Chapter 1

Introduction

INTRODUCTION

This chapter is intended to give the reader an overview of the field of power electronics and its applications. Basic block diagrams will be provided for a power electronics system and its major functions. Different types of power electronic circuits used to achieve power conversion will be presented.

1.1 WHAT IS POWER ELECTRONICS?

To date, there is no widely accepted definition that clearly and specifically delimits the field of power electronics. In fact, many experts in the academic and industrial communities feel that the name itself does not do justice to the field, which is applications oriented and multidisciplinary in nature, and which also encompasses many subareas in electrical engineering.[1] Because of the multidisciplinary nature of the field of power electronics, experts must have a commanding knowledge of several electrical engineering subjects, such as electronic devices, electronic circuits, signal processing, magnetism, electrical machines, control, and power. In a very broad sense, power electronic circuits perform the task of processing one form of energy supplied by a source into a different form required at the load side. Hence, power electronics can be closely identified with the following subdiscipline areas of electrical engineering:

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[1] Many schools today offer power electronics under either the "power" or the "electronics" area, while a limited number of schools present it separately.

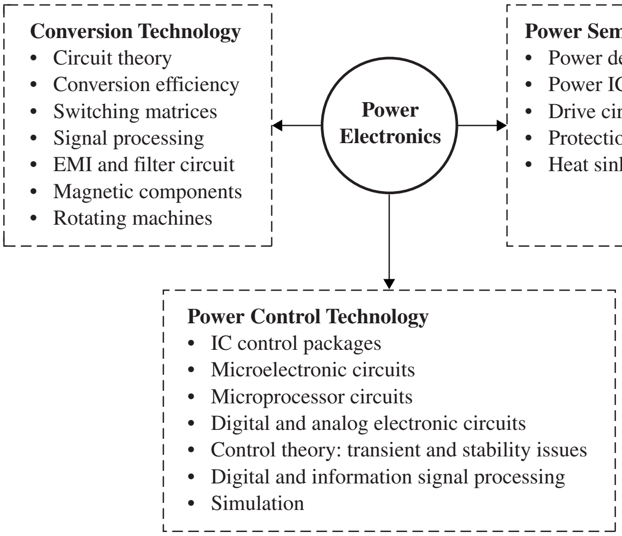

Figure 1.1 Power electronics encompasses three technologies: *power semiconductor, power conversion,* and *power control.*

electronics, power, and control. Here, *electronics* deals with the semiconductor devices and circuits used in signal processing to implement the control functions, *power* deals with both static and rotating equipment that uses electric power, and *control* deals with the steady-state stability of the closed-loop system during the power conversion process. Hence, the subject of power electronics deals specifically with the application of electronic semiconductor devices and circuits in the conversion and control of electric power. In summary, power electronics is a technology that brings together three fundamental technologies: power semiconductor technology, power conversion technology, and power control technology, as illustrated in Fig. 1.1.

A final observation is that in power electronic circuits there exist two types of switching devices: one type in the power stage that handles high power up to hundreds of gigawatts (which represents the muscle of the system) and another type in the feedback control circuit that handles low power up to hundreds of milliwatts, representing the brain or intelligence of the system. Hence, today's power electronic circuits are essentially digital electronic circuits whose switching elements manipulate power from milliwatts to gigawatts. As a result, one may conclude that the task of power electronics is to convert and control power using low-power switching devices that process power that is at much higher levels (a hundred times as great, or even greater). For example, a six-pulse SCR inverter with a power rating of a few kilowatts can process and control megawatts of power.

Recent Growth in Power Electronics

The field of power electronics has recently experienced unprecedented growth in terms of research and educational activities. Its applications have been steadily and rapidly expanded to cover many sectors of our society. This growth is due to several factors; paramount among them is the technological advancement by the semiconductor device industry, which has led to the introduction of very fast high-power capabilities and highly integrated power semiconductor devices. Other factors include (1) the revolutionary advances made in the microelectronics field that have led to the development of very efficient integrated circuits (ICs) used for the generation of control signals for processing and control purposes, (2) the ever-increasing demand for smaller-size and lighter-weight power electronic systems, and (3) the expanding market demand for new power electronic applications that require variable-speed motor drives, regulated power supplies, robotics, and uninterruptible power supplies. This increasing reliance on power electronic systems has made it mandatory that all such systems have radiated and conducted electromagnetic interference (EMI) limited within regulated ranges. The industry's interest in developing power systems with low harmonic content and with an improved power factor will continue to place the field of power electronics at the top of the research priority list.

1.2 THE HISTORY OF POWER ELECTRONICS

Before a review of the history of power electronics in the past century, it might be useful to cover the history of the development of ac and dc electricity in the last two decades of the nineteenth century. The inventions of the 1880s resulted in the present worldwide use of the ac electric power system, providing the energy form that must be processed for any power electronics application.

The History of dc and ac Electricity in the Late Nineteenth Century

It was decided in the middle of the nineteenth century that electrical energy was the most practical and economic form of energy for human use. Electricity was recognized as an excellent form of energy in terms of generation, transmission, and distribution. However, not long afterward, a heated debate began among scientists on whether the future of transmitting and distributing electricity to industries and homes would be based on alternating current (ac) or direct current (dc). George Westinghouse and Nikola Tesla (1856–1943) represented the ac camp, and Thomas Edison (1847–1931) represented the dc camp. After more than 15 years of intellectual debate, supported by new inventions and developmental and experimental studies, the ac advocates won; consequently, the entire world today uses an ac-based power distribution system.[2]

Thomas Edison was a self-educated inventor who was awarded 1033 patents over a 50-year period. He is best known for the invention of the phonograph and the incandescent lamp, which was invented in 1879 after many years of repeated experiments. In 1878, he formulated the concept of a centrally located power station from which power can be distributed to surrounding areas. On September 4, 1882, using dc generators (at that time called dynamos) driven by steam engines, he opened Pearl Street Station in New York City to supply electricity to 59 customers in a one-square-mile area. It was the first dc-based power station in the world, with a total power load of only 30 kW. It was the beginning of the electric utility industry, which grew at a remarkable rate. In 1884, Frank Sprague produced a practical dc motor for Edison's systems. This invention, coupled with the development of three-wire 220 VDC power, enabled Edison to distribute dc electrical power to larger areas and supply heavier loads and consequently more customers. Edison thereby prompted the adoption of

