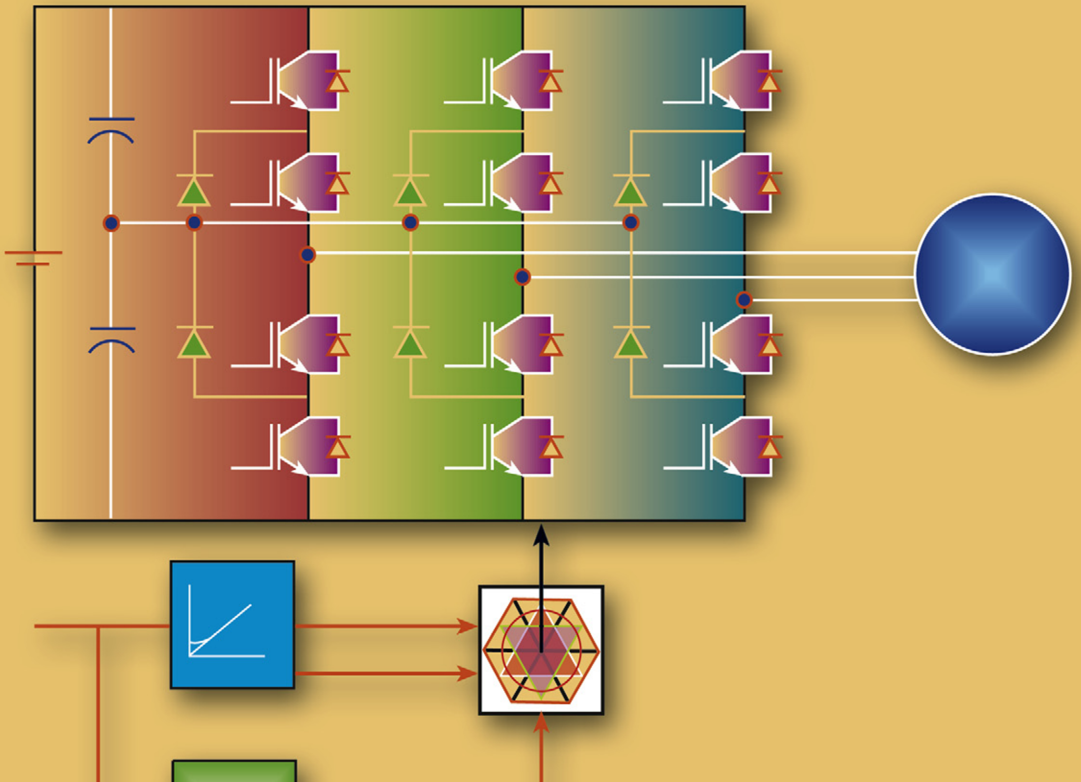
BIMAL BOSE

POWER ELECTRONICS and MOTOR DRIVES

ADVANCES and TRENDS



Power Electronics and Motor Drives

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Power Electronics and Motor Drives

Advances and Trends

Bimal K. Bose

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CONTENTS

	About the Author	***vii***
	Preface	***ix***
	List of Variables and Symbols	***xiii***
Chapter 1	Introduction and Perspective	1
Chapter 2	Power Semiconductor Devices	25
Chapter 3	Phase-Controlled Converters and Cycloconverters	73
Chapter 4	Voltage-Fed Converters and PWM Techniques	155
Chapter 5	Current-Fed Converters	281
Chapter 6	Electrical Machines for Variable-Speed Drives	325
Chapter 7	Induction Motor Drives	391
Chapter 8	Synchronous Motor Drives	477
Chapter 9	Computer Simulation and Digital Control	579

Chapter 10 Fuzzy Logic and Applications 649

Chapter 11 Neural Network and Applications 731

Chapter 12 Some Questions and Answers 851

Index ***901***

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ABOUT THE AUTHOR

Dr. Bimal K. Bose (*Life Fellow, IEEE*) has held the Condra Chair of Excellence in Power Electronics at the University of Tennessee, Knoxville, since 1987. Prior to this, he was a research engineer at General Electric Corporate Research and Development (now GE Global Research Center) in Schenectady, New York (1976–1987), faculty member at Rensselaer Polytechnic Institute, Troy, New York (1971–1976), and faculty member of Bengal Engineering and Science University (formerly Bengal Engineering College) for 11 years. He has done extensive research in power electronics and motor drive areas, including converters, PWM techniques, microcomputer/DSP control, motor drives, and application of expert systems, fuzzy logic, and neural networks to power electronic systems. He has authored or edited seven books, published more than 190 papers, and holds 21 U.S. patents. He has given invited presentations, tutorials, and keynote addresses throughout the world. He is a recipient of a number of awards and honors that include the IEEE Power Electronics Society William E. Newell Award (2005), IEEE Millennium Medal (2000), IEEE Meritorious Achievement Award in Continuing Education (1997), IEEE Lamme Gold Medal (1996), IEEE Industrial Electronics Society Eugene Mittelmann Award for lifetime achievement in power electronics (1994), IEEE Region 3 Outstanding Engineer Award (1994), IEEE Industry Applications Society Outstanding Achievement Award (1993), General Electric Silver Patent Medal (1986) and Publication Award (1987), and the Calcutta University Mouat Gold Medal (1970).

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PREFACE

I am presenting this novel book on advances and trends in power electronics and motor drives to the professional community with the expectation that it will be given the same wide and enthusiastic acceptance by practicing engineers, R&D professionals, university professors, and even graduate students that my other books in this area have. Unlike the traditional books available in the area of power electronics, this book has a unique presentation format that makes it convenient for group presentations that use Microsoft's PowerPoint software. In fact, a disk is included that has a PowerPoint file on it that is ready for presentation with the core figures. Presentations can also be organized using just selected portions of the book.

As you know, power electronics and motor drive technology is very complex and multidisciplinary, and it has gone through a dynamic evolution in recent years. Power electronics engineers and researchers are having a lot of difficulty keeping pace with the rapid advancements in this technology. This book can be looked on as a text for a refresher or continuing education course for those who need a quick review of recent technological advancements. Of course, for completeness of the subject, the core technology is described in each chapter. A special feature of the book is that many examples of recent industrial applications have been included to make the subject interesting. Another novel feature is that a separate chapter has been devoted to the discussion of typical questions and answers.

During the last 40+ years of my career in the industrial and academic environment, I have accumulated vast amounts of experience in the area of power electronics and motor drives. Besides my books, technical publications, and U.S. patents, I have given tutorials, invited presentations, and keynote addresses in different countries around the world at many IEEE as well as non-IEEE conferences. A mission in my life has been to promote power electronics globally. I hope that I have been at least partially successful. I pursued the advancement of power electronics technology aggressively from its beginning and have tried to present my knowledge and experience in the whole subject for the benefit of the professional community. However, the book should not be considered as a first or second course in power electronics. The reader should have a good background in the subject to assimilate the content of the book.

