POWER GENERATION, OPERATION, AND CONTROL

Third Edition

Allen J. Wood • Bruce F. Wollenberg
Gerald B. Sheblé

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Allen Wood passed away on September 10, 2011, during the preparation of this edition. Al was my professor when I was a student in the Electric Power Engineering Program at Rensselaer Polytechnic Institute (RPI) in 1966. Allen Wood and other engineers founded Power Technologies Inc. (PTI) in Schenectady, NY, in 1969. I joined PTI in 1974, and Al recruited me to help teach the course at RPI in 1979. The original text was the outcome of student notes assembled over a 5 year period from 1979 to 1984 and then turned over to John Wiley & Sons. Allen Wood was my professor, my mentor, and my friend, and I dedicate this third edition to him.

BRUCE F. WOLLENBERG

I dedicate this work to my family, my wife Yvette Sheblé, my son Jason Sheblé, my daughter Laura Sheblé, and grandson Kiyan, as they helped me so much to complete this work.

GERALD B. SHEBLÉ

CONTENTS

Preface to the Third Edition xvii

Preface to the Second Edition xix

Preface to the First Edition xxi

Acknowledgment xxiii

1 Introduction 1

1.1 Purpose of the Course / 1
1.2 Course Scope / 2
1.3 Economic Importance / 2
1.4 Deregulation: Vertical to Horizontal / 3
1.5 Problems: New and Old / 3
1.6 Characteristics of Steam Units / 6
1.6.1 Variations in Steam Unit Characteristics / 10
1.6.2 Combined Cycle Units / 13
1.6.3 Cogeneration Plants / 14
1.6.4 Light-Water Moderated Nuclear Reactor Units / 17
1.6.5 Hydroelectric Units / 18
1.6.6 Energy Storage / 21
1.7 Renewable Energy / 22
1.7.1 Wind Power / 23
1.7.2 Cut-In Speed / 23
1.7.3 Rated Output Power and Rated Output Wind Speed / 24
1.7.4 Cut-Out Speed / 24
1.7.5 Wind Turbine Efficiency or Power Coefficient / 24
1.7.6 Solar Power / 25
APPENDIX 1A Typical Generation Data / 26
APPENDIX 1B Fossil Fuel Prices / 28
APPENDIX 1C Unit Statistics / 29

References for Generation Systems / 31
Further Reading / 31

2 Industrial Organization, Managerial Economics, and Finance 35

2.1 Introduction / 35
2.2 Business Environments / 36
2.2.1 Regulated Environment / 37
2.2.2 Competitive Market Environment / 38
2.3 Theory of the Firm / 40
2.4 Competitive Market Solutions / 42
2.5 Supplier Solutions / 45
2.5.1 Supplier Costs / 46
2.5.2 Individual Supplier Curves / 46
2.5.3 Competitive Environments / 47
2.5.4 Imperfect Competition / 51
2.5.5 Other Factors / 52
2.6 Cost of Electric Energy Production / 53
2.7 Evolving Markets / 54
2.7.1 Energy Flow Diagram / 57
2.8 Multiple Company Environments / 58
2.8.1 Leontief Model: Input–Output Economics / 58
2.8.2 Scarce Fuel Resources / 60
2.9 Uncertainty and Reliability / 61
PROBLEMS / 61
Reference / 62

3 Economic Dispatch of Thermal Units and Methods of Solution 63

3.1 The Economic Dispatch Problem / 63
3.2 Economic Dispatch with Piecewise Linear Cost Functions / 68
3.3 LP Method / 69
3.3.1 Piecewise Linear Cost Functions / 69
3.3.2 Economic Dispatch with LP / 71
3.4 The Lambda Iteration Method / 73
3.5 Economic Dispatch Via Binary Search / 76
3.6 Economic Dispatch Using Dynamic Programming / 78
3.7 Composite Generation Production Cost Function / 81
3.8 Base Point and Participation Factors / 85
3.9 Thermal System Dispatching with Network Losses Considered / 88

