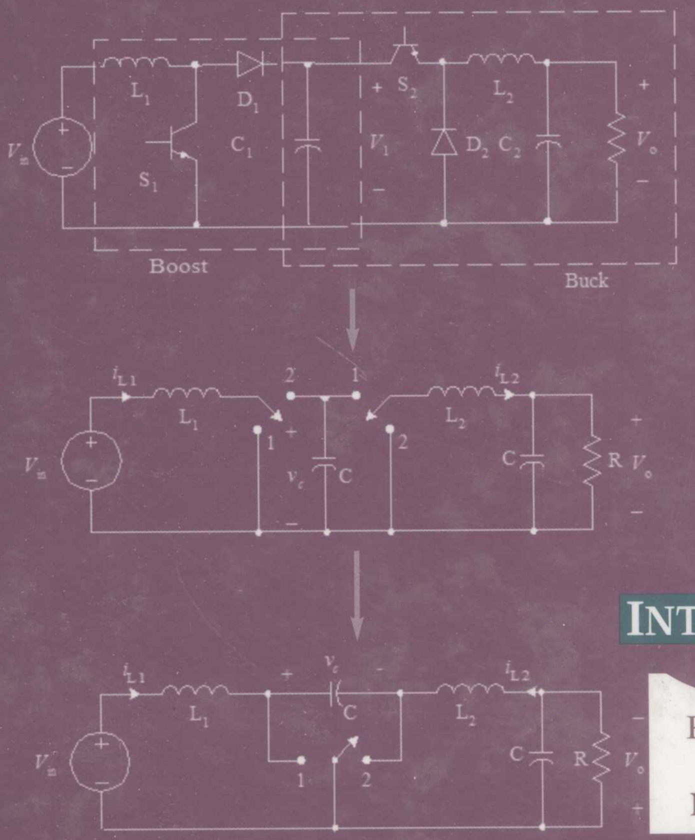
POWER ELECTRONIC CIRCUITS



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ISSA BATARSEH

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Preface

In recent years the field of power electronics has witnessed unprecedented research and teaching growth worldwide, emerging as a specialization in electrical engineering. This growth is due to expanding market demand for power electronic circuits for the energy conversion process. The need for power electronics engineers equipped with knowledge of new energy conversion technologies has never been greater.

Power Electronic Circuits is intended as a textbook to teach the subject of modern power electronics to senior undergraduate and first-year graduate electrical engineering students. Because of the breadth of the field of power electronics, teaching this subject to undergraduate students is a challenge. This textbook is designed to introduce the basic concepts of power electronics to students and professionals interested in updating their knowledge of the subject. The objective of this textbook is to provide students with the ability to analyze and design power electronic circuits used in various industrial applications.

The prerequisites for this text are a first course in circuit analysis techniques and a basic background in electronic circuits. Chapter 3 gives an overview of diode switching circuits and basic analysis techniques that students will find useful in the remaining chapters.

Material Presentation

Since the text is intended to be used in a three-credit-hour course in power electronics, topics such as power semiconductor devices, machine drives, and utility applications are not included. Because of limited lecture times, one course at the undergraduate level cannot adequately cover such topics and still present all power electronic circuits used in energy conversion. This text contains sufficient material for a single-semester introductory power electronics course, while giving the instructor flexibility in topic treatment and course design.

The text is written in such a way as to equip students with the necessary background material in such topics as devices, switching circuit analysis techniques, converter types, and methods of conversion in the first three chapters. The presentation of the material is new and has been recommended by many power electronics faculty. The discussion begins by introducing high-frequency, nonisolated dc-to-dc converters in Chapter 4, followed by isolated dc-to-dc converters in Chapter 5. Resonant soft-switching converters are treated early on in Chapter 6. The traditional diode and SCR converters and dc-ac inverters are presented in the second part of the text, in Chapters 7, 8, and 9, respectively.

Examples, Exercises, and Problems

Unlike many existing texts, this text provides students with a large number of examples, exercises, and problems, with detailed discussion of resonant and softswitching dc-to-dc converters.

Examples are used to help students understand the material presented in the chapter. To drill students in applying the basic concepts and equations, and to help them understand basic circuit operations, several exercises are given within each chapter. The text has more than 250 problems at different levels of complexity and difficulty. These problems are intended not only to strengthen students' understanding of the materials presented, but also to introduce many new concepts and circuits. To help meet recent Accreditation Board for Engineering and Technology (ABET) requirements for design in the engineering curriculum, special emphasis is made on providing students with opportunities to apply design techniques. Such problems are designated with the letter "D" next to the problem number, such as D5.32. Students should be aware that such problems are open-ended without unique solutions.