Each page contains one or more figures or a bulleted chart with explanations given below it—just like a tutorial presentation. The bulk of the figures are taken from my personal presentation materials from tutorials, invited seminars, and class notes. A considerable amount of material is also taken from my other publications, including the published books.

Unlike a traditional text, the emphasis is on physical explanation rather than mathematical analysis. Of course, exceptions have been made where it is absolutely necessary. After description of the core material in each chapter, the relevant advances and trends are given from my own experience and perspective. For further digging into the subject, selected references have been included at the end of each chapter. I have not seen a similar book in the literature. With its novel and unique presentation format, I describe it as a 21st-century book on power electronics. If opportunity arises, I will create a complete video course on the entire subject in the near future.

The content of the book has been organized to cover practically the entire field of power electronics. Chapter 1 gives a broad introduction and perspective on importance and applications of the technology. Chapter 2 describes modern power semiconductor devices that are viable in industrial applications. Chapter 3 deals with the classical power electronics, including phase-controlled converters and cycloconverters, which are still very important today. Chapter 4 describes voltage-fed converters, which are the most important type of converter in use today and will remain so tomorrow. The chapter includes a discussion of different PWM techniques, static VAR compensators, and active filters. Chapter 5 describes current-fed converters, which have been used in relatively large power applications. Chapter 6 describes different types of ac machines for variable-frequency drives. Chapter 7 deals with control and estimation techniques for induction motor drives, whereas Chapter 8 deals with control and estimation techniques for synchronous motor drives. Chapter 9 covers simulation and digital control in power electronics, including modern microcomputers and DSPs. The content of this chapter is somewhat new and very important. Chapter 10 describes fuzzy logic principles and their applications, and Chapter 11 provides comprehensive coverage of artificial neural networks and their applications. Finally, Chapter 12 poses some selected questions and their answers which are typical after any tutorial presentation.

This book could not have been possible without active contributions from several of my professional colleagues, graduate students, and visiting scholars in my laboratory. The most important contribution came from Lu Qiwei, a graduate student of China University of Mining and Technology (CUMT), Beijing, China, who devoted a significant amount of time to preparing a large amount of the artwork for this book. Professor Joao Pinto of the Federal University of Mato Grosso do Sul (UFMS) in Brazil made significant contributions to the book in that he prepared the demonstration programs in fuzzy logic and neural network applications. I also acknowledge the help of his graduate students. Dr. Wang Cong of CUMT provided help in preparation of the book. Dr. Kaushik Rajashekara of Rolls-Royce gave me a lot of ideas for the book and worked hard in checking the manuscript. Dr. Hirofumi Akagi of the Tokyo Institute of Technology, Japan, gave me valuable advice. Dr. Marcelo Simoes of the Colorado School of Mines and Ajit Chattopadhyay of Bengal Engineering and Science University, India, also deserve thanks for their help. Finally, I would like to thank my graduate students and visiting scholars for their outstanding work, which made the book possible. Some of them are Drs. Marcelo Simoes; Jason Lai of Virginia Tech; Luiz da Silva of Federal University of Itajuba, Brazil; Gilberto Sousa of Federal University of Espirito Santo, Brazil; Wang Cong; Jin Zhao of Huazhong University of Science and Technology, China; M. H. Kim of Yeungnam College of Science & Technology, Korea; and Nitin Patel of GM Advanced Technology Vehicles. In my opinion, they are the best scholars in the world—it is often said that great graduate students and visiting scholars make the professor great. I am also thankful to the University of Tennessee for providing me with opportunities to write this book. Finally, I acknowledge the immense patience and sacrifice of my wife Arati during preparation of the book during the past 2 years.

Bimal K. Bose
June 2006

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LIST OF VARIABLES AND SYMBOLS

d^e-q^e	Synchronously rotating reference frame direct and quadrature axes
d^s-q^e	Stationary reference frame direct and quadrature axes (also known as α-β axes)
f	Frequency (Hz)
I_d	dc current (A)
I_f	Machine field current
I_L	rms load current
I_m	rms magnetizing current
I_P	rms active current
I_Q	rms reactive current
I_r	Machine rotor rms current (referred to stator)
I_s	rms stator current
$i_{dr}{}^s$	d^s axis rotor current
$i_{ds}{}^s$	d^s axis stator current
i_{dr}	d^e axis rotor current (referred to stator)
i_{qr}	q^e axis rotor current (referred to stator)
i_{qs}	q^e axis stator current
J	Rotor moment of inertia (kg-m^2)
X_r	Rotor reactance (referred to stator) (ohm)
X_s	Synchronous reactance
X_{ds}	d^e axis synchronous reactance
X_{lr}	Rotor leakage reactance (referred to stator)
X_{ls}	Stator leakage reactance
X_{qs}	q^e axis synchronous reactance

α	Firing angle
β	Advance angle
γ	Turn-off angle
δ	Torque or power angle of synchronous machine
θ	Thermal impedance (Ohm); also torque angle
θ_e	Angle of synchronously rotating frame ($\omega_e t$)
θ_r	Rotor angle
θ_{sl}	Slip angle ($\omega_{sl} t$)
μ	Overlap angle
τ	Time constant (s)
L_c	Commutating inductance (H)
L_d	dc link filter inductance
L_m	Magnetizing inductance
L_r	Rotor inductance (referred to stator)
L_s	Stator inductance
L_{lr}	Rotor leakage inductance (referred to stator)
L_{ls}	Stator leakage inductance
L_{dm}	d^e axis magnetizing inductance
L_{qm}	q^e axis magnetizing inductance
m	PWM modulation factor for SPWM (m = 1.0 at undermodulation limit, i.e., m' = 0.785)
m'	PWM modulation factor, where m' = 1 at square wave
p	Number of poles
P	Active power
P_g	Airgap power (W)
P_m	Mechanical output power
Q	Reactive power
R_r	Rotor resistance (referred to stator)
R_s	Stator resistance
S	Slip (per unit)

T	Time period(s); also temperature (°C)
T_e	Developed torque (Nm)
T_L	Load torque
t_{off}	Turn-off time
V_c	Counter emf
V_d	dc voltage
V_I	Inverter dc voltage
V_f	Induced emf
V_m	Peak phase voltage (V)
V_g	rms airgap voltage
V_R	Rectifier dc voltage
v_s	Instantaneous supply voltage
v_d	Instantaneous dc voltage
v_f	Instantaneous field voltage
v_{dr}^s	d^s axis rotor voltage (referred to stator)
v_{ds}^s	d^s axis stator voltage
v_{dr}	d^e axis rotor voltage (referred to stator)
v_{qr}	q^e axis rotor voltage (referred to stator)
v_{qs}	q^e axis stator voltage
φ	Displacement power factor angle
ψ_a	Armature reaction flux linkage (Weber-turns)
ψ_f	Field flux linkage
ψ_m	Airgap flux linkage
ψ_r	Rotor flux linkage
ψ_s	Stator flux linkage
ψ_{dr}^s	d^s axis rotor flux linkage (referred to stator)
ψ_{ds}^s	d^s axis rotor flux linkage
ψ_{dr}	d^e axis rotor flux linkage (referred to stator)
ψ_{qr}	q^e axis rotor flux linkage (referred to stator)

