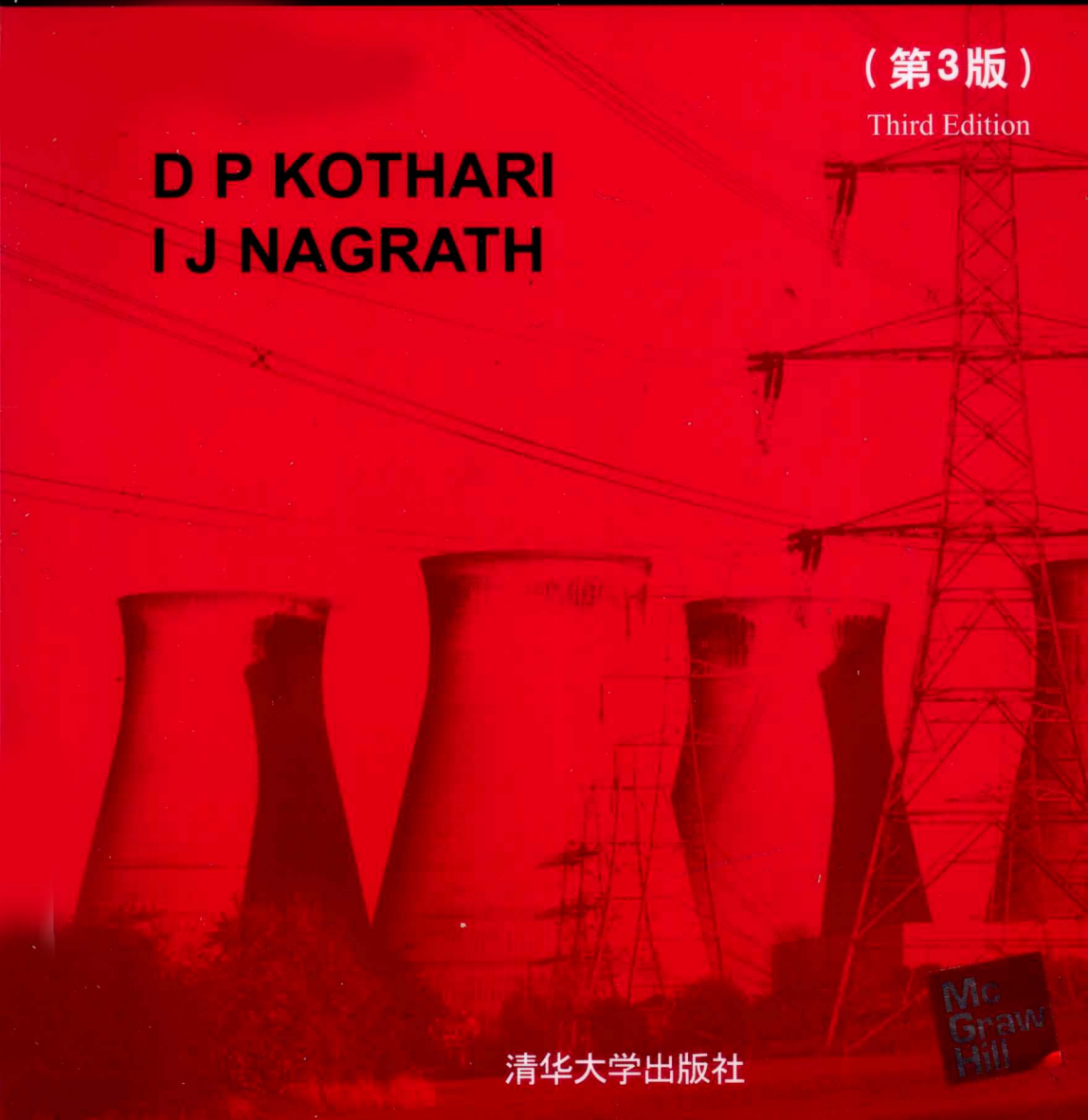
现代电力系统分析

MODERN POWER SYSTEM ANALYSIS

（第3版）

Third Edition

D P KOTHARI
I J NAGRATH



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影 印 版 序

由于电力系统规划、设计、运行和控制都要进行电力系统分析，因此，在国内外的高等院校中都把“电力系统分析”作为本科生的重要专业课程之一，有的在研究生阶段还进一步将它列为学位课程。作为这门课程的教材，国内外已经有十多种，本书为印度理工学院 Kothari 和贝拉理工学院 Nagrath 两位教授编写的第 3 版。

书中的第 2 章到第 12 章内容属于电力系统分析的传统和基本内容，主要包括电力系统元件的参数、等值电路和稳态运行特性，电力系统的潮流计算，电力系统的运行优化以及自动发电和电压控制，对称和不对称故障分析，电力系统稳定性等。