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[2] Tesla and Edison worked together for a short time, and soon developed hatred for one another, resulting in Tesla opening his own business, believing in ac transmission systems. In 1912, both were nominated for the Nobel Prize in physics. Because of the feud between them, Tesla declared that he had nothing to do with Edison, and the prize was given to a third party!

dc-based power distribution systems. As transmission distances and load demands increased, Edison's dc systems ran into trouble. The dc distribution lines suffered very high power losses because of the high voltage and current that existed simultaneously. This severely limited the transmission distance and resulted in highly inefficient systems. In order to sustain the power level, Edison had to build a dc power station every 20 km! This was costly and very impractical. However, he didn't give up on the dc transmission idea and insisted that these problems could be overcome.

George Westinghouse and Nikola Tesla didn't hesitate to develop ac-based power distribution systems, despite Edison's plans to continue to construct dc transmission systems in New York. In 1885, Westinghouse took a major step in developing ac systems when he bought the American patents of L. Gaulard and J. D. Gibbs of Paris for ac systems. Westinghouse challenged the dc transmission system and went ahead with developing an ac system.

A major step in supporting ac systems occured in 1885, when William Stanley, an early associate of George Westinghouse, developed a commercially practical transformer, allowing the possible distribution of ac-based electricity. Using transformers, it was possible to transmit high-level voltages with a very low-level current, resulting in a very low voltage drop (low power dissipation) in the transmission line. In the winter of 1886, Stanley installed the first experimental ac distributed system in Great Barrington, Massachusetts, supplying power to 150 lamps in the covered area. In 1889, the first single-phase distributed power system was operational in the United States between Oregon City and Portland, covering a 21 km distance with 4 kVA of power.

The second major event that boosted the potential of ac systems took place on May 16, 1888, when Tesla presented a paper at the annual meeting of the American Institute of Electrical Engineers, discussing two-phase induction and synchronous motors. Basically, he showed that it is more practical and more efficient to use polyphase systems to distribute power. The first three-phase ac transmission power system was installed in Germany in 1891; it was rated at 12 kV and transmitted over a distance of 179 km. Two years later (1893), the first three-phase power transmission system in the United States was installed in California, rated at 2.3 kV and covering a distance of 12 km. Also in 1893, a two-phase distributed system was demonstrated at the Colombian Exposition in Chicago. The apparent advantages of ac, especially the three-phase systems, over the dc system led to the gradual replacement of dc by ac systems. Today, the transmission of electricity is done almost entirely by means of ac. However, dc transmission of electric power is used in some locations in Europe and is rarely used in the United States. Since the late nineteenth century, economic studies have shown that ac transmission is much more cost-effective, resulting in its worldwide acceptance.

The History of dc and ac Electricity in the Late Twentieth Century

Over the last 25 years, the technological advancement by the semiconductor device industry, the revolutionary advances made in the microelectronics field, and the ever-increasing demand for smaller and lighter-weight power systems for space, industrial, and residential applications has led to renewed interest in using dc transmission systems. Many experts believe that because of technological advances, it is now possible to develop dc transmission electric power systems economically and efficiently. Today's systems for conversion from ac to dc and back to ac can be produced using very fast, high-power, and highly integrated semiconductor devices. What we can achieve using today's technology was unimaginable only 10 years ago. This is why many power electronics researchers believe that the old debate between dc and ac camps is coming back under a new set of technological rules.

In the mid-1890s, ac was declared a winner over dc, and in the mid-1990s, the dc promoters, mostly power electronics experts, had another shot at the ac camp! History repeats itself! The twenty-first century might very well be friendlier to dc transmission system advocates! Who will win the next century is still to be seen!

The History of Modern Power Electronics

Many agree that the history of power electronics began in 1900, when the glass-bulb mercury-arc rectifiers were introduced, signaling the beginning of the age of vacuum tube electronics, also called glass tube–based industrial electronics. This period continued until 1947, when the germanium transistor was invented at Bell Telephone Laboratory by Bardeen, Bratain, and Shockley, signaling the end of the age of vacuum tubes and the beginning of the age of transistor electronics. During the 1930s and 1940s several new power electronic circuits (then known as industrial electronics) were introduced, including the metal-tank rectifier, the grid-controlled vacuum-tube rectifier, the thyratron motor, and gas/vapor tube switching devices such as hot-cathode thyratrons, ignatrons, and phanotrons. In the 1940s and early 1950s, solid-state magnetic amplifiers, using saturable reactors, were introduced.

The modern era of power electronics began in 1958, when the General Electric Company introduced a commercial thyristor, two years after it was invented by Bell Telephone Laboratory. Soon all industrial applications that were based on mercury-arc rectifiers and power magnetic amplifiers were replaced by silicon-controlled rectifiers (SCRs). In less than 20 years after commercial SCRs were introduced, significant improvements in semiconductor fabrication technology and physical operation were made, and many different types of power semiconductor devices appeared. The growth in power electronics was made possible with the microelectronic revolution of the 1970s and 1980s, in which the low-power IC control chips provided the brain and the intelligence to control the high-power semiconductor devices. Moreover, the introduction of microprocessors made it possible to apply modern control theory to power electronics. In the last 20 years, the growth in power electronics applications has been remarkable because of the introduction of very fast and high-power switching devices, coupled with the utilization of state-of-the-art control algorithms. Today power electronics is a mature technology. The future direction of the era of power electronics is hard to predict, but it is certain that as long as humans seek to improve the quality of life, produce a cleaner environment, and implement energy-saving measures, the demand for clean energy will continue to grow. This implies that power electronics must be used to address the tremendous changes in the way we generate, transmit, and distribute electricity as we cross the bridge into the new century. For a more detailed discussion of the modern history of power electronics, see the paper by D. Wyke.