3.10 The Concept of Locational Marginal Price (LMP) / 92
3.11 Auction Mechanisms / 95
3.11.1 PJM Incremental Price Auction as a Graphical Solution / 95
3.11.2 Auction Theory Introduction / 98
3.11.3 Auction Mechanisms / 100
3.11.4 English (First-Price Open-Cry = Ascending) / 101
3.11.5 Dutch (Descending) / 103
3.11.6 First-Price Sealed Bid / 104
3.11.7 Vickrey (Second-Price Sealed Bid) / 105
3.11.8 All Pay (e.g., Lobbying Activity) / 105
APPENDIX 3A Optimization Within Constraints / 106
APPENDIX 3B Linear Programming (LP) / 117
APPENDIX 3C Non-Linear Programming / 128
APPENDIX 3D Dynamic Programming (DP) / 128
APPENDIX 3E Convex Optimization / 135
PROBLEMS / 138
References / 146

4 Unit Commitment 147

4.1 Introduction / 147
4.1.1 Economic Dispatch versus Unit Commitment / 147
4.1.2 Constraints in Unit Commitment / 152
4.1.3 Spinning Reserve / 152
4.1.4 Thermal Unit Constraints / 153
4.1.5 Other Constraints / 155
4.2 Unit Commitment Solution Methods / 155
4.2.1 Priority-List Methods / 156
4.2.2 Lagrange Relaxation Solution / 157
4.2.3 Mixed Integer Linear Programming / 166
4.3 Security-Constrained Unit Commitment (SCUC) / 167
4.4 Daily Auctions Using a Unit Commitment / 167
APPENDIX 4A Dual Optimization on a Nonconvex Problem / 167
APPENDIX 4B Dynamic-Programming Solution to Unit Commitment / 173
4B.1 Introduction / 173
4B.2 Forward DP Approach / 174
PROBLEMS / 182

5 Generation with Limited Energy Supply 187

5.1 Introduction / 187
5.2 Fuel Scheduling / 188
5.3 Take-or-Pay Fuel Supply Contract / 188
5.4 Complex Take-or-Pay Fuel Supply Models / 194
  5.4.1 Hard Limits and Slack Variables / 194
5.5 Fuel Scheduling by Linear Programming / 195
5.6 Introduction to Hydrothermal Coordination / 202
  5.6.1 Long-Range Hydro-Scheduling / 203
  5.6.2 Short-Range Hydro-Scheduling / 204
5.7 Hydroelectric Plant Models / 204
5.8 Scheduling Problems / 207
  5.8.1 Types of Scheduling Problems / 207
  5.8.2 Scheduling Energy / 207
5.9 The Hydrothermal Scheduling Problem / 211
  5.9.1 Hydro-Scheduling with Storage Limitations / 211
  5.9.2 Hydro-Units in Series (Hydraulically Coupled) / 216
  5.9.3 Pumped-Storage Hydroplants / 218
5.10 Hydro-Scheduling using Linear Programming / 222
APPENDIX 5A Dynamic-Programming Solution to hydrothermal Scheduling / 225
5.A.1 Dynamic Programming Example / 227
  5.A.1.1 Procedure / 228
  5.A.1.2 Extension to Other Cases / 231
  5.A.1.3 Dynamic-Programming Solution to Multiple Hydroplant Problem / 232
PROBLEMS / 234

6 Transmission System Effects 243

6.1 Introduction / 243
6.2 Conversion of Equipment Data to Bus and Branch Data / 247
6.3 Substation Bus Processing / 248
6.4 Equipment Modeling / 248
6.5 Dispatcher Power Flow for Operational Planning / 251
6.6 Conservation of Energy (Tellegen's Theorem) / 252
6.7 Existing Power Flow Techniques / 253
6.8 The Newton–Raphson Method Using the Augmented Jacobian Matrix / 254
  6.8.1 Power Flow Statement / 254
6.9 Mathematical Overview / 257

6.10 AC System Control Modeling / 259
6.11 Local Voltage Control / 259
6.12 Modeling of Transmission Lines and Transformers / 259
6.12.1 Transmission Line Flow Equations / 259
6.12.2 Transformer Flow Equations / 260
6.13 HVDC links / 261
6.13.1 Modeling of HVDC Converters and FACT Devices / 264
6.13.2 Definition of Angular Relationships in HVDC Converters / 264
6.13.3 Power Equations for a Six-Pole HVDC Converter / 264
6.14 Brief Review of Jacobian Matrix Processing / 267
6.15 Example 6A: AC Power Flow Case / 269
6.16 The Decoupled Power Flow / 271
6.17 The Gauss–Seidel Method / 275
6.18 The "DC" or Linear Power Flow / 277
6.18.1 DC Power Flow Calculation / 277
6.18.2 Example 6B: DC Power Flow Example on the Six-Bus Sample System / 278
6.19 Unified Eliminated Variable HVDC Method / 278
6.19.1 Changes to Jacobian Matrix Reduced / 279
6.19.2 Control Modes / 280
6.19.3 Analytical Elimination / 280
6.19.4 Control Mode Switching / 283
6.19.5 Bipolar and 12-Pulse Converters / 283
6.20 Transmission Losses / 284
6.20.1 A Two-Generator System Example / 284
6.20.2 Coordination Equations, Incremental Losses, and Penalty Factors / 286
6.21 Discussion of Reference Bus Penalty Factors / 288
6.22 Bus Penalty Factors Direct from the AC Power Flow / 289
PROBLEMS / 291