ψ_{qs} q^e axis stator flux linkage

ω_e Stator or line frequency ($2\pi f$) (rad/s)

ω_m Rotor mechanical speed

ω_r Rotor electrical speed

ω_{sl} Slip frequency

$\hat{X}$ Peak value of a sinusoidal phasor or sinusoidal space vector magnitude; also estimated parameter, where X is any arbitrary variable

$\bar{X}$ Space vector variable; also designated by the peak value $\hat{X}$ where it is a sinusoid

CHAPTER 1

Introduction and Perspective

Figure 1.1	What is power electronics?
Figure 1.2	Features of power electronics.
Figure 1.3	Why is power electronics important?
Figure 1.4	Power electronics applications.
Figure 1.5	Application examples in variable-speed motor drives.
Figure 1.6	Power electronics in industrial competitiveness.
Figure 1.7	How can we solve or mitigate environmental problems?
Figure 1.8	Energy saving with power electronics.
Figure 1.9	Electric and hybrid vehicle scenario.
Figure 1.10	Wind energy scenario.
Figure 1.11	Photovoltaic energy scenario.
Figure 1.12	Fuel cell power scenario.
Figure 1.13	Fuel cell EV and the concept of a hydrogen economy.
Figure 1.14	Power electronics—an interdisciplinary technology.
Figure 1.15	Evolution of power electronics.
Figure 1.16	Four generations of solid-state power electronics.
Figure 1.17	Some significant events in the history of power electronics and motor drives.
Figure 1.18	Where to find information on power electronics.
Summary	
References	

FIGURE 1.1 What is power electronics?

CONVERSION AND CONTROL OF ELECTRICAL POWER
BY
POWER SEMICONDUCTOR DEVICES

MODES OF CONVERSION

- RECTIFICATION: AC – to – DC
- INVERSION: DC – to – AC
- CYCLOCONVERSION: AC – to – AC
  (Frequency changer)
- AC CONTROL: AC – to – AC
  (Same frequency)
- DC CONTROL: DC – to – DC

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.

FIGURE 1.2 Features of power electronics.

- HARMONICS AND EMI AT LOAD AND SOURCE SIDE
- NONLINEAR DISCRETE TIME SYSTEM
- COMPLEXITY IN ANALYSIS, MODELING, SIMULATION, DESIGN, AND TESTING
- FAST ADVANCING TECHNOLOGY IN LAST THREE DECADES
- FAST GROWTH IN APPLICATIONS

  INDUSTRIAL
  COMMERCIAL
  RESIDENTIAL
  AEROSPACE
  MILITARY
  UTILITY SYSTEM
  TRANSPORTATION

- GLOBAL EXPANSION OF TECHNOLOGY AND APPLICATIONS

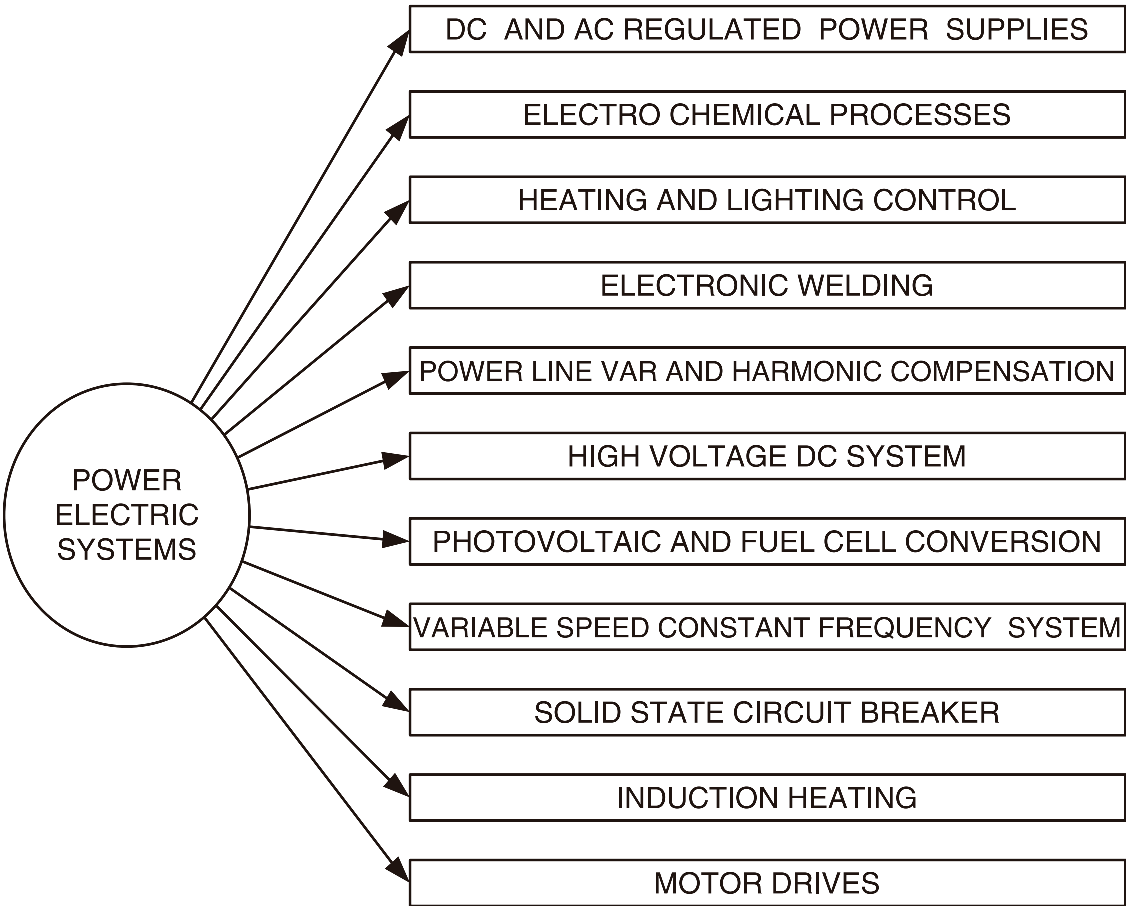
Because power electronics equipment is based on nonlinear switching devices, it generates undesirable harmonics in a wide frequency range that flow in the load as well as in supply lines. A fast rate of change in voltage (dv/dt) and current (di/dt) due to switching creates electromagnetic interference (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.