第 13 章到第 17 章是第 3 版新增的内容，包括电力系统静态安全分析，电力系统状态估计，FACTS(柔性交流输电系统)元件及其对系统参数和功率的补偿，电力负荷预测，电力系统电压稳定性。此外，在第 1 章中还增加了新能源和可再生能源发电、分散和分布式发电、电力市场以及电能生产对环境的影响等方面的基本知识。

在传统部分的编写中，内容比较全面、完整。例如，在潮流计算中，包括了近似潮流、高斯-赛得尔法、牛顿-拉夫逊法以及快速解耦法；在运行方式优化方面，从经典的基于等微增率的经济调度，到最优潮流和机组经济组合；在对称和不对称故障分析中，除了简单系统的分析方法以外，介绍了复杂系统的计算机分析方法，等等。新增加的内容使本书更贴近电力系统的运行和控制。

此外，本书还有以下的显著特点：

1. 书中包含了大量的例题，它们除了说明具体的计算方法和过程以外，还可以让读者顺便了解很多实际知识（例如元件及系统的结构和参数等）。有的则通过例题介绍其他方面的内容和知识（例如，在例 2.4 中引入通信干扰和谐波等知识），从而扩大了本书所包含的信息量。另外，书中还给出了大量的习题并附有相应的答案，以便读者进一步巩固和深化有关的理论和分析方法。特别地，这些例题和习题有助于读者进行自学。

2. 不但整个内容的取材和组织都立足于应用计算机进行分析计算，而且在附录中给出了应用 MATLAB 和 SIMULINK 进行编程计算的基本方法和详细范例。这不但可以教会学生掌握一种强有力的计算手段，以节约做习题所花的

时间，而且可以使他们在以后的工作过程中继续发挥作用，避免过分依赖专门的电力系统分析软件包。

3. 书中各章都附有适当的参考书籍和参考文献，它们有助于读者进一步深入学习和进行研究，这对于研究生来说更为有用。

总之，本书是一本很有特色的电力系统分析课程教材，它对于从事电力系统研究和生产的工程技术人员来说，也是一本很好的参考书。

夏道止

2008 年 12 月

About the Authors

D P Kothari is Professor, Centre for Energy Studies, and Deputy Director (Administration) Indian Institute of Technology, Delhi. He has also been the Head of the Centre for Energy Studies (1995–97) and Principal (1997–98), Visvesvaraya Regional Engineering College, Nagpur. 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 Engineers (India), Prof. Kothari has published/presented 450 papers in national and international journals/conferences. He has authored/co-authored more than 15 books, including *Power System Engineering, Electric Machines, 2/e, Power System Transients, Theory and Problems of Electric Machines, 2/e.*, and *Basic Electrical Engineering.* His research interests include power system control, optimisation, reliability and energy conservation.

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 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 2/e, Power System Engineering, Signals and Systems* and *Systems: Modelling and Analysis.* He has also published several research papers in prestigious national and international journals.

Preface to the Third Edition

Since the appearance of the second edition in 1989, the overall energy situation has changed considerably and this has generated great interest in non-conventional and renewable energy sources, energy conservation and management, power reforms and restructuring and distributed and dispersed generation. Chapter 1 has been therefore, enlarged and completely rewritten. In addition, the influences of environmental constraints are also discussed.

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

Modern power systems have grown larger and spread over larger geographical area with many interconnections between neighbouring systems. Optimal planning, operation and control of such large-scale systems require advanced computer-based techniques many of which are explained in the student-oriented and reader-friendly manner by means of numerical examples throughout this book. Electric utility engineers will also be benefitted by the book as it will prepare them more adequately to face the new challenges. The style of writing is amenable to self-study. The wide range of topics facilitates versatile selection of chapters and sections for completion in the semester time frame.

Highlights of this edition are the five new chapters. Chapter 13 deals with power system security. Contingency analysis and sensitivity factors are described. An analytical framework is developed to control bulk power systems in such a way that security is enhanced. Everything seems to have a propensity to fail. Power systems are no exception. Power system security practices try to control and operate power systems in a defensive posture so that the effects of these inevitable failures are minimized.

Chapter 14 is an introduction to the use of state estimation in electric power systems. We have selected Least Squares Estimation to give basic solution. External system equivalencing and treatment of bad data are also discussed.

The economics of power transmission has always lured the planners to transmit as much power as possible through existing transmission lines. Difficulty of acquiring the right of way for new lines (the corridor crisis) has always motivated the power engineers to develop compensatory systems. Therefore, Chapter 15 addresses compensation in power systems. Both series and shunt compensation of lines have been thoroughly discussed. Concepts of SVS, STATCOM and FACTS have been briefly introduced.

Chapter 16 covers the important topic of load forecasting technique. Knowing load is absolutely essential for solving any power system problem.

Chapter 17 deals with the important problem of voltage stability. Mathematical formulation, analysis, state-of-art, future trends and challenges are discussed.

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. The help rendered by Shri Sunil Bhat of VNIT, Nagpur in writing this appendix is thankfully acknowledged.