1.3 THE NEED FOR POWER CONVERSION

With the invention of a practical transformer by Stanley in 1885 and of polyphase ac systems by Tesla in 1891, the advantages of low-frequency ac over dc were compelling to power engineers. The basis of utility power system generation, transmission, and distribution since the beginning of this century has been ac at a fixed frequency of either 50 or 60 Hz. The most outstanding advantage of ac over dc is the maintenance of high voltage over long transmission lines and the simplicity of designing distribution networks. However, the nature of the electricity being distributed is totally different from the nature of the energy required by the electrical load.

At the consumer end many applications may need dc or ac power at line, higher, lower, or variable frequencies. Therefore, it is necessary to convert the available ac systems to dc with precise control. Furthermore, in some cases the generated power is from dc sources such as batteries, fuel cells, or photovoltaic, and in other cases the available power is generated as variable-frequency ac from sources such as wind or gas turbines. The need for this power conversion, ac-to-dc, became more acute with the invention of vacuum tubes, transistors, ICs, and computers. Moreover, modern electric conversion goes beyond ac-to-dc conversion, as we shall shortly discuss.

In the late 1880s, power conversion from ac to dc was done by using ac motors along with dc generators in series (motor-generator set). The motor-generator arrangement was used in dc and with 50/60 Hz motors and generators. The difficulties of using the electromechanical conversion system include large weight and size, noisy operation, servicing and maintenance problems, short lifetime, low efficiency, limited range of conversion, and slow recovery time. To avoid the problems of electromechanical conversion systems, industrial engineers turned to linear electronics in the late 1960s, where power semiconductor devices are operated in their linear (active) region. To obtain electrical isolation, input line-frequency transformers were used, resulting in bulky, heavy power converter systems. Furthermore, with power devices operating in the linear region, the overall efficiency of the system is low. Compared with electromechanical systems and linear electronic systems, power electronics has many advantages, including (1) high energy conversion efficiency, (2) highly integrated power electronic systems, (3) reduced EMI and electronic pollution, (4) higher reliability, (5) use of environmentally clean voltage sources such as photovoltaic and fuel cells to generate electric power, (6) the integration of electrical and mechanical systems, and (7) maximum adaptability and controllability.

In short, all forms of electrical power conversion will be needed as long as consumers live in homes and use light, heat, electronic devices, and equipment and interface with industry.

1.4 POWER ELECTRONIC SYSTEMS

Most power electronic systems consist of two major modules: (1) The power stage (forward circuit) and (2) the control stage (feedback circuit). The power stage handles the power transfer from the input to the output, and the feedback circuit controls the amount of power transferred to the output.

A generalized block diagram of a power electronic system with *n* sources and *m* loads is given in Fig. 1.2 where,

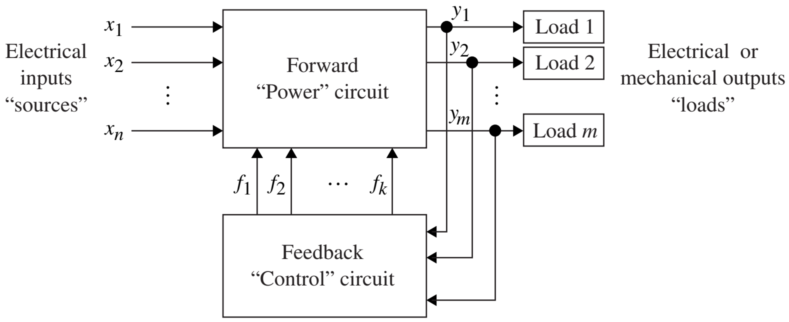


Figure 1.2 Simplified block diagram for a power electronic system.

$x_1, x_2, \ldots, x_n$ are input signals (voltage, current, or angular frequency).

$y_1, y_2, \ldots, y_m$ are output signals (voltages, currents, or angular frequency).

$p_{\text{in}}(t)$ is the total instantaneous input power in watts.

$p_{\text{out}}(t)$ is the total instantaneous output power in watts.

$f_1, f_2, \ldots, f_k$ are feedback signals: voltages or currents in an electrical system, or angular speed or angular position in a mechanical system.

Efficiency, η, is defined as follows:

$$\eta = \frac{p_{\text{out}}}{p_{\text{in}}} \times 100\%$$

Figure 1.3 shows a more detailed description of a block diagram for a power electronic input system with electrical and mechanical output loads. The main function of a power electronic circuit is to process energy from a given source to a required load. In many applications, the conversion process concludes with mechanical motion.

1.4.1 Classification of Power Converter Circuits

The function of the *power converter stage* is to perform the actual power conversion and processing of the energy from the input to the output by incorporating a matrix of power switching devices. The control of the output power is carried out through control signals applied to these switching devices. Broadly speaking, power conversion refers to the power electronic circuit that changes one of the following: voltage form (ac or dc), voltage level (magnitude), voltage frequency (line or otherwise), voltage waveshape (sinusoidal or nonsinusoidal, such as square, triangle, or sawtooth), or voltage phase (single- or three-phase).

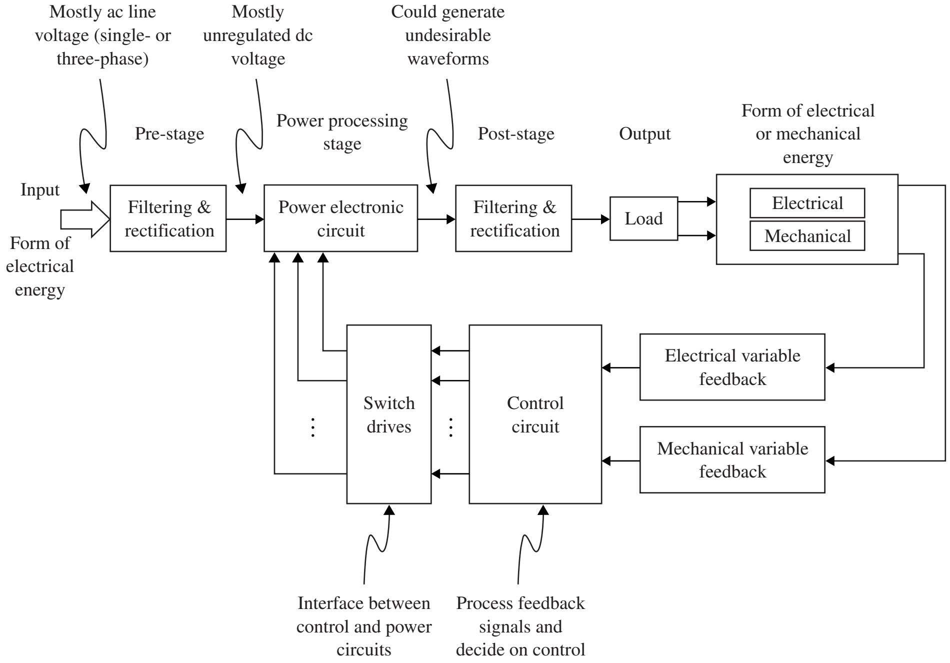


Figure 1.3 Detailed block diagram of a power electronic system.

