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Power Electronic Systems

Theory and Design

电力电子系统 —— 理论与设计

Jai P.Agrawal

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JAI P. AGRAWAL

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出　版　说　明

郑大钟

清华大学信息技术科学与技术学院

当前，在我国的高等学校中，教学内容和课程体系的改革已经成为教学改革中的一个非常突出的问题，而为数不少的课程教材中普遍存在"课程体系老化，内容落伍时代，本研层次不清"的现象又是其中的急需改变的一个重要方面。同时，随着科教兴国方针的贯彻落实，要求我们进一步转变观念扩大视野，使教学过程适应以信息技术为先导的技术革命和我国社会主义市场经济的需要，加快教学过程的国际化进程。在这方面，系统地研究和借鉴国外知名大学的相关教材，将会对推进我们的课程改革和推进我国大学教学的国际化进程，乃至对我们一些重点大学建设国际一流大学的努力，都将具有重要的借鉴推动作用。正是基于这种背景，我们决定在国内推出信息技术学科和电气工程学科国外知名大学原版系列教材。

本系列教材的组编将遵循如下的几点基本原则。(1)书目的范围限于信息技术学科和电气工程学科所属专业的技术基础课和主要的专业课。(2)教材的范围选自于具有较大影响且为国外知名大学所采用的教材。(3)教材属于在近 5 年内所出版的新书或新版书。(4)教材适合于作为我国大学相应课程的教材或主要教学参考书。(5)每本列选的教材都须经过国内相应领域的资深专家审看和推荐。(6)教材的形式直接以英文原版形式印刷出版。

本系列教材将按分期分批的方式组织出版。为了便于使用本系列教材的相关教师和学生从学科和教学的角度对其在体系和内容上的特点和特色有所了解，在每本教材中都附有我们所约请的相关领域资深教授撰写的影印版序言。此外，出于多样化的考虑，对于某些基本类型的课程，我们还同时列选了多于一本的不同体系、不同风格和不同层次的教材，以供不同要求和不同学时的同类课程的选用。

本系列教材的读者对象为信息技术学科和电气工程学科所属各专业的本科生，同时兼顾其他工程学科专业的本科生或研究生。本系列教材，既可采用作为相应课程的教材或教学参考书，也可提供作为工作于各个技术领域的工程师和技术人员的自学读物。

组编这套国外知名大学原版系列教材是一个尝试。不管是书目确定的合理性，教材选择的恰当性，还是评论看法的确切性，都有待于通过使用和实践来检验。感谢使用本系列教材的广大教师和学生的支持。期望广大读者提出意见和建议。

Power Electronic Systems-Theory and Design
(第 2 版)

影 印 版 序

这是一本较为系统和全面地反映了当今电力电子学的主要内容,具有新技术、新观念和集中了一些最新研究成果的电力电子学书籍。它既照顾到学科的延续性,又补充了电力电子学的一些最新发展,诸如软开关技术、PFC、EMC、电能质量、无功补偿器及新型整流器件等。这样一来,该书就为初学者进一步深造提供了所需的基础知识、基本原理、基本要领和基本方法,同时也扩大了读者的视野。

该书相当重视对组成电力电子变换电路的元器件所起的核心作用。为了使读者能够更深入地理解它们在电路中的行为,作者从应用的观点对其做了较大篇幅的阐述,并在适当的地方介绍了一些有关元器件的基础知识——半导体物理、电磁原理和电磁场理论。同时作者还对一般电力电子学书籍不常提到的热学问题做了较全面的介绍。

高性能的变换器离不开精确的控制。该书第 13 章为“变换器的控制”,专门讨论了变换器的动态模型——平均电路模型、线性化模型和状态空间平均模型以及反馈控制,并在有关电力电子技术应用章节中对系统的控制做了必要的阐述。

电力电子技术是一门渗透性极强的应用技术。为此,作者在第 14 和 15 章对开关电源、电池充电、UPS、电子镇流器、感应加热、高频逆变—整流焊机以及直流电机、感应电机和同步电机的驱动做了简要的介绍,以便增加读者的实际知识。