FIGURE 1.3 Why is power electronics important?

- ELECTRICAL POWER CONVERSION AND CONTROL AT HIGH EFFICIENCY
- APPARATUSES HAVE LOW COST, SMALL SIZE, HIGH RELIABILITY, AND LONG LIFE
- VERY IMPORTANT ELEMENT IN MODERN ELECTRICAL POWER PROCESSING AND INDUSTRIAL PROCESS CONTROL
- FAST GROWTH IN GLOBAL ENERGY CONSUMPTION
- ENVIRONMENTAL AND SAFETY PROBLEMS EXPERIENCED BY FOSSIL AND NUCLEAR POWER PLANTS
- INCREASING EMPHASIS ON ENERGY SAVING AND POLLUTION CONTROL FEATURES BY POWER ELECTRONICS
- GROWTH OF ENVIRONMENTALLY CLEAN SOURCES OF POWER THAT ARE POWER ELECTRONICS INTENSIVE (WIND, PHOTOVOLTAIC, AND FUEL CELLS)

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.

FIGURE 1.4 Power electronics applications.



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.

FIGURE 1.5 Application examples in variable-speed motor drives.

- TRANSPORTATION—EV/HV, SUBWAY, LOCOMOTIVES, ELEVATORS
- HOME APPLIANCES—BLENDERS, MIXERS, DRILLS, WASHING MACHINES
- PAPER AND TEXTILE MILLS
- WIND POWER GENERATION
- AIR CONDITIONERS AND HEAT PUMPS
- ROLLING AND CEMENT MILLS
- MACHINE TOOLS AND ROBOTICS
- PUMPS AND COMPRESSORS
- SHIP PROPULSION
- COMPUTERS AND PERIPHERALS
- SOLID-STATE STARTERS FOR MACHINES

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.

FIGURE 1.6 Power electronics in industrial competitiveness.

- COMMUNICATION AND TRANSPORTATION TECHNOLOGY ADVANCEMENTS HAVE TURNED REMOTE COUNTRIES INTO CLOSE NEIGHBORS—WE NOW LIVE IN GLOBAL VILLAGE
- NATIONS ARE INCREASINGLY MORE INTERDEPENDENT
- FUTURE WARS WILL BE FOUGHT ON AN ECONOMIC FRONT, RATHER THAN A MILITARY FRONT
- INDUSTRIAL AUTOMATION AND GLOBAL COMPETITIVENESS OF NATIONS—KEY TO SURVIVAL AND ECONOMIC PROSPERITY
- POWER ELECTRONICS WITH MOTION CONTROL AND COMPUTERS ARE THE MOST IMPORTANT TECHNOLOGIES FOR INDUSTRIAL AUTOMATION IN 21st CENTURY

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.

FIGURE 1.7 How can we solve or mitigate environmental problems?

- PROMOTE ALL ENERGY USAGE IN ELECTRICAL FORM
- CENTRALIZE FOSSIL FUEL POWER GENERATION AND APPLY ADVANCED EMISSION STANDARDS
- MOVE TOWARD GREATER USE OF RENEWABLE ENERGY SOURCES: HYDRO, WIND, AND PHOTOVOLTAIC
- REPLACE ICE VEHICLES WITH ELECTRIC AND HYBRID VEHICLES
- CONSERVE ENERGY BY EFFICIENT USE OF ELECTRICITY
- PREVENT ENERGY WASTE

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 negligenct. 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.

FIGURE 1.8 Energy saving with power electronics.

- CONTROL OF POWER BY ELECTRONIC SWITCHING IS MORE EFFICIENT THAN OLD RHEOSTATIC CONTROL
- ROUGHLY 60% TO 65% OF GENERATED ENERGY IS CONSUMED IN ELECTRICAL MACHINES, MAINLY PUMPS AND FANS
- VARIABLE-SPEED, FULL-THROTTLE FLOW CONTROL CAN IMPROVE EFFICIENCY BY 30% AT LIGHT LOAD
- LIGHT-LOAD REDUCED-FLUX MACHINE OPERATION CAN FURTHER IMPROVE EFFICIENCY
- VARIABLE-SPEED AIR CONDITIONERS/HEAT PUMPS CAN SAVE ENERGY BY 30%
- 20% OF GENERATED ENERGY IS USED IN LIGHTING
- HIGH-FREQUENCY FLUORESCENT LAMPS ARE TWO TO THREE TIMES MORE EFFICIENT THAN INCANDESCENT LAMPS

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.

FIGURE 1.9 Electric and hybrid vehicle scenario.

- POWER ELECTRONICS AND DRIVES INTENSIVE—SOMEWHAT MATURE TECHNOLOGY
- LIMITATION OF BATTERY TECHNOLOGY
- EV HAS LIMITED RANGE—SUITABLE FOR SHORT-RANGE AND INDOOR APPLICATIONS
- HYBRID VEHICLE CAN REPLACE ICEV, BUT IS MORE EXPENSIVE
- POSSIBLE STORAGE DEVICES:
    - BATTERY
    - FLYWHEEL
    - ULTRACAPACITOR
- POSSIBLE POWER DEVICES:
    - IC ENGINE
    - DIESEL ENGINE
    - STIRLING ENGINE
    - GAS TURBINE
    - FUEL CELL
- CURRENTLY, HVs ARE MORE VISIBLE DUE TO RISE OF GASOLINE PRICE

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.)

FIGURE 1.10 Wind energy scenario.

- MOST ECONOMICAL, ENVIRONMENTALLY CLEAN, AND SAFE "GREEN" POWER
- ENORMOUS WORLD RESOURCES—TAPPING ONLY 10% CAN SUPPLY ELECTRICITY NEED FOR THE ENTIRE WORLD
- COMPETITIVE COST WITH FOSSIL FUEL POWER ($0.05/kWh, $1.00/kW)
- TECHNOLOGY ADVANCEMENT IN POWER ELECTRONICS, VARIABLE-SPEED DRIVES, AND VARIABLE-SPEED WIND TURBINES
- CURRENTLY, GERMANY IS THE WORLD LEADER (4800 MW); NEXT IS UNITED STATES (2600 MW)
- CURRENTLY, 1.0% ELECTRICITY NEED IN UNITED STATES; WILL INCREASE TO 5% BY 2020
- CURRENTLY, 13% ELECTRICITY NEED IN DENMARK; WILL INCREASE TO 40% BY 2030
- PROBLEM OF STATISTICAL AVAILABILITY—NEEDS BACKUP POWER
- KEY ENERGY SOURCE FOR FUTURE HYDROGEN ECONOMY

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.

FIGURE 1.11 Photovoltaic energy scenario.