Tata McGraw-Hill and the authors would like to thank the following reviewers of this edition: Prof. J.D. Sharma, IIT Roorkee; Prof. S.N. Tiwari, MNNIT Allahabad; Dr. M.R. Mohan, Anna University, Chennai; Prof. M.K. Deshmukh, BITS, Pilani; Dr. H.R. Seedhar, PEC, Chandigarh; Prof. P.R. Bijwe and Dr. Sanjay Roy, IIT Delhi.

While revising the text, we have had the benefit of valuable advice and suggestions from many professors, students and practising engineers who used the earlier editions 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.

D P Kothari
I J Nagrath

Preface to the First Edition

Mathematical modelling and solution on digital computers is the only practical approach to systems analysis and planning studies for a modern day power system with its large size, complex and integrated nature. The 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 practising power system engineer is constantly faced with the challenge of the rapidly advancing 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 is designed for a two-semester course at the undergraduate level. With a judicious choice of advanced topics, some institutions may also find it useful for a first course for postgraduates.

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, optimisation 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 summarised in an appendix for quick reference.

The digital computer being an indispensable tool for power system analysis, computational algorithms for various system studies such as load flow, fault level analysis, stability, etc. have been included at appropriate places in the book. It is suggested that where computer facilities exist, students should be encouraged to build 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, e.g. optimal scheduling. An important novel feature of the book is the inclusion of the latest and practically useful topics like unit commitment, generation reliability, optimal thermal scheduling, optimal hydro-thermal scheduling and decoupled load flow in a text which is primarily meant for undergraduates.

The introductory chapter contains a discussion on various methods of electrical energy generation and their techno-economic comparison. A glimpse is given into the future of electrical energy. The reader is also exposed to the Indian power scenario with facts and figures.

Chapters 2 and 3 give the transmission line parameters and these are included for the sake of completness of the text. Chapter 4 on the representation of power system components gives the steady state models 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 right 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 air for putting across the concept of load flow and line compensation. *ABCD* constants are generally well covered in the circuit theory course and are, therefore, relegated to an appendix.

Chapter 6 gives power network modelling and load flow analysis, while Chapter 7 gives optimal system operation with both approximate and rigorous treatment.

Chapter 8 deals with load frequency control wherein both conventional and modern control approaches have been adopted for analysis and design. Voltage control is briefly discussed.

Chapters 9–11 discuss fault studies (abnormal system operation). The synchronous machine model for transient studies is heuristically introduced to the reader.

Chapter 12 emphasises the concepts of various types of stability in a power system. In particular the concepts 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 advanced.

Every concept and technique presented is well supported through examples employing mainly a two-bus structure while sometimes three- and four-bus illustrations wherever necessary 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 develop a deeper insight and illustrate some points beyond what is directly covered by the text.

The internal organisation of various chapters is flexible and permits the teacher to adapt 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 specially adapted to self-study. Exploiting this fact a teacher will have enough time at his disposal to extend the coverage of this book to suit his particular syllabus and to include tutorial work on the numerous examples suggested in the text.

The authors are indebted to their colleagues at the Birla Institute of Technology and Science, Pilani and the Indian Institute of Technology, Delhi for the encouragement and various useful suggestions they received from them while writing this book. They are grateful to the authorities of the Birla Institute of Technology and Science, Pilani and the Indian Institute of Technology, Delhi for providing facilities necessary for writing the book. The authors welcome any constructive criticism of the book and will be grateful for any appraisal by the readers.

I J Nagrath
D P Kothari

Contents

1

Introduction

1.1 A PERSPECTIVE

Electric energy is an essential ingredient for the industrial and all-round development of any country. It is a coveted form of energy, because it can be generated centrally in bulk and transmitted economically over long distances. Further, it can be adapted easily and efficiently to domestic and industrial applications, particularly for lighting purposes and mechanical work*, e.g. drives. The per capita consumption of electrical energy is a reliable indicator of a country's state of development—figures for 2001 are 425 kWh for India and 5600 kWh for UK and 13000 kWh for USA.

Conventionally, electric energy is obtained by conversion from fossil fuels (coal, oil, natural gas), and nuclear and hydro sources. Heat energy released by burning fossil fuels or by fission of nuclear material is converted to electricity by first converting heat energy to the mechanical form through a thermocycle and then converting mechanical energy through generators to the electrical form. Thermocycle is basically a low efficiency process—highest efficiencies for modern large size plants range up to 40%, while smaller plants may have considerably lower efficiencies. The earth has fixed non-replenishable resources of fossil fuels and nuclear materials, with certain countries over-endowed by nature and others deficient. Hydro energy, though replenishable, is also limited in terms of power. The world's increasing power requirements can only be partially met by hydro sources. Furthermore, ecological and biological factors place a stringent limit on the use of hydro sources for power production. (The USA has already developed around 50% of its hydro potential and hardly any further expansion is planned because of ecological considerations.)

* Electricity is a very inefficient agent for heating purposes, because it is generated by the low efficiency thermocycle from heat energy. Electricity is used for heating purposes for only very special applications, say an electric furnace.