CHAPTER 1

Introduction and Perspective

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Summary
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Power electronics deals with conversion and control of electrical power with the help of electronic switching devices. The magnitude of power may vary widely, ranging from a few watts to several gigawatts. Power electronics differs from signal electronics, where the power may be from a few nanowatts to a few watts, and processing of power may be by analog (analog electronics) or digital or switching devices (digital electronics). One advantage of the switching mode of power conversion is its high efficiency, which can be 96% to 99%. High efficiency saves electricity. In addition, power electronic devices are more easily cooled than analog or digital electronics devices. Power electronics is often defined as a hybrid technology that involves the disciplines of power and electronics. The conversion of power may include ac-to-dc, dc-to-ac, ac-to-ac at a different frequency, ac-to-ac at the same frequency, and dc-to-dc (also called chopper). Often, a power electronic system requires hybrid conversion, such as ac-to-dc-to-ac, dc-to-ac-to-dc, ac-to-ac-to-ac, etc. Conversion and regulation of voltage, current, or power at the output go together. A power electronics apparatus can also be looked on as a high-efficiency switching mode power amplifier. If charging of a battery is required from an ac source, an ac-to-dc converter along with control of the charging current is needed. If a battery is the power source and the speed of an induction motor is to be controlled, an inverter is needed. If 60-Hz ac is the power source, a frequency converter or ac controller is needed for speed control of the induction motor. A dc-to-dc converter is needed for speed control of a dc motor in a subway or to generate a regulated dc supply from a storage battery. Motor drives are usually included in power electronics because the motors require variable-frequency and/or variable-voltage power supplies with the help of power electronics.
Because power electronics equipment is based on nonlinear switching devices, it generates undesirable harmonics in a wide frequency range that flow in the load as well as in supply lines. A fast rate of change in voltage \((\frac{dv}{dt})\) and current \((\frac{di}{dt})\) due to switching creates electromagnetic interference (EMI) that couples with sensitive control circuits in its own and neighboring equipment. A switching mode converter with a discrete mode of control constitutes a nonlinear discrete time system and adds complexity to the analysis, mathematical modeling, computer simulation, design, and testing of the equipment. The design and testing phases become especially difficult at high power due to harmonics and EMI problems. In spite of this complexity, power electronics technology has been advancing at a rapid rate during the last three decades. Dramatic cost and size reductions and performance improvements in recent years are promoting extensive application of power electronics in the industrial, commercial, residential, aerospace, military, utility, and transportation environments. Power electronics–based energy and industrial motion control systems are now expanding globally to include the developing countries.
Modern solid-state power electronic apparatus is highly efficient compared to the traditional M-G sets, mercury-arc converters, and gas tube electronics. The equipment is static and has a low cost, small size, high reliability, and long life. Power electronics and motion control constitute vital elements in modern industrial process control that result in high productivity and improved product quality. Essentially, the importance of power electronics can be defined as close to that of computers. In a modern automobile plant, for example, power electric-controlled robots are routinely used for assembling, material handling, and painting. In a steel-rolling mill, motor drives with high-speed digital signal processor (DSP) control produce steel sheets in high volume with precise control of widths and thicknesses. Globally, electrical energy consumption is growing by leaps and bounds to improve our standard of living. Most of the world’s energy is produced in fossil and nuclear fuel power plants. Fossil fuel plants create environmental pollution problems, whereas nuclear plants have safety problems. Power electronics helps energy conservation by improved efficiency of utilization. This not only provides an economic benefit, but helps solve environmental problems. Currently, there is a growing trend toward using environmentally clean and safe renewable power sources, such as wind and photovoltaics, which are heavily dependent on power electronics. Fuel cell power generation also makes intensive use of power electronics.