7 Power System Security 296

7.1 Introduction / 296
7.2 Factors Affecting Power System Security / 301
7.3 Contingency Analysis: Detection of Network Problems / 301
7.3.1 Generation Outages / 301
7.3.2 Transmission Outages / 302

7.4 An Overview of Security Analysis / 306
7.4.1 Linear Sensitivity Factors / 307
7.5 Monitoring Power Transactions Using "Flowgates" / 313
7.6 Voltage Collapse / 315
7.6.1 AC Power Flow Methods / 317
7.6.2 Contingency Selection / 320
7.6.3 Concentric Relaxation / 323
7.6.4 Bounding / 325
7.6.5 Adaptive Localization / 325
APPENDIX 7A AC Power Flow Sample Cases / 327
APPENDIX 7B Calculation of Network Sensitivity Factors / 336
7B.1 Calculation of PTDF Factors / 336
7B.2 Calculation of LODF Factors / 339
7B.2.1 Special Cases / 341
7B.3 Compensated PTDF Factors / 343
PROBLEMS / 343
References / 349

8 Optimal Power Flow 350

8.1 Introduction / 350
8.2 The Economic Dispatch Formulation / 351
8.3 The Optimal Power Flow Calculation Combining Economic Dispatch and the Power Flow / 352
8.4 Optimal Power Flow Using the DC Power Flow / 354
8.5 Example 8A: Solution of the DC Power Flow OPF / 356
8.6 Example 8B: DCOPF with Transmission Line Limit Imposed / 361
8.7 Formal Solution of the DCOPF / 365
8.8 Adding Line Flow Constraints to the Linear Programming Solution / 365
8.8.1 Solving the DCOPF Using Quadratic Programming / 367
8.9 Solution of the ACOPF / 368
8.10 Algorithms for Solution of the ACOPF / 369
8.11 Relationship Between LMP, Incremental Losses, and Line Flow Constraints / 376
8.11.1 Locational Marginal Price at a Bus with No Lines Being Held at Limit / 377
8.11.2 Locational Marginal Price with a Line Held at its Limit / 378

8.12 Security-Constrained OPF / 382
8.12.1 Security Constrained OPF Using the DC Power Flow and Quadratic Programming / 384
8.12.2 DC Power Flow / 385
8.12.3 Line Flow Limits / 385
8.12.4 Contingency Limits / 386
APPENDIX 8A Interior Point Method / 391
APPENDIX 8B Data for the 12-Bus System / 393
APPENDIX 8C Line Flow Sensitivity Factors / 395
APPENDIX 8D Linear Sensitivity Analysis of the AC Power Flow / 397
PROBLEMS / 399

9 Introduction to State Estimation in Power Systems 403

9.1 Introduction / 403
9.2 Power System State Estimation / 404
9.3 Maximum Likelihood Weighted Least-Squares Estimation / 408
9.3.1 Introduction / 408
9.3.2 Maximum Likelihood Concepts / 410
9.3.3 Matrix Formulation / 414
9.3.4 An Example of Weighted Least-Squares State Estimation / 417
9.4 State Estimation of an AC Network / 421
9.4.1 Development of Method / 421
9.4.2 Typical Results of State Estimation on an AC Network / 424
9.5 State Estimation by Orthogonal Decomposition / 428
9.5.1 The Orthogonal Decomposition Algorithm / 431
9.6 An Introduction to Advanced Topics in State Estimation / 435
9.6.1 Sources of Error in State Estimation / 435
9.6.2 Detection and Identification of Bad Measurements / 436
9.6.3 Estimation of Quantities Not Being Measured / 443
9.6.4 Network Observability and Pseudo-measurements / 444
9.7 The Use of Phasor Measurement Units (PMUS) / 447
9.8 Application of Power Systems State Estimation / 451
9.9 Importance of Data Verification and Validation / 454
9.10 Power System Control Centers / 454