- SAFE, RELIABLE, STATIC, AND ENVIRONMENTALLY CLEAN
- DOES NOT REQUIRE REPAIR AND MAINTENANCE
- PV PANELS ARE EXPENSIVE—CURRENTLY AROUND $5.00/W, $0.20/kWh
- SOLAR POWER CONVERSION EFFICIENCY IS AROUND 16%
- APPLICATIONS:
  - SPACE POWER
  - ROOFTOP INSTALLATIONS
  - OFF-GRID REMOTE APPLICATIONS
- SPORADIC AVAILABILITY—REQUIRES BACKUP POWER
- CURRENT INSTALLATION (290 MW):
  - JAPAN—45%
  - USA—26%
  - EUROPE—21%
- TREMENDOUS EMPHASIS ON TECHNOLOGY ADVANCEMENT

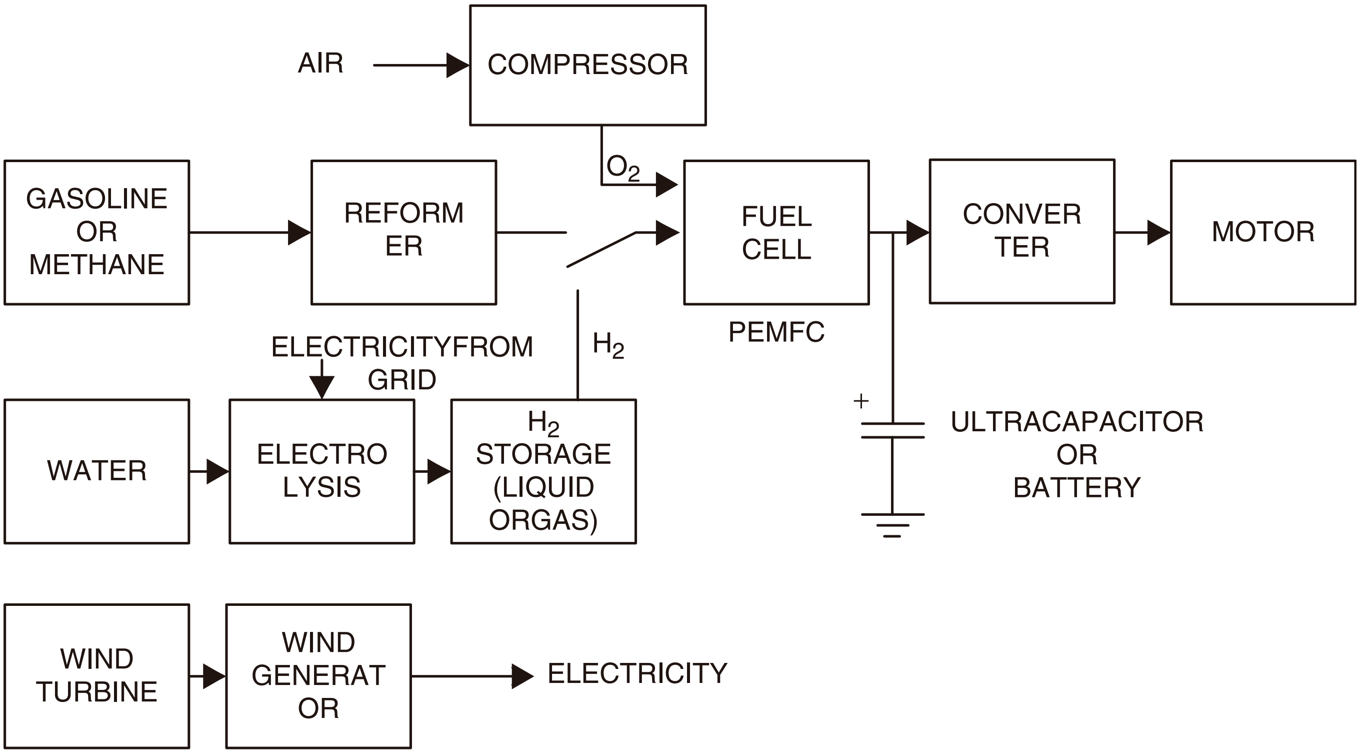
Photovoltaic devices, such as silicon (crystalline and amorphous), convert sunlight directly into electricity. They are safe, reliable, static, environmentally clean (green), and do not require any repair and maintenance as do wind power systems. The lifetime of a PV panel is typically 20 years. However, 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.

FIGURE 1.12 Fuel cell power scenario.

- HYDROGEN AND OXYGEN COMBINE TO PRODUCE ELECTRICITY AND WATER
- SAFE, STATIC, VERY EFFICIENT AND ENVIRONMENTALLY CLEAN
- FUEL CELL TYPES:
  - PROTON EXCHANGE MEMBRANE (PEMFC)
  - PHOSPHORIC ACID (PAFC)
  - DIRECT METHANOL (DMFC)
  - MOLTEN CARBONATE (MCFC)
  - SOLID OXIDE (SOFC)
- GENERATE HYDROGEN BY ELECTROLYSIS OR BY REFORMER (FROM GASOLINE, METHANOL)
- BULKY AND VERY EXPENSIVE IN CURRENT STATE OF TECHNOLOGY
- SLOW RESPONSE
- POSSIBLE APPLICATIONS:
  - FUEL CELL CAR
  - PORTABLE POWER
  - BUILDING COGENERATION
  - DISTRIBUTED POWER FOR UTILITY
  - UPS SYSTEM
- SIGNIFICANT FUTURE PROMISE

