Second Edition

POWER SYSTEM ENGINEERING

电力系统工程

（第2版）

D P KOTHARI
I J NAGRATH

清华大学出版社

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影 印 版 序

《电力系统工程（*Power System Engineering*）》于1994年出了第1版，在印度和世界许多国家发行，很受广大师生和电力工程技术人员的喜爱。2008年出的第2版在第1版的基础上有很多扩充，主要增加了电力工程领域的最新发展。

本书由印度工学院Kothari教授和贝拉理工学院Nagrath教授共同编写。

全书有22章和10篇附录。第1~15章是电力系统工程的基础知识，这一部分在第1版的基础上有更新与扩充，内容包括输电线参数和特性、潮流计算、故障分析、电力系统优化运行和自动发电控制、电弧和断路器、电力系统稳定和保护等。与第1版相比，第1章进行了较多的扩充和重写，新增了非常规和可再生能源、能源保存、能源管理、电力改革和重组、分布式发电及环境约束的影响等内容；在第2章和第3章中分别增加了磁场感应和静电感应；第4章中增加了电力变压器的内容；在第5章中引入了新的电压控制方法；第6章中增加了包含电力电子控制设备的AC-DC潮流计算；在第7章中包括了维修计划和电力系统可靠性；在第8章中，增加了电力市场下的自动发电控制；在第14章中增加了隔离器、熔断器和接触器等的介绍；在第15章中引入了数字继电器及其新趋势。

第16~22章分别是地下电缆、架空线绝缘子、输电线机械设计、电晕、HVDC输电、配电系统和电压稳定性，其中大部分章节在第一版中是作为附录的，而电压稳定性是新加的1章。

10篇附录分别是向量和矩阵代数引论、通用电路常数、三角因子分解和优化排序、电力系统雅可比矩阵元素、科恩-杜克理论、电力系统实时计算机控制、MATLAB和SIMULINK引论、变电站、各种潮流方法的收敛性、电能质量（综述）。其中，MATLAB和SIMULINK引论，电能质量（综述）是第2版新增的内容。

作为电力系统工程专业的教材，本书具有以下的显著特点：

（1）内容很广泛，几乎涵盖了电力系统工程专业的全部技术领域，把电力系统工程多门专业课都集成在一本书中，每部分内容既有基本理论，又有当前技术发展趋势，且注重工程应用。

（2）书中讲述的概念和技术都通过算例等加以支持。每章习题在附录中有

答案，可供学生练习和自我测评。MATLAB 和 SIMULINK 的引入有利于提高学生应用计算机解决电力系统问题的能力。每一章的引言和总结的撰写也是本书的一个亮点。

（3）附录内容丰富，对学生和电力工程技术人员很有用。其中的基本理论和知识可供学生查阅。附录中还列了各章的选择性思考题和解答，有助于学生对概念理解的深化。

（4）作者是为大学生两个学期，研究生一个学期写的教学用书。但内容可灵活组合，不影响教学的连贯性。

本书是电力系统工程学科大学本科生和研究生教学用的一本优秀教材，也是电力系统工程师作为手册查阅和参考用的好帮手。

周双喜

2009 年 5 月

About the Authors

D P Kothari is Professor, Centre for Energy Studies, Indian Institute of Technology, Delhi. He has been Head of the Centre for Energy Studies (1995–97) and Principal (1997–98) Visvesvaraya Regional Engineering College, Nagpur. He has been Director-incharge, IIT Delhi (2005), Deputy Director (Admn.) (2003–2006). Earlier (1982–83 and 1989), he was a visiting fellow at RMIT, Melbourne, Australia. He obtained his BE, ME and Ph.D degrees from BITS, Pilani. A fellow of the Institution of Engineers (India), fellow of National Academy of Engineering, fellow of National Academy of Sciences, Senior Member IEEE, Member IEE, Life Member ISTE, Professor Kothari has published/presented around 500 papers in national and international journals/conferences. He has authored/co-authored more than 18 books, including *Power System Optimization, Modern Power System Analysis, Electric Machines, Power System Transients, Theory and Problems of Electric Machines and Basic Electrical Engineering*. His research interests include power system control, optimization, reliability and energy conservation. He has received the National Khosla award for Lifetime Achievements in Engineering for 2005 from IIT Roorkee.

I J Nagrath is Adjunct Professor, BITS, Pilani, and retired as Professor of electrical engineering and Deputy Director of Birla Institute of Technology and Science, Pilani. He obtained his BE with Hons. in electrical engineering from the University of Rajasthan in 1951 and MS from the University of Wisconsin in 1956. He has co-authored several successful books which include *Electric Machines, Modern Power System Analysis* and *Systems: Modelling and Analysis*. He has also published several research papers in prestigious national and international journals.