APPENDIX 9A Derivation of Least-Squares Equations / 456
9A.1 The Overdetermined Case ($N_m > N_s$) / 457
9A.2 The Fully Determined Case ($N_m = N_s$) / 462
9A.3 The Underdetermined Case ($N_m < N_s$) / 462
PROBLEMS / 464

10 Control of Generation **468**

10.1 Introduction / 468
10.2 Generator Model / 470
10.3 Load Model / 473
10.4 Prime-Mover Model / 475
10.5 Governor Model / 476
10.6 Tie-Line Model / 481
10.7 Generation Control / 485
10.7.1 Supplementary Control Action / 485
10.7.2 Tie-Line Control / 486
10.7.3 Generation Allocation / 489
10.7.4 Automatic Generation Control (AGC) Implementation / 491
10.7.5 AGC Features / 495
10.7.6 NERC Generation Control Criteria / 496
PROBLEMS / 497
References / 500

11 Interchange, Pooling, Brokers, and Auctions **501**

11.1 Introduction / 501
11.2 Interchange Contracts / 504
11.2.1 Energy / 504
11.2.2 Dynamic Energy / 506
11.2.3 Contingent / 506
11.2.4 Market Based / 507
11.2.5 Transmission Use / 508
11.2.6 Reliability / 517
11.3 Energy Interchange between Utilities / 517
11.4 Interutility Economy Energy Evaluation / 521
11.5 Interchange Evaluation with Unit Commitment / 522
11.6 Multiple Utility Interchange Transactions—Wheeling / 523
11.7 Power Pools / 526

11.8 The Energy-Broker System / 529
11.9 Transmission Capability General Issues / 533
11.10 Available Transfer Capability and Flowgates / 535
11.10.1 Definitions / 536
11.10.2 Process / 539
11.10.3 Calculation ATC Methodology / 540
11.11 Security Constrained Unit Commitment (SCUC) / 550
11.11.1 Loads and Generation in a Spot Market Auction / 550
11.11.2 Shape of the Two Functions / 552
11.11.3 Meaning of the Lagrange Multipliers / 553
11.11.4 The Day-Ahead Market Dispatch / 554
11.12 Auction Emulation using Network LP / 555
11.13 Sealed Bid Discrete Auctions / 555
PROBLEMS / 560

12 Short-Term Demand Forecasting 566

12.1 Perspective / 566
12.2 Analytic Methods / 569
12.3 Demand Models / 571
12.4 Commodity Price Forecasting / 572
12.5 Forecasting Errors / 573
12.6 System Identification / 573
12.7 Econometric Models / 574
12.7.1 Linear Environmental Model / 574
12.7.2 Weather-Sensitive Models / 576
12.8 Time Series / 578
12.8.1 Time Series Models Seasonal Component / 578
12.8.2 Auto-Regressive (AR) / 580
12.8.3 Moving Average (MA) / 581
12.8.4 Auto-Regressive Moving Average (ARMA): Box-Jenkins / 582
12.8.5 Auto-Regressive Integrated Moving-Average (ARIMA): Box-Jenkins / 584
12.8.6 Others (ARMAX, ARIMAX, SARMAX, NARMA) / 585
12.9 Time Series Model Development / 585
12.9.1 Base Demand Models / 586
12.9.2 Trend Models / 586
12.9.3 Linear Regression Method / 586

12.9.4 Seasonal Models / 588
12.9.5 Stationarity / 588
12.9.6 WLS Estimation Process / 590
12.9.7 Order and Variance Estimation / 591
12.9.8 Yule-Walker Equations / 592
12.9.9 Durbin-Levinson Algorithm / 595
12.9.10 Innovations Estimation for MA and ARMA Processes / 598
12.9.11 ARIMA Overall Process / 600
12.10 Artificial Neural Networks / 603
12.10.1 Introduction to Artificial Neural Networks / 604
12.10.2 Artificial Neurons / 605
12.10.3 Neural network applications / 606
12.10.4 Hopfield Neural Networks / 606
12.10.5 Feed-Forward Networks / 607
12.10.6 Back-Propagation Algorithm / 610
12.10.7 Interior Point Linear Programming Algorithms / 613
12.11 Model Integration / 614
12.12 Demand Prediction / 614
12.12.1 Hourly System Demand Forecasts / 615
12.12.2 One-Step Ahead Forecasts / 615
12.12.3 Hourly Bus Demand Forecasts / 616
12.13 Conclusion / 616
PROBLEMS / 617

