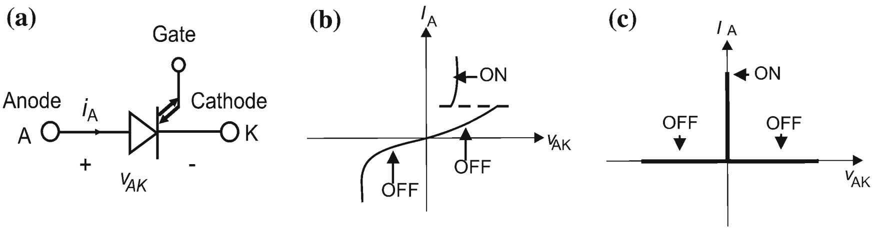


Fig. 2.12 The GTO: **a** symbol, **b** *i-v* characteristics, and **c** idealized characteristics

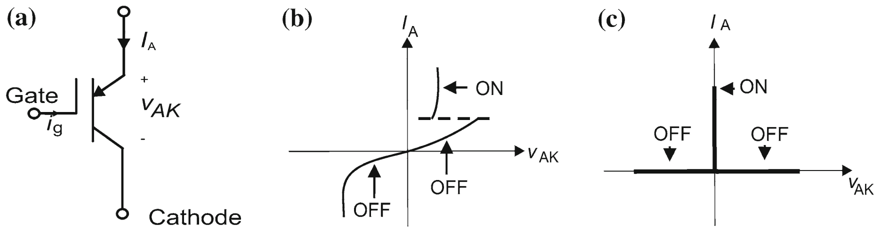


Fig. 2.13 The MCT: **a** symbol, **b** *i-v* characteristics, and **c** idealized characteristics

E. *The MOS-Controlled Thyristor*

Similar to the IGBT, the MCT is a hybrid or double mechanism device that was designed to have a control port of a MOSFET and a power port of a thyristor. The circuit symbol for the device is shown in Fig. 2.13a. The real device characteristics and the idealized characteristics are shown in Fig. 2.13b, c. The characteristics are similar to the GTO, except that the gate drive circuitry for the MCT is less complicated than the design for a GTO as the control circuit of the MCT uses a MOSFET instead of a transistor. As a result, the MCT was supposed to have higher switching frequency. Although the MCT was invented at the same time period of the IGBT it never became fully commercially available and at the time of writing this book it is unknown the future market plans.

2.3 Power Electronic Converter Topologies

Power electronic converters are switch-mode circuits that process power between two electrical systems using power semiconductor switches. The electrical systems can be either DC or AC. Therefore, there are four possible types of converters; namely DC/DC, DC/AC, AC/DC, and AC/AC. The four converter types are described below:

1. *DC/DC Converter*: is also known as “Switching Regulator”. The circuit will change the level voltage available from a DC source such as a battery, solar cell, or a fuel cell to another DC level, either to supply a DC load or to be used as an intermediate voltage for an adjacent power electronic conversion such as a DC/AC converter. DC/DC converters coupled together with AC/DC converters enable the use of high voltage DC (HVDC) transmission which has been adopted in transmission lines throughout the world.
2. *DC/AC Converter*: Also described as “Inverter” is a circuit that converts a DC source into a sinusoidal AC voltage to supply AC loads, control AC motors, or even connect DC devices that are connected to the grid. Similar to a DC/DC converter, the input to an inverter can be a stiff source such as battery, solar cell, or fuel cell or can be from an intermediate DC link that can be supplied from an AC source.

3. *AC/DC Converter*: This type of converter is also known as "Rectifier". Usually the AC input to the circuit is a sinusoidal voltage source that operates at 120 V, 60 Hz or a 230 V, 50 Hz, which are used for power distribution applications. The AC voltage is rectified into a unidirectional DC voltage, which can be used directly to supply power to a DC resistive load or control a DC motor. In some applications the DC voltage is subjected to further conversion using a DC/DC or DC/AC converter. A rectifier is typically used as a front-end circuit in many power system applications. If not applied correctly, rectifiers can cause harmonics and low power factor when they are connected to the power grid.
4. *AC/AC Converter*: This circuit is more complicated than the previous converters because AC conversion requires change of voltage, frequency, and bipolar voltage blocking capabilities, which usually requires complex device topologies. Converters that have the same fundamental input and output frequencies are called "AC controllers". The conversion is from a fixed voltage fixed frequency (FVFF) to a variable voltage fixed frequency (VVFF). Applications include: light dimmers and control of single-phase AC motors that are typically used in home appliances. When both voltage and frequency are changed, the circuits are called "Cycloconverters", which convert a FVFF to variable voltage variable frequency (VVVF) and when fully controlled switches are used, this class of circuit is called "Matrix Converter". Another way of achieving AC/AC conversion is by using AC/DC and DC/AC through an intermediate DC link. This type of combined converter approach can be complex as the correct control approach must be implemented including simultaneous regulation of the DC link, injection of power with a prescribed power factor and bidirectional control of energy flow.