Broadly speaking, there are four *conversion circuits* that are used in the majority of today's power electronic circuits:

a. ac-to-ac
b. ac-to-dc
c. dc-to-ac
d. dc-to-dc

In terms of the functional description, modern power electronic systems perform one or more of the following conversion functions:

1. Rectification (ac-to-dc)
2. Inversion (dc-to-ac)
3. Cycloconversion (ac-to-ac, different frequencies) or ac controllers (ac-to-ac, same frequency)
4. Conversion (dc-to-dc)

Rectification (ac-to-dc)

The term *rectification* refers to the power circuit whose function is to alter the ac characteristic of the line electric power to produce a "rectified" ac power at the load site that contains the dc value. Figure 1.4(*a*) and (*b*) shows the block diagram representation of an ac-to-dc converter and its typical input and output waveforms, respectively. To smooth out the output voltage by removing the unwanted ac component, an additional "filtering" circuit is added at the output side. Depending on the switch implementations, these converters are further divided into two types, *diode converter circuits* (*uncontrolled*) and *thyristor converters* (*phase-controlled*); each type can have either single-phase or three-phase input voltages. Both types are extensively used in various off-line applications. Rectification circuits will be discussed in Chapters 7 and 8. The topologies that perform the rectification function include half-wave, full-wave (full-bridge), semi-bridge, and transformer-coupled center-tapped. From the beginning of the industrial electronics era, the ac-to-dc line commutation converter class, utilizing thy-

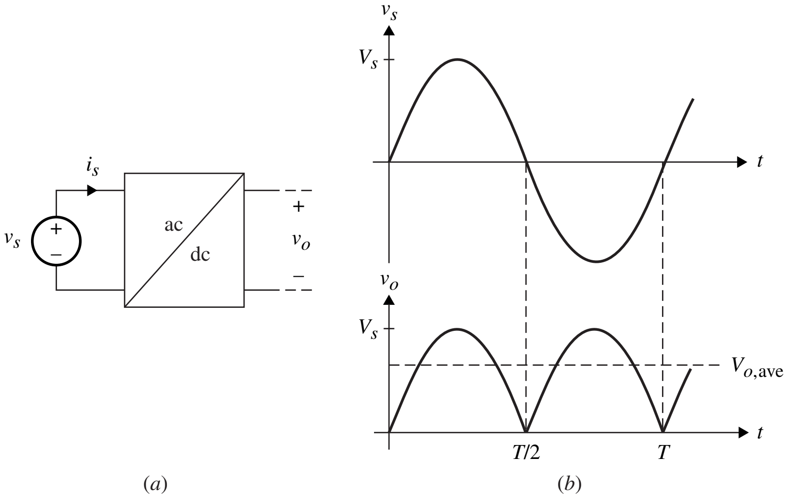
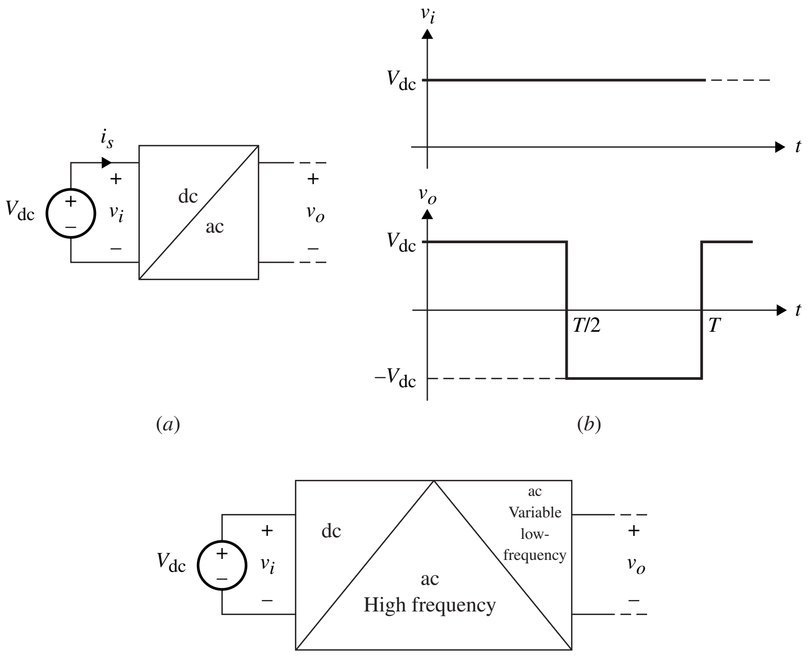


Figure 1.4 ac-dc rectification. (*a*) Simplified block diagram representation. (*b*) Example of ac-dc conversion.

ristors, has been the most popular among power electronics converters because of their simplicity in design, efficiency, and higher current and voltage ratings.