Index **620**

PREFACE TO THE THIRD EDITION

It has now been 17 years from the second edition (and a total of 28 years from the publishing of the first edition of this text). To say that much has changed is an understatement. As noted in the dedication, Allen Wood passed away during the preparation of this edition and a new coauthor, Gerald Sheblé, has joined Bruce Wollenberg in writing the text. Dr. Sheblé brings an expertise that is both similar and different from that of Dr. Wollenberg to this effort, and the text clearly shows a new breadth in topics covered.

The second edition was published in 1996, which was in the midst of the period of "deregulation" or more accurately "reregulation" of the electric industry both in the United States and worldwide. New concepts such as electric power spot markets, Independent System Operators (ISOs) in the United States, and independent generation, transmission, and distribution companies are now common. Power system control centers have become much larger and cover a much larger geographic area as markets have expanded. The U.S. government has partnered with the North American Electric Reliability Corporation (formerly the North American Electric Reliability Council) and has begun a much tighter governance of electric company practices as they affect the system's reliability and security since the events of 9/11.

We have added several new chapters to the text to both reflect the increased importance of the topics covered and broaden the educational and engineering value of the book. Both Sheblé and Wollenberg are professors at major universities and have developed new examples, problems, and software for the text. Both Wollenberg and Sheblé are consultants and expert witnesses to the electric energy industry. We hope this effort is of value to the readers.

Today, students and working engineers have access to much more information directly through the Internet, and if they are IEEE members can access the very extensive IEEE Explore holdings directly from their home or office computers. Thus, we felt it best not to attempt to provide lists of references as was done in earlier editions.

We would like to extend our thanks to those students who provided excellent programming and development skills to difficult problems as they performed research tasks under our direction. Among them are Mohammad Alsaffar and Anthony Giacomoni at the University of Minnesota; George Fahd, Dan Richards, Thomas Smed, and David Walters at Auburn University; and Darwin Anwar, Somgiat Dekrajangpetch, Kah-Hoe Ng, Jayant Kumar, James Nicolaisen, Chuck Richter, Douglas Welch, Hao Wu, and Weiguo Yang at Iowa State University; Chin-Chuen Teoh, Mei P. Cheong, and Gregory Bingham at Portland State University; Zhenyu Wan at University of South Wales.

Last of all, we announce that we are planning to write a sequel to the third edition in which many of the business aspects of the electric power industry will be presented, along with major chapters on topics such as extended auction mechanisms and reliability.

BRUCE F. WOLLENBERG
GERALD B. SHEBLÉ

PREFACE TO THE SECOND EDITION

It has been 11 years since the first edition was published. Many developments have taken place in the area covered by this text and new techniques have been developed that have been applied to solve old problems. Computing power has increased dramatically, permitting the solution of problems that were previously left as being too expensive to tackle. Perhaps the most important development is the changes that are taking place in the electric power industry with new, nonutility participants playing a larger role in the operating decisions.

It is still the intent of the authors to provide an introduction to this field for senior or first-year graduate engineering students. The authors have used the text material in a one-semester (or two-quarter) program for many years. The same difficulties and required compromises keep occurring. Engineering students are very comfortable with computers but still do not usually have an appreciation of the interaction of human and economic factors in the decisions to be made to develop "optimal" schedules, whatever that may mean. In 1995, most of these students are concurrently being exposed to courses in advanced calculus and courses that explore methods for solving power flow equations. This requires some coordination. We have also found that very few of our students have been exposed to the techniques and concepts of operations research, necessitating a continuing effort to make them comfortable with the application of optimization methods. The subject area of this book is an excellent example of optimization applied in an important industrial system.

The topic areas and depth of coverage in this second edition are about the same as in the first, with one major change. Loss formulae are given less space and supplemented by a more complete treatment of the power-flow-based techniques in a new chapter that treats the optimal power flow (OPF). This chapter has been put at the end of the text. Various instructors may find it useful to introduce parts of this material earlier in the sequence; it is a matter of taste, plus the requirement to coordinate with other course coverage. (It is difficult to discuss the OPF when the students do not know the standard treatment for solving the power flow equations.)