为了帮助读者掌握书的内容,作者还在适当的地方给出设计例子和仿真结果,同时附了每章的思考题。

综上所述,该书正如作者所言,可作为电子电子学课程的教材,同时也为从事研发的工程师们提供了一本很好的自学读物。

赵良炳　教授
清华大学电机工程与应用电子技术系
2001 年 5 月

PREFACE

The field of power electronics encompasses the application of fundamental concepts in several disciplines: electronic devices and circuits, signals and systems, motor drives, and control systems. A course in power electronics should tie together all these diverse fundamental concepts into a consolidated core and add the considerations of power utilization, quality, interfacing, and design issues, which are special to the field of power electronics. This book is written with the above focus in mind with a conscious effort to simplify mathematics by use of MATLAB™ and to concentrate on developing a robust understanding of the subject. This book is intended as a textbook for a course on power electronics for junior and senior undergraduate students in electrical engineering programs. It could also serve as a self-learning book for practicing engineers. The prerequisites for this book are courses on electrical circuits and systems, electronic devices and circuits, and mathematics courses in calculus, differential equations, Fourier series and transformations, and linear algebra.

This book, intended for a one- or two-semester course, is divided into four parts. Part I presents an overview of the field of power electronics and the review of important mathematical concepts such as determining the average and rms values and the harmonic profile of waveforms, which are essential for understanding the rest of the chapters.

Part II provides an understanding of components used in the design of power electronics circuits in the generic categories of power diodes, transistors, and thyristors. Design of current sources, inductors, and transformers illustrated using design examples. Concepts are introduced for power losses during switching transitions, and on-state and off-state of semiconductor devices. This part also introduces the driver and protection circuits for each device discussed.

Part III discusses the classes of switch-mode converters: dc-dc, dc-ac, ac-dc, ac-ac, and the resonant converters. The focus is on topologies, performance measures, and performance characteristics.

Part IV covers the application systems such as power factor correction, electric utility interfacing, converter control, power supply, electronic ballast, and motor drives. This part also presents practical design issues such as temperature control, selection of heat sinks, protection, packaging, shielding, and layout.

Each chapter contains several, design examples to reinforce the concept learned, which illustrate the decision choices and selection of components. MATLAB® has been used extensively in these examples and also in the elaboration of the converter operation. PSPICE® simulation examples are included wherever possible.

Chapters 1 and 2 provide review and focus on the characteristics of components used in power electronic circuits. Chapters 3 to 5, on semiconductor switching components, may be covered at a faster pace if students have a strong prerequisite in semiconductor devices. Chapters 6 to 11 form the core of the course. Chapters 12, 14, and 15 discuss the design requirements of some specific illustrations and, therefore, can be covered at a faster rate. Chapter 16 on thermal and other design issues, in my opinion, must not be excluded. Chapter 13 presents the development of average and state-space average models of power converter systems followed by the derivation of the transfer function. It is left to instructor's discretion whether to cover it in the undergraduate course or not.

Several reviewers provided valuable assistance during the development of this text, and I am grateful for their input. They are Charles L. Bachman, Southern Polytechnic State University; Shamala Chickamenahalli, Wayne State University; Alexander E. Emanuel, Worcester Polytechnic Institute; Michael L. Holcombe, Purdue University; Rickie L. Miller, Ferris State University; Medhat M. Morcos, Kansas State University; and Shekhar Pradhan, Bluefield State College. As a final note, I am grateful to my wife Vaidehi, my children Sanjay, Vivek and Kshama for their patience and encouragement during the time I devoted to writing and revising this book.