Other books by the same authors

978 007 0435896	KOTHARI & NAGRATH	Basic Electrical Engineering, 2e
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978 007 0494893	KOTHARI & NAGRATH	Modern Power System Analysis, 3e
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Preface to the Second Edition

The excellent response to the first edition of the book by students and faculty of Indian and foreign universities and the practicing engineers has motivated the authors to venture for the second edition. The main aim was to include the latest developments in the field of power system engineering.

A large number of teaching appendices of the first edition has now been rewritten as full-fledged chapters, since all these topics continue to be important and are part of the curriculum. We hope students and teachers will welcome this.

This edition covers a wide variety of topics in power system engineering which are normally not found in a single volume. Since the appearance of the first edition in 1994, the overall energy situation has changed considerably and this has generated great interest in nonconventional and renewable energy sources, energy conservation, energy management, power reforms and restructuring and distributed/dispersed generation. Chapter 1 has been therefore, enlarged and completely re-written. In addition, the influences of environmental constraints are also discussed.

In Chapter 6, load flow under power electronic control, that is, AC-DC-LF has been added. In Chapter 7, maintenance scheduling, power system reliability, have been included. For the first time, unit commitment has been further elaborated as an appendix to Chapter 7 In Chapter 8, AGC of restructured power system is added, keeping in line with the latest changes in the power sector.

In Chapter 4; a few more sections/topics such as power transformer have been added. In chapters 2 and 3, magnetic field induction and electrostatic induction have been added, respectively. In Chapter 5, voltage control topic has been boosted by including control by midline boosters. Two appendices, K and I of the first edition on lightning phenomenon and neutral grounding, have now been brought in the main chapters as per the wishes of readers for completeness and clarity. In Chapter 14, new topics such as isolators, fuses and contractors, kilometric faults have now been included as per the review reports. In Chapter 15, numerical (digital) relay has now been introduced along with new trends.

The present edition, like the earlier one, is designed for a two-semester course at the undergraduate level or for first-semester postgraduate study.

With all these features, this is an indispensable text for electrical engineering students. AMIE, GATE, and UPSC Engineering services and IAS candidates along with practicing engineers would also find this book extremely valuable as a text/reference book.

A first-level PG course may be taught from sections (1.17, 1.18) chapters 6, 7, 8, sections 9.6, 9.7, 11.7, chapters 12, 13, 15, 20, 22. For UG courses a combination of chapters may be chosen depending on the syllabus of a university and type of the course.

Salient Features

- Recent developments in various power system topics included
- Computational algorithm for various system studies presented
- Large number of solved examples and unsolved problems with answers presented at the end of each chapter for practice and self-evaluation
- New chapter added on voltage stability
- Old appendices of the first edition have been enlarged into full-fledged chapters 16–21 such as HVDC and Distribution Systems
- New appendices on:
  MATLAB and SIMULINK demonstrating their use in problem solving
  Real time computer control of power systems
  Power Quality

MATLAB and SIMULINK ideal programs for power system analysis are included in this book as an appendix along with 18 solved examples illustrating their use in solving representative power system problems.

A new chapter on voltage stability has been added. A new appendix on real time computer control of power systems has also been added to more students aware of latest methods of power system control and monitoring in load dispatch centers. A new appendix on power quality has also been included.

Tata McGraw-Hill and the authors would like to thank the following reviewers of this edition: Prof. S. Dasgupta of S.I.T. Siliguri, Prof. P. R. Bijwe of I.I.T. Delhi, Prof. S. Roy of B.I.T.S. Pilani, PG and doctoral students of the first author, Mr. Sunil Bhat of VNIT Nagpur, Mr. Jayaprakash of GCEK Kerala, Mr. Praveen Verma, Mr. Abhishek Rathore, Mr. Jitender Malik, Mr. Vijay Pratap, Mr. Rajeev Ranjan Kumar, Mr. Sivananda, Dr. Subir Sen of Power Grid, Dr. Shekhar of Alstrom, Mr. K.P. Singh of NPTI Guwahati for their help in preparing the manuscript.

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While revising the text, we have been greatly encouraged by many colleagues, students and practicing engineers, reviewers who used the earlier edition of this book. All these individuals have influenced this edition. We express our thanks and appreciation to them. We hope this support/response would continue in the future also.

We also thank TMH personnel and our families who supported us during this period and given all possible help so that this book can see the light of the day.

New Delhi
June 2007

D.P. Kothari
I.J. Nagrath

Preface to the First Edition

Mathematical modelling and solutions on digital computers constitute an extremely viable approach to system analysis and planning studies for a modern-day power system with its large size and complex and integrated nature. A stage has, therefore, been reached where an undergraduate must be trained in the latest techniques of analysis of large-scale power systems. A similar need also exists in the industry where a practicing power system engineer is constantly faced with the challenge of the rapid advances in the field. This book has been designed to fulfil this need by integrating the basic principles of power system analysis illustrated through the simplest system structure with analysis techniques for practical size systems. In this book large-scale system analysis follows as a natural extension of the basic principles. The form and level of some of the well-known techniques are presented in such a manner that undergraduates can easily grasp and appreciate them.