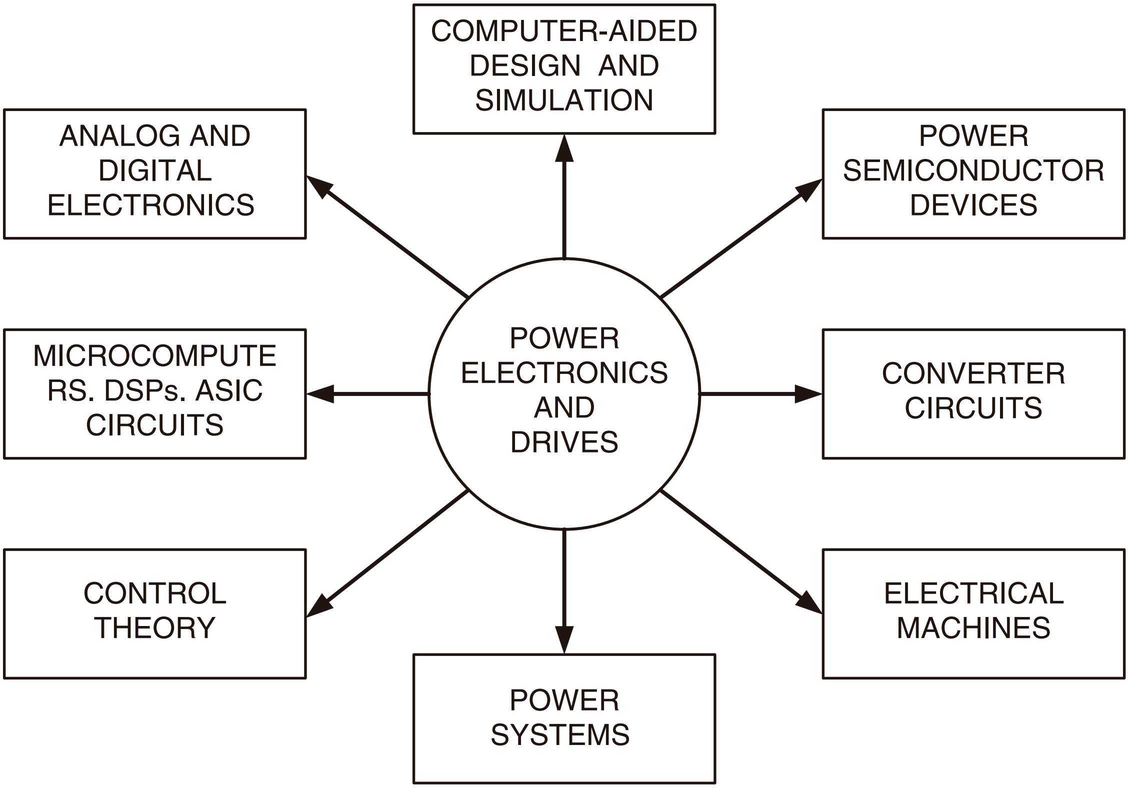
A fuel cell is an electrochemical device that operates on the reverse process of electrolysis of water; that is, it combines hydrogen and oxygen to produce electricity and water. It is a safe, static, highly efficient (up to 60%), and environmentally clean source of power [16, 17]. Fuel cell stacks can 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 hydrocarbon fuels (gasoline, methanol) by 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.

FIGURE 1.13 Fuel cell EV and the concept of a hydrogen economy.



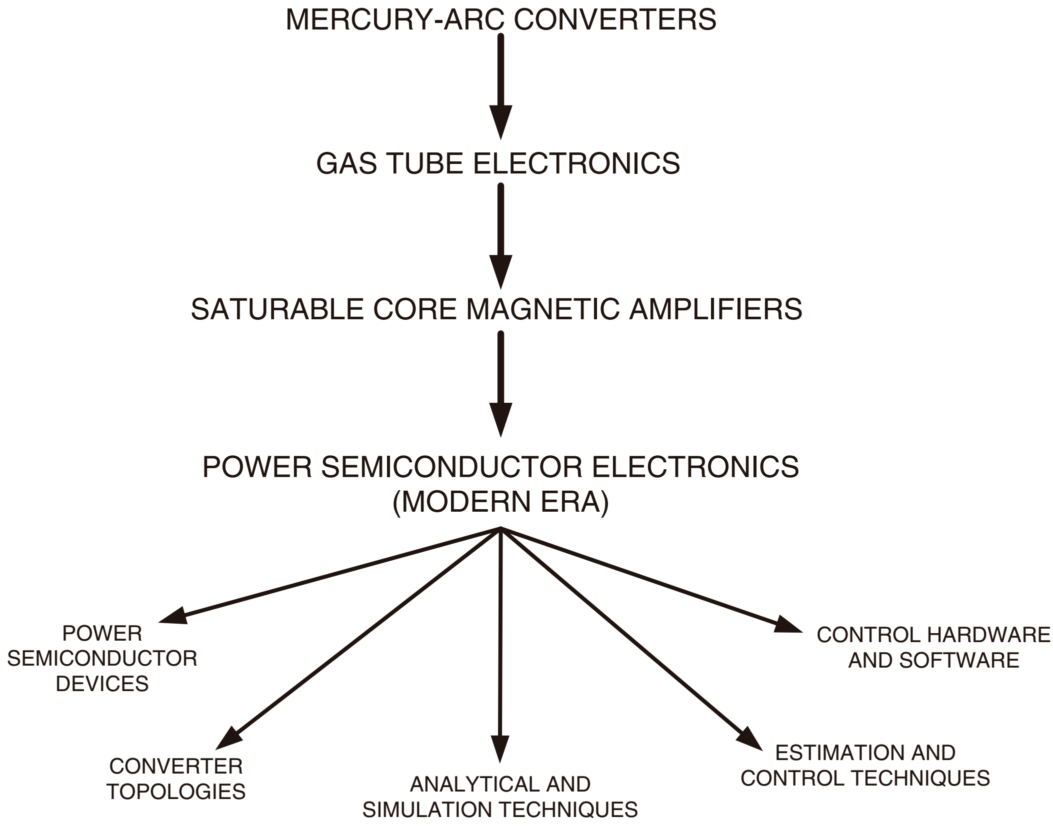
The figure shows the concept for a future fuel cell (FC) vehicle with different possible sources for the H_2 fuel. In an FC vehicle, a PEMFC usually generates the dc power, which is converted to variable-frequency ac for driving the ac motor. Because FCs can not absorb regenerative power, a battery or ultracapacitor storage is needed at the FC terminal. The battery also supplies power during acceleration because of the sluggish response of FCs. The H_2 fuel can be supplied from a tank where it can be stored in liquid or gaseous form. H_2 can be generated by electrolysis of water or H_2-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 O_2 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, H_2 generation is a good way for storing wind energy.

FIGURE 1.14 Power electronics—an interdisciplinary technology.



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.

FIGURE 1.15 Evolution of power electronics.



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.

FIGURE 1.16 Four generations of solid-state power electronics.

- *FIRST GENERATION* (1958–1975) (Thyristor Era)
  - Diode
  - Thyristor
  - Triac
- *SECOND GENERATION* (1975–1985)
  - Power BJT
  - Power MOSFET
  - GTO
  - Microprocessor
  - ASIC
  - PIC
  - Advanced control
- *THIRD GENERATION* (1985–1995)
  - IGBT
  - Intelligent power module (IPM)
  - DSPs
  - Advanced control
- *FOURTH GENERATION* (1995–)
  - IGCT
  - Cool MOS
  - PEBB
  - Sensorless control
  - AI techniques: fuzzy logic, neural networks, genetic algorithm

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.

FIGURE 1.17 Some significant events in the history of power electronics and motor drives.