The spectrum of power electronics applications is very wide, and this figure illustrates some key application areas. One end of the spectrum consists of dc and ac regulated power supplies. The dc switching mode power supplies (SMPS) from an ac line or dc source are routinely used in electronics apparatuses, such as a computer, radio, TV, VCR, or DVD player. An example of an ac-regulated supply is an uninterruptible power supply (UPS) system, in which single- or three-phase 60/50-Hz ac can be generated from a battery source. The power supply may also be generated from another ac source where the voltage and frequency may be unregulated. Electrochemical processes, such as electroplating, anodizing, production of chemical gases (hydrogen, oxygen, chlorine, etc.), metal refining, and metal reduction, require dc power that is rectified from ac. Heating control, light dimming control, and electronic welding control are
based on power electronics. Modern static VAR compensators (SVC or SVG), based on converters, help improve a system’s power factor. They are also key elements for modern flexible ac transmission systems (FACTS). Active harmonic filters (AHFs) are being increasingly used to filter out harmonics generated by traditional diode and thyristor converters. High voltage dc (HVDC) systems are used for long-distance power transmission or to inter-tie two systems with dissimilar frequencies. Here, the line power is rectified to dc and then converted back to ac for transmission. Photovoltaic (PV) arrays and fuel cells generate dc, which is converted to ac for normal consumption or feeding to the grid. A variable-speed constant frequency (VSCF) system converts a variable frequency power from a variable-speed ac generator to a constant frequency, for use in, for example, wind generation systems and aircraft ac power supplies. Solid-state dc and ac circuit breakers and high-frequency induction and dielectric heating equipment are widely used. The dc and ac motor drives possibly constitute the largest area of applications in power electronics.
This figure shows some examples of motor drive applications that will be discussed later in detail. A drive can be based on a dc or ac motor. For speed control, a dc motor requires variable dc voltage (or current), whereas an ac motor requires a variable-frequency, variable-voltage (or variable-current) power supply. Although dc drives constitute the bulk of current applications, modern advancements in ac drive technology are promoting their increasing acceptance, leading the dc drives toward obsolescence. Although process control is the main motivation for most of the drives, energy saving is the goal in some applications (e.g., air conditioning and heat pumps). The range of power, speed, and torque varies widely in various applications. Rolling mills and ship propulsion need high power (multi-megawatts); transportation, wind generation, starter-generator, pumps, etc., normally fall into the medium-power range (a few kilowatts to several megawatts), whereas computer and residential applications normally require low power (hundreds of watts to several kilowatts). While the majority of applications require speed control, some applications require position control and torque control. Again, ac motor drives can be based on induction or synchronous motors. Often, solid-state starters are used for soft-starting of ac motors, which normally operate at constant speed. An engineer has to design or select an economical and reliable drive system based on an appropriate machine, converter, and control system. These will be discussed later in detail.
The figure highlights the important role of power electronics in terms of the industrial competitiveness of the world in the 21st century. Power electronics with motion control is now an indispensable technology for industrial process control applications. Fortunately, we are now living in an era of industrial renaissance when not only the power electronics and motion control technologies, but also computers, communication, information, and transportation technologies are advancing rapidly. The advancement of these technologies has turned geographically remote countries in the world into close neighbors day by day. We now practically live in a global society, particularly with the recent advancement in Internet communication. The nations of the world have now become increasingly dependent on each other as a result of this closeness. In the new political order of the world in the post-Communism era, the possibility of global war appears remote. In spite of great diversity among nations, we can safely predict that in this century major wars in the world will be fought on an economic front rather than a military front. In the new global market, free from trade barriers, the nations around the world will face fierce industrial competitiveness for survival and improvement of standards of living. In the highly automated industrial environment, where companies struggle to produce high-quality, cost-effective products, it appears that two technologies will be most dominant: computers and power electronics with motion control.
Environmental pollution problems due to burning of fossil fuels (coal, oil, and natural gas) are becoming dominant issues in our society [1, 21]. The pollutant gases, such as CO$_2$, SO$_2$, NO$_x$, HC, O$_3$, and CO, cause global warming, acid rain, and urban pollution problems. With the rapidly increasing energy consumption trend, pollution is posing a serious threat for the future. The question is how can we solve or mitigate our environmental problems? As a first step, all of our energy consumption should be promoted in electrical form, and then advanced emission control standards can be applied in central fossil fuel power plants. The problems then become easier to handle when compared to distributed consumption of coal, oil, and natural gas. As emission control technologies advance, more and more stringent controls can be enforced in central power stations. The emission problems can be mitigated by emphasizing safe and environmentally clean renewable energy sources, such as hydro, wind, and photovoltaics of which hydro has been practically tapped in full. Urban pollution can be solved by widespread use of EV, HV, trolley buses/trams, and subway transportation. Wind, PV, EV, HV, trolley buses/trams, and subway drives are all heavily dependent on power electronics. Conservation of energy by more efficient use of electricity with the help of power electronics, and thus reduction of fuel consumption, is not only a definite way to reduce environmental pollution, but also to preserve our dwindling fuel resources. Unfortunately, availability of cheap energy promotes wastage. It has been estimated that approximately one-third of the energy generated is simply wasted in the United States [3] because energy is cheap, and consumers are negligent. In Japan, for example, energy is typically four times more expensive and, therefore, the desire to conserve energy, particularly with power electronics, is far greater.