The treatment of unit commitment has been expanded to include the Lagrange relaxation technique. The chapter on production costing has been revised to change the emphasis and introduce new methods. The market structures for bulk power transactions have undergone important changes throughout the world. The chapter on interchange transactions is a "progress report" intended to give the students an appreciation of the complications that may accompany a competitive market for the generation of electric energy. The sections on security analysis have been updated to incorporate an introduction to the use of bounding techniques and other contingency selection methods. Chapter 13 on the OPF includes a brief coverage of the security-constrained OPF and its use in security control.

The authors appreciate the suggestions and help offered by professors who have used the first edition, and our students. (Many of these suggestions have been incorporated; some have not, because of a lack of time, space, or knowledge.) Many of our students at Rensselaer Polytechnic Institute (RPI) and the University of Minnesota have contributed to the correction of the first edition and undertaken hours of calculations for homework solutions, checked old examples, and developed data for new examples for the second edition. The 1994 class at RPI deserves special and honorable mention. They were subjected to an early draft of the revision of Chapter 8 and required to proofread it as part of a tedious assignment. They did an outstanding job and found errors of 10 to 15 years standing. (A note of caution to any of you professors that think of trying this; it requires more work than you might believe. How would you like 20 critical editors for your lastest, glorious tome?)

Our thanks to Kuo Chang, of Power Technologies, Inc., who ran the computations for the bus marginal wheeling cost examples in Chapter 10. We would also like to thank Brian Stott, of Power Computer Applications, Corp., for running the OPF examples in Chapter 13.

ALLEN J. WOOD
BRUCE F. WOLLENBERG

PREFACE TO THE FIRST EDITION

The fundamental purpose of this text is to introduce and explore a number of engineering and economic matters involved in planning, operating, and controlling power generation and transmission systems in electric utilities. It is intended for first-year graduate students in electric power engineering. We believe that it will also serve as a suitable self-study text for anyone with an undergraduate electrical engineering education and an understanding of steady-state power circuit analysis.

This text brings together material that has evolved since 1966 in teaching a graduate-level course in the electric power engineering department at Rensselaer Polytechnic Institute (RPI). The topics included serve as an effective means to introduce graduate students to advanced mathematical and operations research methods applied to practical electric power engineering problems. Some areas of the text cover methods that are currently being applied in the control and operation of electric power generation systems. The overall selection of topics, undoubtedly, reflects the interests of the authors.

In a one-semester course it is, of course, impossible to consider all the problems and "current practices" in this field. We can only introduce the types of problems that arise, illustrate theoretical and practical computational approaches, and point the student in the direction of seeking more information and developing advanced skills as they are required.

The material has regularly been taught in the second semester of a first-year graduate course. Some acquaintance with both advanced calculus methods (e.g., Lagrange multipliers) and basic undergraduate control theory is needed. Optimization methods are introduced as they are needed to solve practical problems and used without recourse to extensive mathematical proofs. This material is intended for an engineering course: mathematical rigor is important but is more properly the province of an applied or theoretical mathematics course. With the exception of Chapter 12, the text is self-contained in the sense that the various applied mathematical techniques are presented and developed as they are utilized. Chapter 12, dealing with state estimation, may require more understanding of statistical and probabilistic methods than is provided in the text.

The first seven chapters of the text follow a natural sequence, with each succeeding chapter introducing further complications to the generation scheduling problem and new solution techniques. Chapter 8 treats methods used in generation system planning and introduces probabilistic techniques in the computation of fuel consumption and energy production costs. Chapter 8 stands alone and might be used in any position after the first seven chapters. Chapter 9 introduces generation control and discusses practices in modern U.S. utilities and pools. We have attempted to provide the “big picture” in this chapter to illustrate how the various pieces fit together in an electric power control system.

The topics of energy and power interchange between utilities and the economic and scheduling problems that may arise in coordinating the economic operation of interconnected utilities are discussed in Chapter 10. Chapters 11 and 12 are a unit. Chapter 11 is concerned with power system security and develops the analytical framework used to control bulk power systems in such a fashion that security is enhanced. Everything, including power systems, seems to have a propensity to fail. 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. Finally, Chapter 12 is an introduction to the use of state estimation in electric power systems. We have chosen to use a maximum likelihood formulation since the quantitative measurement–weighting functions arise in a natural sense in the course of the development.