- 1891 – Ward-Leonard dc motor speed control is introduced
- 1897 – Development of three-phase diode bridge rectifier (Graetz circuit)
- 1901 – Peter Cooper Hewitt demonstrates glass-bulb mercury-arc rectifier
- 1906 – Kramer drive is introduced
- 1907 – Scherbius drive is introduced
- 1926 – Hot cathode thyratron is introduced
- 1930 – New York subway installs grid-controlled mercury-arc rectifier (3 MW) for dc drive
- 1931 – German railways introduce mercury-arc cycloconverters for universal motor traction drive
- 1933 – Slepian invents ignitron rectifier
- 1934 – Thyratron cycloconverter—synchronous motor(400 hp) was installed in Logan power station for ID fan drive (first variable-frequency ac drive)
- 1948 – Transistor is invented at Bell Labs
- 1956 – Silicon power diode is introduced
- 1958 – Commercial thyristor (or SCR) was introduced to the marketplace by GE
- 1971 – Vector or field-oriented control for ac motor is introduced
- 1975 – Giant power BJT is introduced in the market by Toshiba
- 1978 – Power MOSFET is introduced by IR
- 1980 – High-power GTOs are introduced in Japan
- 1981 – Multilevel inverter (diode clamped) is introduced
- 1983 – IGBT is introduced
- 1983 – Space vector PWM is introduced
- 1986 – DTC control is invented for induction motors
- 1987 – Fuzzy logic is first applied to power electronics
- 1991 – Artificial neural network is applied to dc motor drive
- 1996 – Forward blocking IGCT is introduced by ABB

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.

FIGURE 1.18 Where to find information on power electronics.

- Key Books in Power Electronics
  – Bose, Mohan, Rashid, etc.
- IEEE Publications (ieeexplore.ieee.org)
- Individual Author Publication Websites (scholar.google.com, scopus.com, etc.)
- Conference Records and Transactions – IAS, IES, PELS, PES, SES, APEC, PEDS/PEDES, CIEP – Mexico, etc.
  Proc. of the IEEE
- Conference Records of:
  EPE (Europe)
  ICEM
  IPEC (Japan)
  PCC (Japan)
  PCIM, etc.
- Product Information in Key Power Electronic Company Websites:
  ABB, GE, Fuji, Toshiba, Hitachi, Mitsubishi, Siemens, Rockwell, Samsung, etc.

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.

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CHAPTER 2

Power Semiconductor Devices

Figure 2.1 Evolution of power semiconductor devices.

Figure 2.2 Power frequency trends of the devices.

Figure 2.3 (a) Diode *V-I* characteristics and (b) turn-off switching characteristics.

Figure 2.4 (a) Thyristor structure with two-transistor analogy and (b) *V-I* characteristics.

Figure 2.5 Thyristor features.

Figure 2.6 (a) Triac symbol with *V-I* characteristics and (b) incandescent light dimmer circuit with triac.

Figure 2.7 Triac features.

Figure 2.8 (a) GTO dc-to-dc converter and (b) switching waveforms.

Figure 2.9 GTO energy recovery snubbers: (a) passive snubber for chopper and (b) active snubber for half-bridge inverter.

Figure 2.10 GTO features.

Figure 2.11 (a) Double Darlington transistor and (b) triple Darlington.

Figure 2.12 (a) FBSOA of BJT (Powerex KD221K03) and (b) RBSOA.

Figure 2.13 BJT features.

Figure 2.14 (a) Power MOSFET and (b) *V-I* characteristics (Harris IRF140).

Figure 2.15 Safe operating area (SOA) of power MOSFET (Harris IRF140).

Figure 2.16 Power MOSFET features.

Figure 2.17 Device T_j rise curves with junction power loss waves.

Figure 2.18 (a) IGBT symbol with *V-I* characteristics (Powerex CM50TF-28H), (b) saturation characteristics, and (c) transient thermal impedance characteristics.

Figure 2.19 (a) IGBT half-bridge inverter and (b) switching characteristics of Q_1.

Figure 2.20 IGBT features.

Figure 2.21 IGBT six-pack intelligent power module (IPM) with gate drive interface logic.

Figure 2.22 IGCT with integrated packaging of gate driver.

Figure 2.23 IGCT features.

Figure 2.24 Comparison of power MOSFETs, IGBTs, GTOs, and IGCTs.

Figure 2.25 Next-generation power semiconductor materials.

Figure 2.26 Comparison of total power loss in Si- and SiC-based devices in a half-bridge PWM inverter (V_d = 400 V, I_L = 15 A).

Figure 2.27 Power integrated circuit (PIC) features.

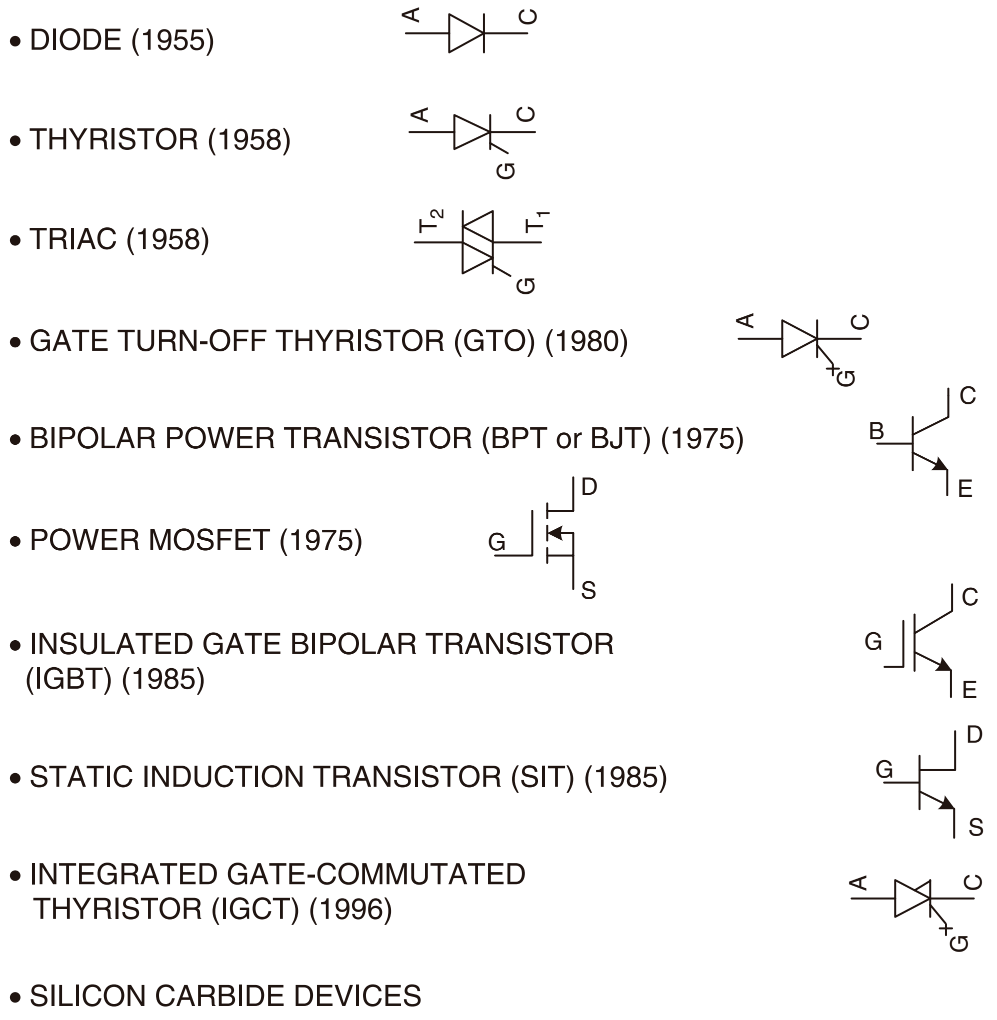
Figure 2.28 Power integrated circuit for dc motor drive (Harris HIP4011).