Energy saving is one of the most important goals for power electronics applications [1]. Switching mode power control instead of traditional rheostatic control is highly efficient. Rheostatic speed control in a subway dc drive is still used in many parts of the world. According to the Electric Power Research Institute (EPRI) estimates, 60% to 65% of generated electrical energy in the United States is consumed in motor drives of which the major part is used for pump- and fan-type drives. The majority of these pumps and fans work in an industrial environment for control of fluid flow. In such applications, traditionally, the motor runs at constant speed and the flow is controlled by a throttle opening, where a lot of energy is lost due to turbulence. In contrast, variable-speed operation of the motor with the help of power electronics at full throttle opening is highly efficient. Again, most of the machines operate at light load most of the time. Motor efficiency can be improved by reduced flux operation instead of operating with rated flux. Air conditioners and heat pumps are normally controlled by on–off switching of thermostats. Instead, variable-speed load-proportional control can provide energy savings of as much as 30%. Roughly 20% of our generated energy is consumed in lighting. If fluorescent lamps are used instead of incandescent lamps, a substantial amount of energy can be saved. Again, use of high-frequency fluorescent lamps with power electronics–based lamp ballasts can save 20% to 30% in energy consumption. Such lamps have other advantages such as longer lamp life, smooth light, and dimming control capability.
Petroleum conservation and environmental (particularly urban) pollution control have been the main motivations for worldwide R&D activities in EV/HV for more than two decades. The world has limited oil reserves, and at the present consumption rate, it will barely last more than 75 years. Industrial nations are primarily dependent on imported oil. Although EV/HVs have been commercially introduced by a number of auto manufacturers around the world, their acceptance level in the market is currently low mainly due to higher initial costs, periodic battery replacement costs, and the difficulty of roadside servicing. Fortunately, they use power electronics extensively, where the technology is somewhat mature for cost and performance. It is essentially the limitations of battery technology that have inhibited the acceptance of EVs in the market. In spite of prolonged R&D, today’s propulsion batteries are too heavy, too expensive, have a low cycle life, and have limited storage capability making them suitable only for short-range driving. Having to replace batteries in EV/HVs every few years is an expensive proposition. In addition, fast and simultaneous charging of a large number of EV/HV batteries on utility distribution systems creates problems. An HV can truly replace an ICEV, but the dual needs of both power and energy sources make it more complex and expensive. Although the battery (Ni-MH, lead-acid, Ni-Cd, Li-ion) is the prime storage device, a flywheel or ultracapacitor could also be considered in HVs for temporary storage.
The IC engine is the traditional power source in HVs, but the diesel engine, Stirling engine, gas turbine, and fuel cell are also potential candidates [7]. Extensive R&D is required in storage and power devices to make EV/HVs more economical and acceptable in the market. (With the current trend toward rising gasoline costs, HVs are becoming more visible in the market.)
Wind is a very safe, environmentally clean, and economically renewable energy source. The world has enormous wind energy resources. According to estimates from the European Wind Energy Association, tapping only 10% of viable wind energy can supply the electricity needs of the whole world [12, 13]. Recent technological advances in variable-speed wind turbines, power electronics, and machine drives have made wind energy very competitive—almost equal with fossil fuel power. Wind and PV energy are particularly attractive to the one-third of the world’s population that lives outside the electric grid. Among the developing countries, for example, India and China have developed large expansion programs for wind energy. Currently, wind is the fastest growing energy technology in the world. Although Germany is currently the world leader in terms of installed capacity, the United States is next. In fact, the U.S. wind potential is so huge that it can meet more than twice its current electricity needs. North Dakota alone has 2.5 times the potential capacity of Germany. Currently, Denmark is the leader in wind energy utilization in terms of its percentage energy need. One of the drawbacks of wind energy is that its availability is sporadic in nature and requires backup power from fossil or nuclear power plants. The so-called future “hydrogen economy” concept will depend on abundant availability of wind energy that can be converted to electricity and then used to produce hydrogen fuel by electrolysis. Stored hydrogen will then be used extensively as an energy source, particularly for fuel cell vehicles.