The book covers a wide variety of topics in power system engineering which are normally not found in a single volume. The book is written in such a comprehensive manner that at least three courses on power systems can be designed—one at the postgraduate level and a two-semester sequence at the undergraduate level.

The reader is expected to have a prior grounding in circuit theory and electrical machines. He should also have been exposed to Laplace transform, linear differential equations, elementary optimization techniques and a first course in control theory. Matrix analysis is applied throughout the book. However, a knowledge of simple matrix operations would suffice and these are summarized in an appendix for quick reference.

The digital computer is an indispensable tool for power system analysis, and therefore, computational algorithms for various system studies such as load flow, fault level analysis, stability, etc. have been included at appropriate places in the book. The students should be encouraged to design computer programs for these studies using the algorithms provided. Further, the students can be asked to pool the various programs for more advanced and sophisticated studies such as optimal scheduling. A novel feature of the book is the inclusion of current trends that are practically useful such as unit commitment, generation reliability, optimal thermal scheduling, optimal hydrothermal scheduling and decoupled load flow.

The introductory chapter presents a discussion of various methods of electrical energy generation including renewable energy sources and their techno-economic comparison. The reader is also exposed to the Indian power scenario.

Chapters 2 and 3 provide the transmission line parameters and these are included for the sake of completeness of the text. Chapter 4 on the representation of power system components highlights the steady state model of the synchronous machine and the circuit models of composite power systems along with the per unit method.

Chapter 5 deals with the performance of transmission lines. The load flow problem is introduced at this stage through the simple two-bus system and basic concepts of watt and var control are illustrated. A brief treatment of circle diagrams is included as this forms an excellent teaching aid for putting across the concept of load flow and line compensation.

Chapter 6 elaborates on power network modelling and important techniques of load flow analysis like Gauss–Siedel, Newton–Raphson and decoupled load flow. Chapter 7 deals with optimal system operation for both thermal and hydrothermal systems. A rigorous treatment for thermal system is also presented.

Chapter 8 deals with load frequency control wherein both conventional and modern control approaches have been adopted for analysis and design. The chapter also covers the treatment of generation rate constraint. Voltage control is also discussed briefly.

Chapters 9–11 discuss fault studies (abnormal system operation). The synchronous machine model for transient studies is heuristically introduced to the reader. Z_{BUS} algorithm is presented and its use illustrated for both symmetrical and unsymmetrical faults.

Chapter 12 elaborates upon the concepts of various types of stability in power system. In particular, the concept of transient stability is well illustrated through the equal area criterion. The classical numerical solution technique of the swing equation as well as the algorithm for large system stability are also dealt with. A step-by-step solution of a 3-machine stability problem is presented.

Chapter 13 deals with power system transients. Topics such as traveling waves or propagation of surges, generation of over-voltages on lines, insulation coordination are discussed at length.

Chapter 14 presents a detailed account of various types of circuit breakers including HVDC breakers. Methods of testing circuit breakers are also explained.

Chapter 15 covers the important topic of power system protection. It includes an exhaustive survey of relaying schemes and also deals with the different types of protective relays used for the protection of various parts of power systems along with their theory, threshold characteristics as well as their merits and demerits. Microprocessor based relaying is also briefly explained.

A large number of appendices have been provided to deal with topics such as Cables, Insulators, Sag and Tension, Neutral Grounding, Corona, Lightning Phenomena, HVDC and Distribution Systems. These topics are still being taught and continue to be very important.

Every concept and technique presented is supported through examples employing a two-bus structure while at times, three- and four-bus illustrations have also been used. A large number of unsolved problems with their answers are included at the end of each chapter. These have been so selected that apart from providing a drill they help the reader to develop a deeper insight and illustrate some points beyond what is directly covered by the text.

The organization of various chapters is flexible and permits the teacher to mould them to the particular needs of the class and curriculum. If desired, some of the advanced level topics could be bypassed without loss of continuity. The style of writing is amenable to self-study.

We are indebted to our colleagues at the Birla Institute of Technology and Science, Pilani, and the Indian Institute of Technology, Delhi, for their encouragement and various useful suggestions. We are also grateful to the authorities at BITS, Pilani, and IIT, Delhi, for providing the facilities necessary for writing this book. Further, we would like to thank the National Book Trust for subsidizing the production of the book and thereby facilitating its availability at an affordable price. We welcome any constructive criticism and will be grateful for any appraisal by the readers.

I.J. Nagrath
D.P. Kothari

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