Figure 2.29 Advances in and trends of power semiconductor devices.

Summary

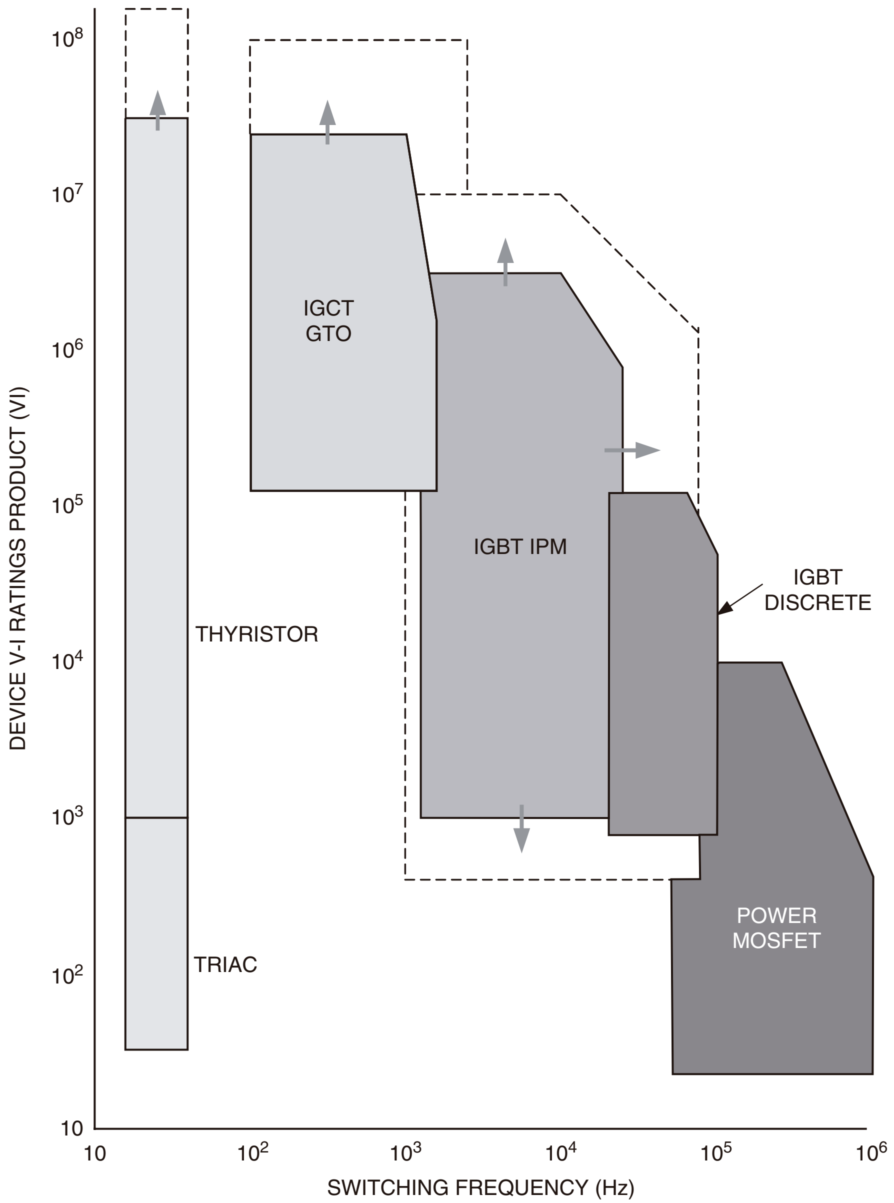
References

FIGURE 2.1 Evolution of power semiconductor devices.



This figure shows the evolution of modern power semiconductor devices with the year of commercial introduction and symbol on the right of each. These power devices constitute the heart of modern power electronics apparatuses and they are almost exclusively based on silicon material. It is no exaggeration to say that today's power electronics evolution has been possible primarily due to device evolution. Again, power semiconductor evolution has closely followed the evolution of microelectronics. Researchers in microelectronics have worked relentlessly to improve semiconductor processing, device fabrication, and packaging, and these efforts have contributed to the successful evolution of so many exotic power devices. Although basically they are on and off switches, practical devices are far more complex, delicate, and "fragile." Thyristors (or silicon-controlled rectifiers) and triacs are essentially the forerunners of modern power semiconductor devices, which operate mainly on a utility system and contribute to power quality and lagging power factor problems. GTOs and IGCTs (or GCTs) are high-power gate-controlled devices that are used in multi-megawatt applications. The BJT, once a very important device, has become obsolete. Power MOSFETs and IGBTs are self-controlled insulated-gate devices that are extremely important today. In particular, the invention of the IGBT in 1983 and its commercial introduction in 1985 have been important milestones in the history of power devices. An SIT is the solid-state equivalent of the vacuum triode; it has a high conduction drop and will not be discussed further. SiC devices with large band-gap semiconducting materials offer extremely high promise for the future. Note that the list does not include devices that did not establish well, such as MOS-controlled thyristors, static induction thyristors, injection-enhanced gate transistors, and MOS turn-off thyristors.

FIGURE 2.2 Power-frequency trends of the devices (from [5]).



The figure (in log-log scale) shows the power-frequency capability of the current devices and their future trends. The power is given by *V-I* ratings product, that is, the product of the maximum blocking voltage and maximum turn-off current. Note that the BJT is completely removed from the figure. Thyristors and triacs are essentially low-frequency (50/60 Hz) devices, and currently the thyristor has the highest power rating. The future trend, as indicated by the dashed curve, also indicates that is has the highest power rating. High-power thyristors are used in high-voltage dc (HVDC) systems, phase-control type static VAR compensators (SVC), and large ac motor drives. GTOs and IGCTs have a higher frequency range (typically a few hundred hertz to one kilohertz) but their power limits are lower than that of a thyristor. Normally, with a higher power rating, the switching frequency becomes lower, and this is indicated by tapering of the areas at higher frequency. However, an IGCT's switching frequency is somewhat higher than that of a GTO (not shown). IGBT intelligent power modules (IPMs) come next with higher frequency but lower power range. The lower power end of GTO/IGCTs overlaps with IGBTs. The discrete IGBTs have higher frequency and lower power range, as shown. Power MOSFETs have the highest frequency and lowest power range. All of these devices will be described later.