Jai P. Agrawal

CONTENTS

Part One
INTRODUCTION

CHAPTER 1

Bird's-Eye View of Power Electronics Systems

OBJECTIVES

1. The overall systems view of power electronic converters
2. The desired performance characteristics, which include power efficiency, power factor, undesirable harmonic content of voltages and currents, input–output relationships, parameters of control, etc.
3. Introduction to modeling of elements and systems of power electronic converters
4. Introduction to MATLAB methods of solution and graphic techniques

1.1 INTRODUCTION

Electric power is the muscle of modern industry and power electronics makes its utilization smarter. Managing power is an essential gradient in system design in all fields of electrical engineering but not necessarily the main concern except in power electronics and power generating and distribution systems. For example, in communication engineering, the premium is placed on the accuracy and quality of signal transmission and reception. Power electronics is solely concerned with the processing of electric energy. The electric energy by itself is not useful to mankind. It must be converted to other energy forms such as heat, light, sound and mechanical energies, which are directly useful to human beings and society. The focus in power electronics is on conversion, efficiency of conversion and control of energy.

Electric power is used in almost every part of modern home and society. An efficient use of power, therefore, is not only tremendously advantageous but has become essential. The objective of power electronics is to improve the quality and utilization of electric power. Generation, transmission, distribution and utilization of electric power takes place at different levels to suit the available components, processes and technologies involved. Interfacing of different technologies needs intelligent control and conversion techniques. Power electronics addresses these issues.

Recent advances in semiconductor switching devices have contributed very significantly to research and reengineering in the field of modern power electronics. Power electronics applications span a wide range on the power scale: milliwatts in

TABLE 1-1 POWER ELECTRONICS APPLICATIONS

Aerospace	
Aircraft power systems	Space vehicle power systems
Satellite power systems	
Automotive	
Alarms and security systems	Electric vehicles
Audio and RF amplifiers	Regulators
Battery chargers	
Commercial	
Advertising neon signs and displays	Electronic ballasts
Battery chargers	Hand power tools
Blenders	Light dimmers
Computers	Mercury-arc lamps
Electric blankets	Photocopiers
Electric fans	Vending machines
	Washing machines
Games and entertainment	
Games and toys	Televisions
Movie projectors	
Home appliances	
Audio and RF amplifiers	Photography
Food warming trays	Refrigerators
Garage door openers	Sewing machines
Phonographic equipment	
Industrial	
Air conditioning	Conveyors
Battery chargers	Cranes and hoists
Blowers	Dryers
Boilers	Electric furnaces and ovens
Chemical processing equipment	Electric vehicles
Contactor and circuit breakers	Electromagnets
	Electroplating
Industrial *(continued)*	
Electronic ignitions	Oil-well drilling equipment
Electrostatic precipitators	Paper mill machinery
Elevators	Power supplies
Flashers	Printing press machinery
Gas turbine starters	Pumps and compressors
Generator exciters	Relays
Grinders and mixers	Servo systems
High-voltage DC (HVDC)	Steel mill instrumentation
Induction heating	Temperature controls
Laser power supplies	Timers
Linear induction motion control	Traffic signal controls
Machine tools	Ultrasonic generators
Mining power equipments	Uninterruptible power supplies (UPS)
Motor drives and starters	Vacuum cleaners
Movers	Welding equipment
Nuclear reactor control	
Medical	
Fitness machines	Medical instrumentation
Laser power supplies	
Security systems	
Alarms and security systems	Radar/Sonar
Telecommunications	
Solar power supplies	VLF transmitters
Uninterruptible power supplies (UPS)	Wireless communication power supplies
Transportation	
Magnetic levitation	Trains and locomotives
Motor drives	
Utility systems	
Power factor correction and VAR compensators	

wireless personal communication sets or cordless screwdrivers to megawatts in High Voltage DC transmission systems and huge industrial motor drives.