A bibliography is included at the end of the text and a list of textbooks is given separately.

About the Text

Like the majority of textbooks, this book was developed from class notes the author prepared over the last eight years while teaching power electronics at the University of Central Florida. The author started teaching power electronics in 1991, when only a limited number of power electronic textbooks were available. Since then, a handful of additional textbooks have been published with very similar material coverage. Unlike many existing texts, *Power Electronic Circuits* targets mainly senior undergraduate students majoring in electrical engineering.

Web-Based Course Material

Ancillaries to this text are available on a dedicated Web site, www.batarseh.org, established for both faculty and students to provide them with access to

- A complete set of lecture notes
- Sample quizzes
- PSPICE- and Mathcad-based simulation examples
- A complete solutions manual
- Transparency masters
- Up-to-date text corrections and the opportunity to submit new corrections

Even though the author's Web site is very useful in providing students and faculty with teaching material, at the time of this writing it doesn't offer an interactive platform. The author believes that due to the nonlinear interdisciplinary nature of the field of power electronics, computer simulations and computer tools must play an important role in delivering effective power electronics education. This is why any useful Web-based education in the area of power electronics must include a platform that allows students to do design and simulation interactively online. To the author's knowledge, this has not been effectively achieved yet. However, one of the most useful interactive Web-based facilities in power electronics is the Interactive Power Electronics Seminar (iPES) developed by the Swiss Federal Institute of Technology, Zurich (ETH Zurich), http://www.ipes.ethz.ch/. The Java applets are designed to allow a degree of interactivity and animation to aid in learning the basics of power electronics typically taught in an introductory course. The Web site is designed as a list of seminar topics and made "available on the Internet for private use and non-commercial use in classroom only." Also, the site provides course translations in Japanese, Korean, Chinese, and Spanish!

Acknowledgments

Over the last five years, many of my power electronics students have had the opportunity to read my lecture notes and solve many problems. Their feedback and comments were instrumental in presenting, to the best of our knowledge, error-free examples, exercises, and problems. I am grateful for reviewers' constructive suggestions for the students' sake. I am highly indebted to Khalid Rustom, Chris Iannelo, and Osama Abdel-Ruhman for spending many hours reviewing the examples, exercises, and problem solutions. Without their tireless work, this text would suffer from numerous errors and omissions! I am very fortunate to have such dedicated people work with me. I was also fortunate to have Dr. Kazi Khairul Islam visit our power electronics laboratory at UCF. He helped greatly in providing insightful suggestions on the inverters chapter, as well as in developing the appendixes. His suggestions and comments are greatly appreciated.

Special thanks go to the young, bright students from Princess Sumaya University for Technology in Amman, Jordan, who helped in typing and solving text problems during their stay at the University of Central Florida (UCF). Their names are Osama Abdul Rahman, Reem Khair, Ruba Amarin, Amjad Awwad, Bashar Nuber, Abeer Sharawi, Rami Beshawi, and Mohhamad Abu-Sumra. Specifically, I wish to acknowledge the help of two of my students, Khalid Rustom and Abdelhalim Alsharqawi, in solving problems and providing helpful insights throughout their undergraduate and graduate study at UCF. I would also like to thank my graduate students Guangyong Zhu, Huai Wei, Joy Mazumdar, Songquan Deng, and Jia Luo for their help and suggestions. Finally, thanks are due to Shadi Harb, Maen Jauhary, Samanthi Nadeeka, and William Said for their help in typing the solutions manual and developing the text Web site. Indeed, it was a pleasure working with all my students who made writing this text a gratifying and enjoyable experience.

Also, I would like to express my sincere thanks to Bill Zobrist, John Wiley & Sons Executive Editor, for his patience and support during the writing of the text, and special thanks to Jan Fisher, Project Manager at Publication Services, for her understanding and for keeping me on schedule.

Finally, I will never forget my late advisor, Professor C. Q. Lee, for introducing me to the field of power electronics and for being my advisor, teacher, mentor, and friend. On behalf of all of his students, I am dedicating this text to him. Of course, without my parents' love, patience, and support, this text would have never been written.