Photovoltaic devices, such as silicon (crystalline and amorphous), convert sunlight directly into electricity. They are safe, reliable, static, environmentally clean (green), and do not require any repair and maintenance as do wind power systems. The lifetime of a PV panel is typically 20 years. However, with the current technology, PV is expensive—typically five times more costly than wind power. A solar conversion efficiency of around 16% has been reported with the commonly used thin-film amorphous silicon, although 24% efficiency has been possible for thick crystalline silicon [11, 15]. PV power has been widely used in space applications, where cost is not a primary concern, but terrestrial applications are limited because of its high cost. Interestingly, because of its high energy costs, Japan has the highest PV installations. Like wind power, PV is extremely important for off-grid remote applications. As the price falls, the market is steadily growing. With the current trends in research, its price is expected to fall sharply in the future, thus promoting extensive applications. Unfortunately, its availability, like wind power, is sporadic and thus requires backup sources.
A fuel cell is an electrochemical device that operates on the reverse process of electrolysis of water; that is, it combines hydrogen and oxygen to produce electricity and water. It is a safe, static, highly efficient (up to 60%), and environmentally clean source of power [16, 17]. Fuel cell stacks can be considered equivalent to series-connected low-voltage batteries. The dc voltage generated by fuel cells is normally stepped up by power electronics based on a dc-to-dc converter and then converted to ac by an inverter depending on the application. The cells are characterized by high output resistance and sluggish transient response (polarization effect). Fuel cell types are defined by the nature of their electrolytes. Hydrogen or hydrogen-rich gas for fuel cells can be generated, respectively, by electrolysis of water or by reformer (from gasoline, methanol) means of a reformer. In the latter case, pollutant gas is produced. Hydrogen can be stored in cylinders in either a cryogenically cooled liquefied form or as compressed gas. Fuel cells can be used in transportation and in portable or stationary power sources. In the current state of the technology, fuel cells are bulky and very expensive. Phosphoric acid fuel cells are currently available commercially with a typical cost of $5.50/W. However, with intensive R&D, fuel cells look extremely promising for the future. Automakers in the United States, Europe, and Japan have invested heavily to produce competitive fuel cell cars in the future with a target PEMFC fuel cell cost of $0.05/W.
The figure shows the concept for a future fuel cell (FC) vehicle with different possible sources for the H₂ fuel. In an FC vehicle, a PEMFC usually generates the dc power, which is converted to variable-frequency ac for driving the ac motor. Because FCs can not absorb regenerative power, a battery or ultracapacitor storage is needed at the FC terminal. The battery also supplies power during acceleration because of the sluggish response of FCs. The H₂ fuel can be supplied from a tank where it can be stored in liquid or gaseous form. H₂ can be generated by electrolysis of water or H₂-rich gas can be obtained from gasoline/methane by means of a reformer as shown. The electrolysis process requires electricity, which can be supplied from the grid or obtained from a wind generation system as shown. The O₂ for FCs can be obtained from the air by means of a compressor. The problem of air pollution remains with gasoline/methane fuel. The equipment is very expensive, and the need for multiple power conversions makes wind-generated power less efficient. However, H₂ generation is a good way for storing wind energy.
After several decades of evolution, power electronics and motor drives have been established as a complex and multidisciplinary technology. An engineer specializing in this area should have in-depth knowledge of power semiconductor devices, converter circuits, electrical machines, control electronics, microprocessors and DSPs, ASIC chips, control theories, power systems, and computer-aided design and simulation techniques. Knowledge of electromagnetic interference, the passive components (such as inductors, capacitors, and transformers) of such a system, and the accompanying specialized design, fabrication, and testing techniques are equally important. Very recently, the advent of artificial intelligence (AI) techniques, such as expert systems, fuzzy logic, artificial neural networks, and genetic algorithms, have advanced the frontier of the technology. Again, each of these component disciplines is advancing and creating challenges for power electronic engineers. Power semiconductors are extremely delicate and are often defined as the heart of modern power electronics. In-depth knowledge of devices is essential to make the equipment design reliable, efficient, and cost effective. A number of viable converter topologies may exist for a particular conversion function. The selection of optimum
topology depends on the power capacity of the equipment, interactions with the load and source, and various trade-off considerations. Electrical machines used in drives, particularly in closed-loop systems, require complex dynamic models. In modern high-performance drives, precise knowledge of machine parameters in the running condition often becomes very difficult to obtain. Power electronic control systems, particularly the drives, are nonlinear, multivariable, discrete time, and often very complex. Therefore, computer-aided design and simulation are often desirable. The complexity of control and signal estimation usually demands the use of microcomputers or DSPs that are going through endless evolution. Because power electronic equipment interfaces with power systems and their applications in utility systems are expanding, an in-depth knowledge of power systems is important.