1.2 A SIMPLE VOLTAGE CONVERTER

Consider a simple example of designing a 5-volts dc power supply for TTL ICs from a 12-volts battery. A voltage divider circuit, shown in Figure 1.1(a), is the first thought that comes to mind. Selecting resistor $\mathbf{R_2}$ arbitrarily to be 1 kohm, $\mathbf{R_1}$ is determined to be 1.4 kohms.

$$\frac{R_2}{R_1 + R_2} = \frac{5}{12}, \quad Rs = \frac{R_1 R_2}{R_1 + R_2} = 583.3\ ohms$$

The Thevenin equivalent circuit of voltage divider, given in Figure 1.1(b), consists of a 5 volts dc source in series with a source resistance R_S of 583.3 ohms. This circuit has two problems:

1. The voltage at the terminals of voltage divider, V_O, is 5 volts only when no current is drawn. It reduces rapidly as more current is drawn from it.

   $$V_O = 5 - 583.3\, I_O$$

   I_O is the current drawn from the output terminals, also called the load current. V_O will drop by 0.5 volts (maximum permitted in standard TTL ICs) if a current of 0.86 mA is drawn from it. This current is hardly sufficient for a single IC. The problem of varying output voltage with increasing load current is referred to as the voltage regulation problem. Ideally, V_O should not vary for any amount of current drawn; that is, the output voltage should have 100% regulation, or exhibits zero regulation error.

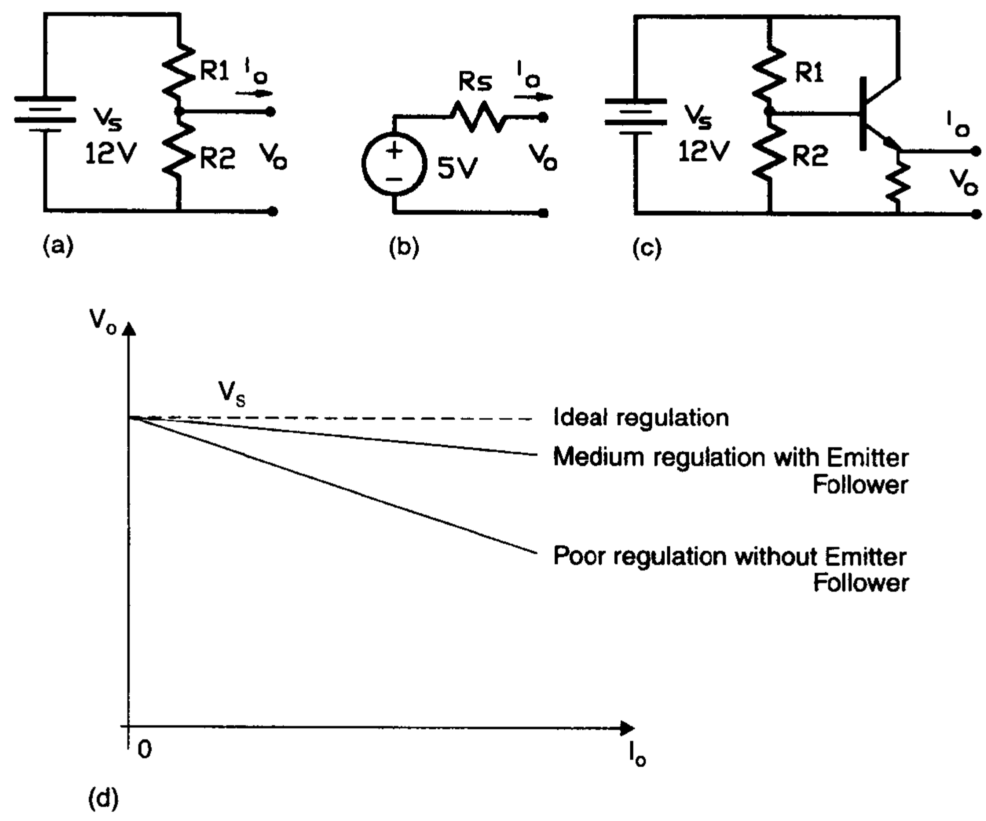

Figure 1.1
(a) A voltage divider (b) Thevenin's equivalent circuit
(c) voltage divider with emitter follower and
(d) voltage regulation characteristics

2. Power is continuously drained from the source even when load current is zero, 60 milliwatts. This power drain is converted to heat in resistors R_1 and R_2. For a load current of 1 mA, the actual power delivered is 4.4 milliwatts, a power efficiency of 6.8%.