Inversion (dc-to-ac)

The term *inversion* is used in power electronic circuits for the function that alters the dc source (e.g., a battery) with no ac components into an "inverted" ac power at the load that has no dc components, as shown in Fig. 1.5(*a*). Example input and output waveforms are shown in Fig. 1.5(*b*). The ac output can have an adjustable magnitude and frequency. Additional filtering is normally used to extract the fundamental component of $v_o(t)$ at $\omega = 2\pi/T$. Generally speaking, dc-to-ac inverters are classified as voltage-fed and current-fed inverter types as discussed in Chapter 9. In the last few years, resonant-link technology that has been successful in the design of PWM power supplies has been applied to the design of dc-to-ac inverters, producing ac outputs at variable voltages and variable frequencies. A resonant-link dc-to-ac inverter is a two-stage conversion circuit that takes the dc voltage and changes it to a high ac resonant voltage, which in turn is changed to a variable low-frequency output, as shown in Fig. 1.5(*c*). Generally speaking, since cascaded systems involve a two-stage conversion, power processing passes through more than one switching device and therefore increases conduction losses. However, in some cases, by using intermediate stages, it is possible to insert an electrical isolation transformer; in other cases, cascaded stages produce high-frequency resonant waveforms that could result in the soft switching of the power devices, which in turn could reduce the overall switching losses of the cascaded system. The ac-to-dc rectification and dc-to-ac inversion represent the broadest functions of power electronic circuits.



(*a*) (*b*)

(*c*)

Figure 1.5 dc-to-ac inversion. (*a*) Simplified block diagram representation. (*b*) Example of dc-ac inversion. (*c*) Block diagram representation with high frequency inversion.

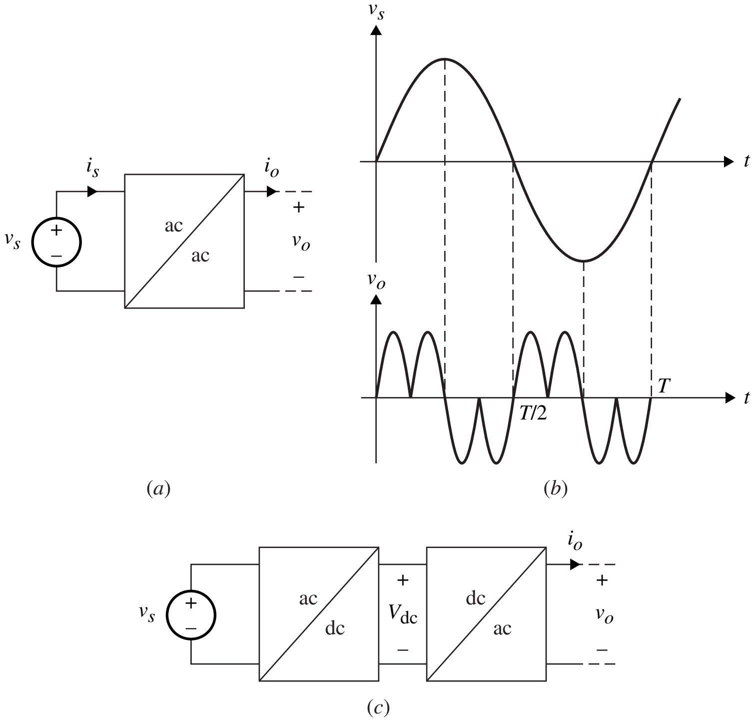


Figure 1.6 Cycloconversion. (*a*) One-stage ac-to-ac cycloconversion. (*b*) Example of ac-to-ac conversion waveforms. (*c*) Two-stage ac-to-ac cycloconversion.

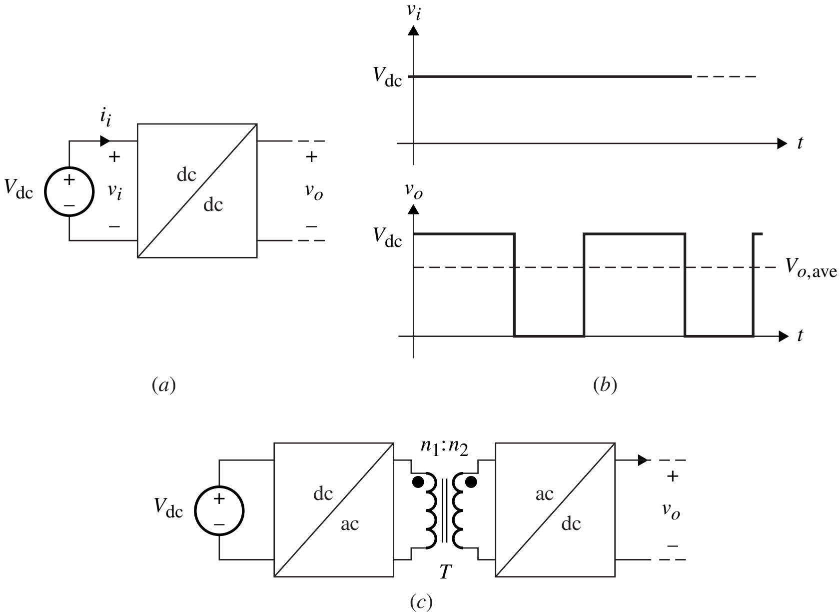
Cycloconversion or Voltage Controllers (ac-to-ac)

The term *cycloconversion* is used for power electronic circuits that convert the ac input power at one frequency to an ac output power at a different frequency using one-stage conversion, as shown in Fig. 1.6. However, two-stage conversion is also possible, as shown in Fig. 1.6(*c*), i.e., ac-to-dc and then dc-to-ac, resulting in what is called a dc-link converter. An ac controller is a power electronic circuit that alters the rms ac input at the same frequency.

Conversion (dc-to-dc)

Dc-to-dc converters are used in power electronic circuits to convert an unregulated input dc voltage to a regulated or variable dc output voltage, as shown by the block diagram and its waveform of Fig. 1.7(*a*) and (*b*), respectively. These circuits dominate the power supply industry, such as in the switch-mode power supplies (SMPS). In high-power dc traction drive applications, dc-to-dc converters are known as *choppers*. High-frequency pulse-width-modulation (PWM) converters with and without output electrical isolation will be discussed in Chapters 4 and 5, respectively. The high-frequency resonant-type dc-to-dc converters, which use two-stage conversion, will be discussed in Chapter 6; here transformers can be used to provide electrical isolation and step-up/step-down features. Figure 1.7(*c*) shows such an implementation.