2.3.1 DC/DC Converters

A generalized circuit for a DC/DC converter is depicted in Fig. 2.14 where all possible switches connecting the input to the output are represented. If one P-switch and one N-switch are used, the resulting circuit is shown in Fig. 2.15a. The switches are controlled ON and OFF within a specified period *T*. The output

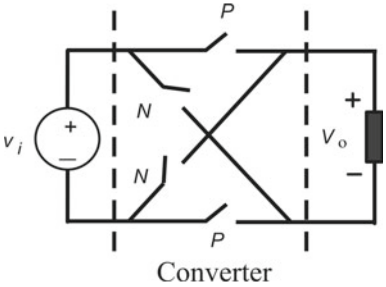


Fig. 2.14 Generalized circuit for DC/DC converter circuits

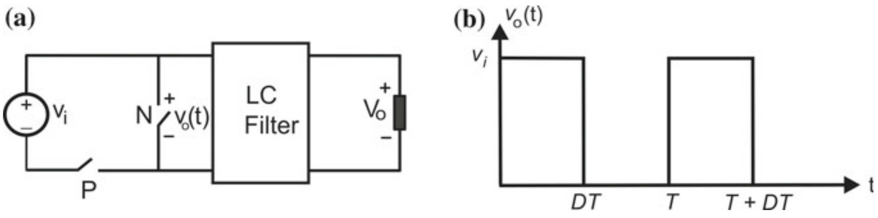


Fig. 2.15 Non-isolated down (buck) DC/DC converter: **a** circuit and **b** waveforms

voltage is equal to the input voltage when the P-switch is ON, and is equal to zero when the N-switch is ON. The ratio of the ON-time of switch P switch to the period T is defined as the duty ratio or duty-cycle (D). The waveform of the output voltage $v_o(t)$ is shown in Fig. 2.15b. Since $v_o(t)$ is a pulsating waveform, an LC circuit is used to filter the voltage to a DC. In this case the average V_o or DC component of the output voltage is given by Eq. (2.1),

$$V_{\text{avg}} = \frac{1}{T}\int_{0}^{DT} V_i = DV_i \tag{2.1}$$

Since $D < 1$, the DC output voltage of this converter is always less than the input voltage.

When all the generalized converter switches are used, the resulting circuit is shown in Fig. 2.16. When the P-switches are ON, the output voltage is equal to the input voltage and when the N-switches are ON, the output voltage is equal to the negative of the input voltage. The resulting waveform is shown in Fig. 2.16b. The DC component or the average of the output voltage is given by:

$$V_{\text{avg}} = \frac{1}{T}\left[\int_{0}^{DT} V_i \text{d}t + \int_{DT}^{T} -V_i \text{d}t\right] = (2D-1)V_i \tag{2.2}$$

Equation (2.2) indicates that the output voltage is less than the input voltage with a changed polarity. For duty-cycle $D > 0.5$ the output has a positive value and for

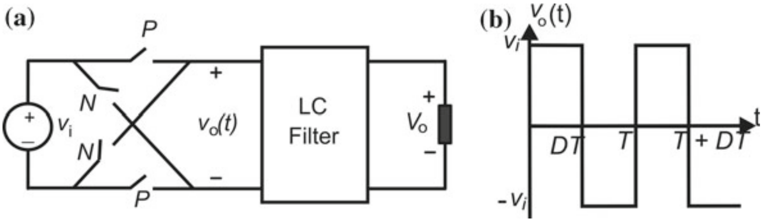


Fig. 2.16 Full-bridge non-isolated down (buck) DC/DC converter: **a** circuit, and **b** waveforms

duty-cycle $D < 0.5$ the output has a negative value. The LC circuit in the design is used to filter the harmonic components of the output voltage so that the load receives a DC voltage with negligible ripple. Both voltages given by Eqs. (2.1) and (2.2) indicate that output has a lower DC value than the input voltage. Therefore, the converters are referred to as step-down or buck converters.

Two other basic DC/DC converters include the boost and buck/boost converters. A boost converter can be defined as when the DC output voltage is higher than the input voltage. This design is also referred to as a step-up converter and a typical design is shown in Fig. 2.17. In this circuit, the switches are inserted between the inductor and the capacitor. If the converter is lossless, the ratio of the output DC voltage to the input DC voltage is given by Eq. (2.3). Since D is less than one, the output voltage is always higher than the input voltage.

$$V_{\text{avg}} = \frac{V_i}{D} \tag{2.3}$$

A buck/boost or step-up/down converter is shown in Fig. 2.18. This converter is capable of providing a DC output voltage that can be lower or higher than the input DC voltage. The input/output conversion ratio is given by Eq. (2.4).

$$\frac{V_o}{V_i} = \frac{D}{1-D} \tag{2.4}$$

When the D, is less than 0.5 the converter operates as a buck or step-down converter and when $D > 0.5$ the converter operates as step-up or boost converter.

For all basic DC/DC converters discussed so far the switch is implemented by a controlled switch (transistor) and an uncontrolled switch (diode). When the transistor and the diode are alternately switched, the mode of operation is referred to as

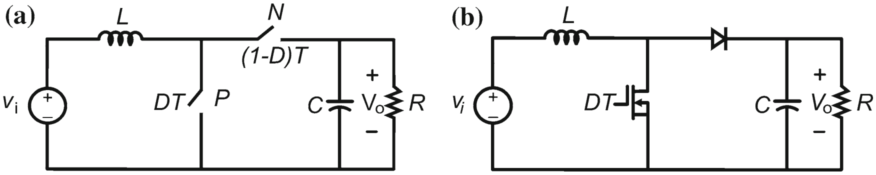


Fig. 2.17 Non-isolated boost (*up*) DC/DC converter: **a** circuit, and **b** switch implementation

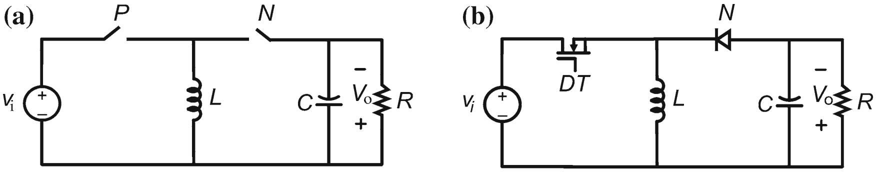


Fig. 2.18 The buck-boost (*up/down*) non-isolated DC/DC converter: **a** circuit, and **b** switch implementation