Issa Batarseh
Orlando, Florida

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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:

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

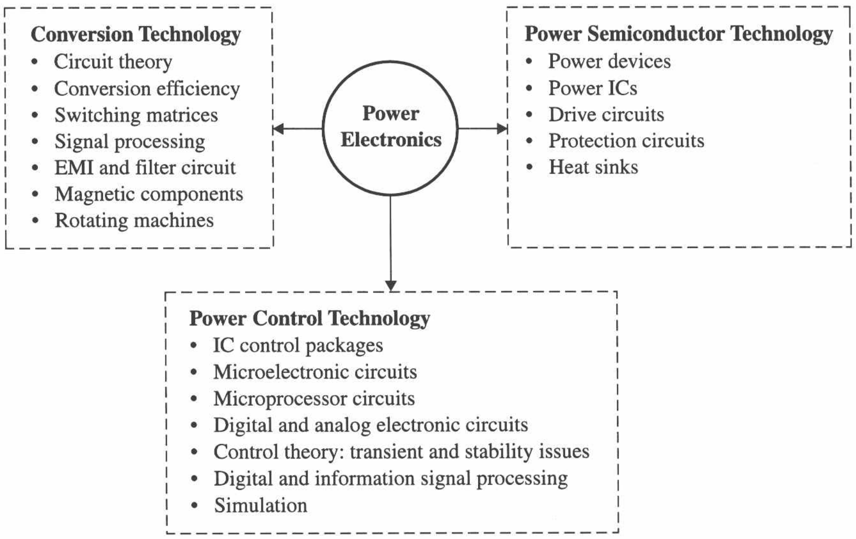

Figure 1.1 Power electronics encompasses three technologies: *power semiconductor, power conversion,* and *power control.*

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

[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,

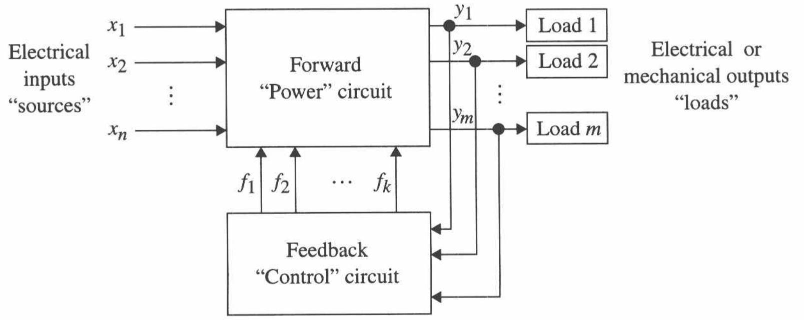

Figure 1.2 Simplified block diagram for a power electronic system.

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

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

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

$p_{out}(t)$ 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:

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

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).

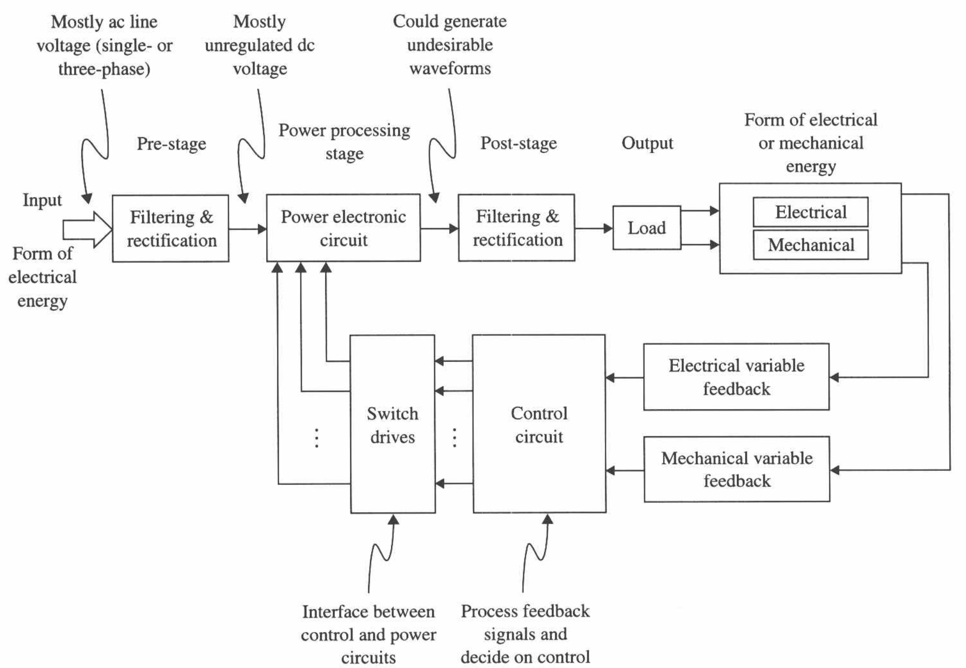

Figure 1.3 Detailed block diagram of a power electronic system.