To achieve this, we need to design converters that operate in the hundreds of kilohertz and up to a few megahertz. In resonant converters, the switching devices are used in such a way that the turn-on or turn-off losses can be reduced or eliminated, depending on the converter operation. Such converters are known as "soft-switching" converters. These



(*a*) (*b*)

(*c*)

Figure 1.7 Dc-to-dc conversion. (*a*) One-stage dc-to-dc conversion. (*b*) Example of waveforms. (*c*) Two-stage dc-to-dc conversion.

converters are used in the design of high-power density dc power supplies for laptop computers, adapters, notebook computers, and aerospace and communication instrumentation.

Figure 1.8 shows a simplified block diagram of a power electronic conversion system representing four possible conversion functions. The literature is rich with power electronic circuit topologies for various applications. When selecting a topology for a given application, one has to consider several factors, including the basic conversion function required; the available switching devices and their characteristics, driving circuits, control and protection, and maximum switching losses; and finally, the cost, size, and weight.

Depending on the topologies used and the types of loads, power electronic circuits are capable of transferring power in only one direction (i.e., unidirectional power flow from the source to the load) in both directions (i.e., bidirectional power flow from the load to the source). The latter is said to operate in the regenerative mode. Since the polarities of

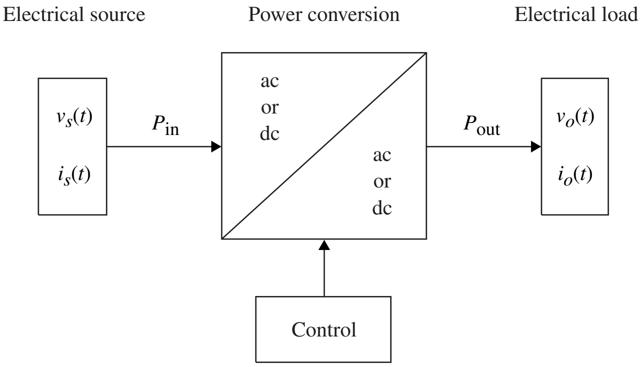


Figure 1.8 Simplified block diagram representation of the power electronic conversion function.

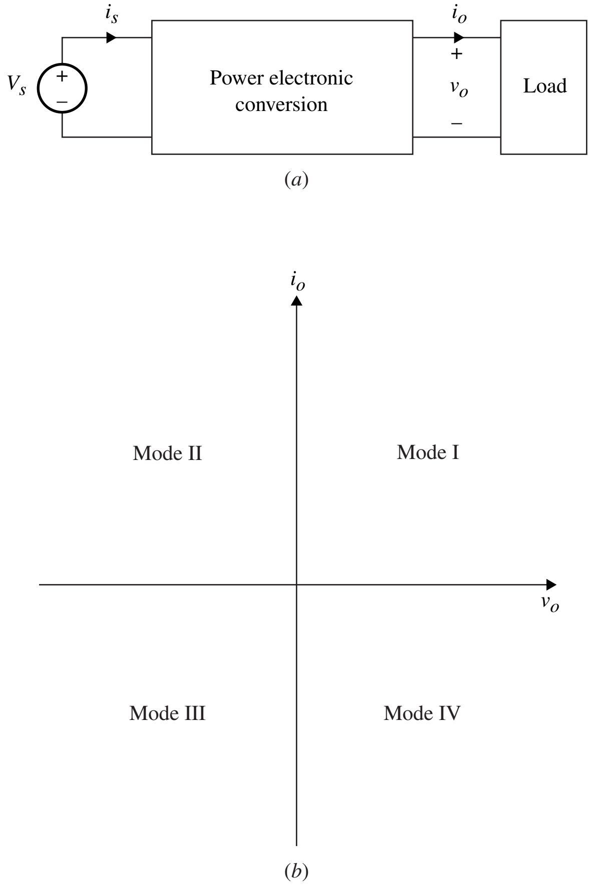


Figure 1.9 (*a*) Simple power electronic circuit with single voltage source and single load. (*b*) Possible converter modes of operation

the load current, i_o, and voltage, v_o, shown in Fig. 1.9(*a*) can be either positive or negative, there exist four modes of operation, as shown in Fig. 1.9(*b*).

In the first quadrant (mode I) the output voltage and current are always positive and the power flows unidirectionally to the load. Examples of such converters are the switch-mode dc-dc buck and boost converters. Similarly, in the third quadrant (mode III) the converter allows unidirectional power flow with both the output voltage and output current negative, as in the dc-dc buck-boost converter. The power electronic circuit with a dc motor can operate in modes I and II since the motor is capable of supporting the forward and reverse directions. Modes II and IV indicate that power is being transferred from the load to the source, as in the case of a dc generator. Converters that can operate in modes I and II or III and IV can support bidirectional power flow. Examples of converters operating in the different quadrants will be discussed in the following chapters.

1.4.2 Power Semiconductor Devices

Because of their high conversion efficiency, semiconductor switching devices are considered the heart of power electronic circuits, as we will see throughout the textbook. The control of power flow from the input to the output is done through a power-processing switching network made of switching devices and energy storage elements. Detailed discussion of the switching circuits will be given in the next chapter.

The need for new power electronic circuits to address the growing market demand for new applications has resulted in intensive research activities in the semiconductor industry to make available semiconductor devices with a wide range of power-handling capabilities and switching speeds.

The direction of power electronics has been, and will continue to be for many years to come, very much tied to the advancements made in power semiconductor technology. Due to the development of high-power, fast-switching, and high-efficiency thyristor-based unipolar and bipolar devices in the late 1950s and 1960s, the field of power electronics has emerged as a separate subarea in electrical engineering. Today, semiconductor switching devices have achieved unprecedented power-handling capabilities and switching speeds.

In the next chapter, we will study the *i-v* characteristics of five basic power devices widely used as switching elements in power electronic circuits. These devices include (1) power diodes, (2) bipolar junction transistors (BJTs), (3) metal oxide semiconductor field-effect transistors (MOSFETs), (4) thyristors or silicon-controlled rectifiers (SCRs), and (5) insulated gate bipolar transistors (IGBTs). Other available devices, such as triacs, diacs, gate-turn-off (GTO) thyristors, static induction transistors (SITs), static induction thyristors (SITHs), and MOS-controlled thyristors (MCTs) are, in one way or another, from the same families of these five basic devices. Many of these devices are rated in the hundreds of kilowatts! Even higher current and voltage ratings can be achieved by connecting devices in parallel and in series, respectively.