Heat generated in resistors must be removed from the circuit for a reliable operation. The power is removed by using large size components or by use of heat sinks.

The voltage regulation can be improved by reducing the value of source resistance $\mathbf{R_S}$ using an emitter follower as shown in Figure 1.1(c). The transistor is biased in the linear region of the characteristics, hence, it dissipates an additional amount of power:

$$P_{loss} = (V_S - V_O)\, I_O$$

High power is dissipated at high load current. Again, this power is converted to heat, and consequently the temperature of the transistor package raises. A raise in temperature reduces the performance and reliability of the transistor. The dissipated heat is removed by using heat sink.

A better design uses a switch in place of the transistor, as shown in Figure 1.2(a). The switch may be a bipolar junction transistor operated either in the cut-off or the saturation region. The switch is turned on and off alternately in a periodic fashion. The output voltage, after the switch, has a pulse waveform, see Figure 1.2(b). The voltage waveform contains a dc component and an ac component. The ac component is removed by passing it through a filter. The voltage V_O at the output terminals is the dc component, the value of which is determined by the on-time of the switch. Assuming the transistor switch to be ideal, no power is lost in the transistor.

The filter circuit consists of inductors and capacitors, so no power is lost in the filter. Overall, no power is lost in the voltage converter. The practical switch-mode converters, however, have some power losses owing to parasitic elements such as the winding resistance of inductors, the leakage resistance in capacitors, and nonideal switching characteristics of semiconductor devices. The switch-mode converter exhibits significantly higher power efficiency than the nonswitch-mode converter.

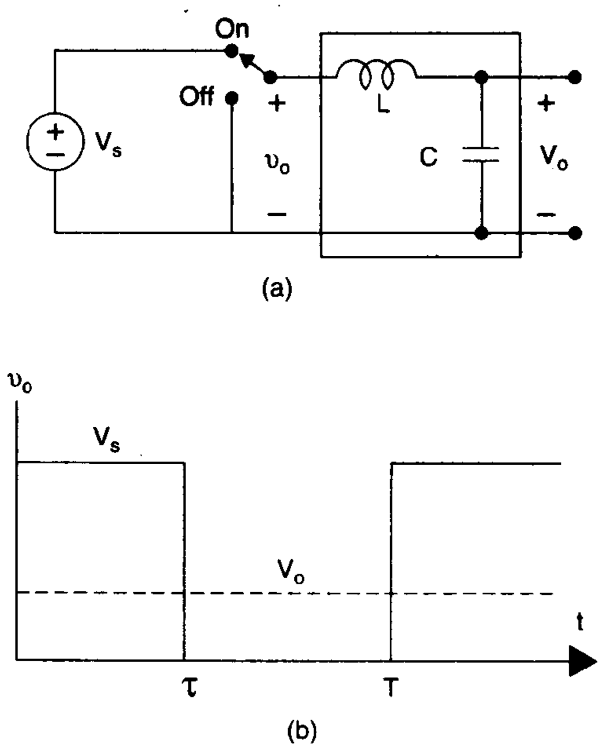

Figure 1.2
(a) The switch-mode voltage divider and (b) output voltage waveform

The power electronic circuit operation requires temporary storage of energy in inductors and capacitors. Sizes of inductors and capacitors are dictated by the amount of energy to be stored. Furthermore, the ac components of voltage or currents cannot be removed completely by filters. These are smaller priced items when high power applications are involved.

1.3 SYSTEMS VIEW OF POWER ELECTRONIC CONVERTERS

Figure 1.3(a) shows a single-input single-output power converter system. The source provides power, the converter converts it into a usable form to suit the sink where the power is utilized, that is, removed out of the system. The source is either a dc