The history of power electronics is around 100 years old. In 1901, Peter Cooper Hewitt of the United States first demonstrated a glass-bulb mercury-arc diode rectifier [20] primarily for supplying power to an arc lamp, which later became the steel tank rectifier. Of course, motor-generator (MG) sets were widely used earlier for power conversion and control. For example, the long-time popularly used Ward-Leonard method of speed control with an MG set was introduced in 1891. Gradually, grid-controlled rectifiers and inverters were introduced. Interestingly, in the New York subway, a mercury-arc rectifier (3000 kW) was first installed in 1930 for dc drives. In 1933, an ignitron rectifier was invented by Slepian, which was another milestone in history. Around the same time (1930s), gas tube electronics using phanotrons and thyratrons were introduced. Gas tube electronics proved unreliable during World War II and, therefore, saturable reactor magnetic amplifiers were introduced and proved to be very rugged and reliable, but bulky. The modern era of solid-state power electronics started with the introduction of the thyristor (or silicon-controlled rectifier). Bell Labs published the historical paper on the PNPN transistor in 1956, and
then in 1958, GE commercially introduced the thyristor into the marketplace. Since then, R&D in power electronics has radiated in different directions as shown in the figure. In power devices, R&D continued in different semiconductor materials, processing, fabrication and packaging techniques, device modeling and simulation, characterization, and development of intelligent modules. Starting with diode and thyristor converters, as new devices were introduced, many new converter topologies were invented along with advanced pulse width modulation (PWM) techniques and analytical and simulation methods. Many new control and estimation methods, particularly for drives, were introduced. These include vector or field-oriented control, adaptive and optimal controls, intelligent control, and sensorless control. Control hardware that is based on microprocessors, DSPs, and ASIC chips was introduced, along with software for control and simulation. The advent of powerful personal computers also played an important role in the power electronics evolution.
The evolution of power electronics can be categorized into four generations as indicated in the figure. The first generation spanning around 17 years, when thyristor-type devices dominated, is defined as the thyristor era. In the second generation, lasting about 10 years, self-controlled power devices (BJTs, power MOSFETs, and GTOs) appeared along with power ICs, microprocessors, ASIC chips, and advanced motor controls. In the third generation, the most dominant power device, the IGBT, was introduced and became an important milestone in power electronics history. In addition, SITs, IPMs, and powerful DSPs appeared with further advancements in control. Finally, in the current or fourth generation, new devices, such as IGCTs and cool MOSs appeared. There is currently a definite emphasis on power converters in the power electronic building block (PEBB) or integrated form. Also, sensorless vector control and intelligent control techniques appeared and are now front-line R&D topics.
The historical evolution of power electronics and motor drives was marked by many innovations in power devices, converters, PWM techniques, motor drives, control techniques, and applications. Some of the significant events in the history are summarized here with an approximate year. Many of these inventions and their applications will be further described later in the book.
Introduction and Perspective

The information on advances and trends in power electronics and drives is scattered widely in recent electrical engineering literature. First, many excellent text and reference books are available, but because the technology is advancing rapidly in recent years, books may not provide the latest information. It is better to start with the books and then fall back into the literature for in-depth information. Again, assimilation of literature information may be difficult without adequate background on the subject. The IEEE transactions publications and the conference records of the IAS (Industry Applications Society), PELS (Power Electronics Society), and IES (Industrial Electronics Society) are very dominant. In addition, the proceedings of the IEEE and other periodically held conference records throughout the world in the English language provide excellent information. Practical product information can be obtained from different company websites (some references are given in Chapter 2). Also, search in general websites (google.com, yahoo.com, etc.) and individual author websites.

Summary

The nature of power electronics and its importance, applications, and historical evolution have been summarized in this introductory chapter. The modern era of power electronics is often defined as an era of “second electronics revolution,” whereas the “first electronics revolution” resulted from the development of solid-state electronics. Besides the role of power electronics in industrial automation and energy systems, its role in energy
saving and environmental pollution control have been highlighted. The environmentally clean renewable energy systems (wind and photovoltaic), which are being so highly emphasized today, are heavily dependent on power electronics. In addition, power electronics has had a tremendous impact on electric/hybrid vehicles and future fuel cell applications. The continuing technological evolution of power electronics has significantly reduced the cost and improved the performance of power electronic devices, and currently their applications are expanding fast in industrial, commercial, residential, utility, aerospace and military applications. This trend will continue with full momentum in the future.

References