1.4.3 Converter Modeling and Control

In any power electronic circuit, the method used to control and stabilize power flow from the source to the load through the system is extremely important since the output must be regulated, whether it is voltage, current, or frequency. Over the last 30 years, tremendous efforts have gone into developing converter modeling methods that can be understood using well-known linear circuit analysis techniques. Moreover, the control of power electronic circuits has been greatly simplified by using microcomputer and commercial ICs that improve reliability, reduce the weight and size of hardware, and provide flexibility to the designer by changing the software algorithms. Also, the analysis and design of control circuits in power electronics have been made even easier with the availability of several simulation packages, such as PSPICE, MATLAB, and Saber. Converter modeling and analysis techniques are not included in the text since the emphasis is on circuits of the power stage.

1.5 APPLICATIONS OF POWER ELECTRONICS

Power electronics covers a wide range of residential, commercial, and industrial applications, including computers, transportation, aircraft/aerospace, information processing, telecommunication, and power utilities. Broadly speaking, these applications may be classified into three categories:

1. *Electrical applications*. Power electronics can be used to design ac and dc regulated power supplies for various electronic equipment, including consumer electronics, instrumentation devices, computers, aerospace, and uninterruptible power supply (UPS) applications. Power electronics is also used in the design of distributed power systems, electric heating and lighting control, power factor correction, and static var compensation.

2. *Electromechanical applications.* Electromechanical conversion systems are widely used in industrial, residential, and commercial applications. These applications include ac and dc machine tools, robotic drives, pumps, textile and paper mills, peripheral drives, rolling mill drives, and induction heating.
3. *Electrochemical applications.* Electrochemical applications include chemical processing, electroplating, welding, metal refining, production of chemical gases, and fluorescent lamp ballasts.

Table 1.1 gives a list of some power electronic application categories according to their conversion functions. We should mention that the examples given in Table 1.1 are not all-inclusive, but rather are given as an illustration of how wide the application spectrum of the field is. Finally, we note that the energy spectrum of the application of power electronics extends from a few watts, such as for a switching regulator, to a few megawatts, such as in high-voltage dc (HVDC) systems.

Table 1.1 Applications of Power Electronics by Conversion Functions (Partial List)

Conversion function	Applications
Uncontrolled ac-dc converters (diode circuits)	Front-end off-line regulated dc-to-ac power supplies and dc-ac inverters Battery chargers Welding dc motor drives
Phase-controlled converters (thyristor circuits)	Regulated dc power supplies ac and dc variable-speed motor control Battery chargers Flexible ac transmission system (FACTS) Utility interface of photovoltaic systems Regulated ac inverters Solid-state circuit breakers dc motor drives Induction heating Electromechanical processing (electroplating, anodizing, metal refining) HVDC systems Light dimmers Active power line conditioning (APLC) (var compensator, harmonic filters) Induction heating
dc-dc converters	High-frequency regulated dc power supplies using both isolated and nonisolated switch-mode and soft-switching resonant topologies Digital and analog electronics Solar energy conversion High-frequency quasi-resonant converters Electric vehicles and trams dc-fed forklifts Fuel cell conversion dc traction drives Distributed power systems Power factor correction Solid-state relays Capacitor chargers

(*continued*)

Table 1.1 (*continued*)

Conversion function	Applications
Linear-mode dc-dc converters	Low-power linear dc regulators Audio amplifiers RF amplifiers
Cycloconverters and ac controllers (ac-ac)	ac motor drives Rolling mill drives Static Scherbius drives Aircraft Frequency changers Solid-state power line conditioners Variable-speed constant-frequency (VSCF) systems Fluorescent lighting Light dimmers Induction heating
dc-to-ac inverters	Aircraft and space power supply systems ac variable-speed motor drives (lifts) Uninterruptible power supplies (UPS) Power factor correction Light dimmers Electric railroad systems Magnetically levitated (maglev) high-speed transportation systems Electric vehicles
Static switching	ac and dc circuit breakers Circuit protection Solid-state relays
Power ICs	Home and office automation Automobiles Telecommunications ac and dc drives dc power supplies

1.6 FUTURE TRENDS

It is hard to predict the direction of future research in the field of power electronics, or any field for that matter. However, based on today's research and teaching activities in power electronics, which are driven by market demands, energy conservation, and cost reduction, it is possible to identify some possible short-term future research activities in power electronics:

- Continued technological improvement of high-power and high-frequency semiconductor devices
- Continued development of power electronic converter topologies to attain further size and weight reduction with increased efficiency and performance
- Improvement in the design of driver circuits for switching devices
- Improvement in control techniques, including optimal and adaptive control
- Integration of power and control circuitry on "smart power" ICs and further development of application-specific modules
- Distributed power system (DPS) approach in applications such as VLSI mainframe computers, military VHSIC systems, and telecom switching equipment

- Power factor correction techniques and EMI reduction
- Additional applications of power electronics in flexible ac transmission systems (FACTS)

As power electronics becomes cheaper, it will extend into various new industrial, residential, aerospace, and telecommunications applications. Based on the growth of power electronics in recent years, future growth is projected to be even greater.

As long as we continue to seek improved standards of living, our quest for cheap and environmentally clean energy will continue. Power electronics will be used widely to address energy conservation and conversion efficiency. It has been reported that energy savings of more than 20% could be achieved with the help of power electronics. The role of power electronics will be greater as it becomes cheaper and more devices and systems become available. The challenge for power electronic circuit engineers is to keep developing new and optimal topologies to match market applications, and the challenge for power device engineers is to come up with new devices that can be used in these new topologies!

1.7 ABOUT THE TEXT AND ITS NOMENCLATURE

About the Text

This text is written in a way to benefit undergraduate students in electrical engineering the most. It is designed to be used in a one-semester power electronics course intended to be covered in an undergraduate introductory course in power electronics or first-year graduate power electronics course. Because of the interdisciplinary nature of power electronics, an expanded introduction (Chapters 1 to 3) has been provided to cover a brief orientation to the field, a review of power semiconductor devices, and general concepts that represent the cornerstone of power electronics.

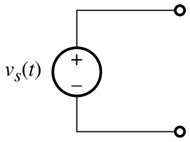
Nomenclature

To avoid confusion and repetition, we establish some definitions, terminology, and notations to be used throughout the text.

1. *Time-dependent variables (pure ac).* All instant time-dependent variables, including current (i), voltage (v), and power (p), will be presented as lowercase letters with lowercase subscripts:

   $$i_a(t),\ v_b(t),\ \text{and}\ p_i(t)$$

   The "(t)" indicates "function of time." For simplicity, the time notation is dropped and the variables are given by i_a, v_b, and p_i.
2. *Average and constant variables.* All average or constant variables will be given in uppercase letters and lowercase subscripts, such as V_s, I_o, $V_{o,\mathrm{rms}}$, and $I_{l,\mathrm{min}}$. To distinguish peak, dc, and rms values and constants, additional subscripts will be added when necessary.
3. The ac voltage source and the dc voltage source will be given as follows:

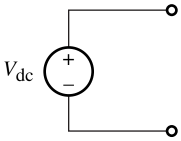


$$v_s(t) = V_s \sin \omega t \qquad \omega = 2\pi f = 2\pi / T$$

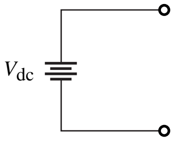
where

V_s = peak voltage
ω = angular frequency in radians/second
f = frequency in hertz
T = period in seconds

Rectified dc source:



Constant dc source (battery):



4. *Time-dependent variables (ac and dc).* Like the conventional notation in electronics, a lowercase variable and an uppercase subscript indicate that the time variable has both ac and dc components:

   $$i_L(t) = I_L + \hat{i}_L(t)$$

   where

   I_L = dc component
   $\hat{i}_L(t)$ = ac component

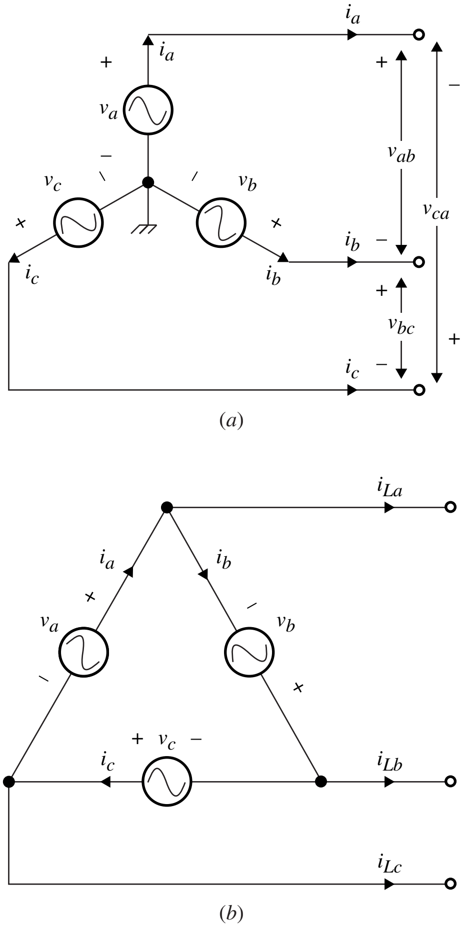
   The "$\hat{}$" notation indicates that the source of the ac component is perturbation around the dc value I_L. These notations are normally used when small-signal analysis and dynamic modeling of dc-dc converters are discussed.
5. The current and voltage sinusoidal harmonics of a periodical signal will be as follows:

   $$i_s(t) = I_{dc} + I_{s,1} \sin \omega t + I_{s,2} \sin 2\omega t + \cdots + I_{s,n} \sin n\omega t$$

   where

   I_{dc} = average value of the signal
   $I_{s,n}$ = peak value of the nth harmonic component of the signal, where $n = 1, 2, \ldots, \infty$
6. We will interchange the integration variables between time t and angular frequency ωt. For example,

   $$\frac{1}{T}\int_0^{T/2} V_s \sin \omega t \, dt = \frac{1}{2\pi}\int_0^{\pi} V_s \sin \omega t d\omega t$$
7. *Three-phase circuit representation.* Balanced three-phase voltage sources consist of three equal sinusoidal voltages each shifted by 120º from the other in such a way that their phase sum is zero. Two well-known three-phase configurations will be used in this text:



(*a*)

(*b*)

Figure 1.10 (*a*) Y-connected three-phase source. (*b*) Δ-connected three-phase source.

- Wye (Y) connected three-phase source as shown in Fig. 1.10(*a*):

$$\text{Phase voltages:}\quad \begin{cases} v_a = V_s \sin \omega t \\ v_b = V_s \sin(\omega t - 120°) \\ v_c = V_s \sin(\omega t - 240°) \end{cases}$$

$$\text{Line voltages:}\quad \begin{cases} v_{ab} = \sqrt{3}V_s \sin(\omega t + 30°) \\ v_{bc} = \sqrt{3}V_s \sin(\omega t - 90°) \\ v_{ca} = \sqrt{3}V_s \sin(\omega t - 210°) \end{cases}$$

Line (phase) currents: i_a, i_b, i_c

- Delta (Δ) connected three-phase source, as shown in Fig. 1.10(*b*):

$$\text{Phase (line) voltages:}\quad \begin{cases} v_a = V_s \sin \omega t \\ v_b = V_s \sin(\omega t - 120°) \\ v_c = V_s \sin(\omega t - 240°) \end{cases}$$

$$\text{Phase currents:}\quad \begin{cases} i_a = I_s \sin \omega t \\ i_b = I_s \sin(\omega t - 120°) \\ i_c = I_s \sin(\omega t - 240°) \end{cases}$$

$$\text{Line currents:}\quad \begin{cases} i_{La} = \sqrt{3} I_s \sin(\omega t + 30°) \\ i_{Lb} = \sqrt{3} I_s \sin(\omega t - 90°) \\ i_{Lc} = \sqrt{3} I_s \sin(\omega t - 210°) \end{cases}$$