Each chapter is provided with a set of problems and an annotated reference list for further reading. Many (if not most) of these problems should be solved using a digital computer. At RPI, we are able to provide the students with some fundamental programs (e.g., a load flow, a routine for scheduling of thermal units). The engineering students of today are well prepared to utilize the computer effectively when access to one is provided. Real bulk power systems have problems that usually call forth Dr. Bellman’s curse of dimensionality—computers help and are essential to solve practical-sized problems.

The authors wish to express their appreciation to K. A. Clements, H. H. Happ, H. M. Merrill, C. K. Pang, M. A. Sager, and J. C. Westcott, who each reviewed portions of this text in draft form and offered suggestions. In addition, Dr. Clements used earlier versions of this text in graduate courses taught at Worcester Polytechnic Institute and in a course for utility engineers taught in Boston, Massachusetts.

Much of the material in this text originated from work done by our past and current associates at Power Technologies, Inc., the General Electric Company, and Leeds and Northrup Company. A number of IEEE papers have been used as primary sources and are cited where appropriate. It is not possible to avoid omitting, references and sources that are considered to be significant by one group or another. We make no apology for omissions and only ask for indulgence from those readers whose favorites have been left out. Those interested may easily trace the references back to original sources.

We would like to express our appreciation for the fine typing job done on the original manuscript by Liane Brown and Bonnalyne MacLean.

This book is dedicated in general to all of our teachers, both professors and associates, and in particular to Dr. E. T. B. Gross.

ALLEN J. WOOD
BRUCE F. WOLLENBERG

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Gerald B. Sheblé

About the companion website

The University of Minnesota offers a set of online courses in power systems and related topics. One of the courses is based on this book. For further information, visit

http://www.cusp.umn.edu

and click on the link for the course.

A companion site containing additional resources for students, and an Instructor's site with solutions to problems found in the text, can be found at

http://www.wiley.com/go/powergenoperation.

1

INTRODUCTION

1.1 PURPOSE OF THE COURSE

The objectives of a first-year, one-semester graduate course in electric power generation, operation, and control include the desire to:

1. Acquaint electric power engineering students with power generation systems, their operation in an economic mode, and their control.
2. Introduce students to the important "terminal" characteristics for thermal and hydroelectric power generation systems.
3. Introduce mathematical optimization methods and apply them to practical operating problems.
4. Introduce methods for solving complicated problems involving both economic analysis and network analysis and illustrate these techniques with relatively simple problems.
5. Introduce methods that are used in modern control systems for power generation systems.
6. Introduce "current topics": power system operation areas that are undergoing significant, evolutionary changes. This includes the discussion of new techniques for attacking old problems and new problem areas that are arising from changes in the system development patterns, regulatory structures, and economics.

Power Generation, Operation, and Control, Third Edition. Allen J. Wood, Bruce F. Wollenberg, and Gerald B. Sheblé.

1.2 COURSE SCOPE

Topics to be addressed include

1. Power generation characteristics
2. Electric power industry as a business
3. Economic dispatch and the general economic dispatch problem
4. Thermal unit economic dispatch and methods of solution
5. Optimization with constraints
6. Optimization methods such as linear programming, dynamic programming, nonlinear optimization, integer programming, and interior point optimization
7. Transmission system effects
   a. Power flow equations and solutions
   b. Transmission losses
   c. Effects on scheduling
8. The unit commitment problem and solution methods
   a. Dynamic programming
   b. Lagrange relaxation
   c. Integer programming
9. Generation scheduling in systems with limited energy supplies including fossil fuels and hydroelectric plants, need to transport energy supplies over networks such as pipelines, rail networks, and river/reservoir systems, and power system security techniques
10. Optimal power flow techniques
11. Power system state estimation
12. Automatic generation control
13. Interchange of power and energy, power pools and auction mechanisms, and modern power markets
14. Load forecasting techniques

In many cases, we can only provide an introduction to the topic area. Many additional problems and topics that represent important, practical problems would require more time and space than is available. Still others, such as light-water moderated reactors and cogeneration plants, could each require several chapters to lay a firm foundation. We can offer only a brief overview and introduce just enough information to discuss system problems.

1.3 ECONOMIC IMPORTANCE

The efficient and optimum economic operation and planning of electric power generation systems have always occupied an important position in the electric power industry. Prior to 1973 and the oil embargo that signaled the rapid escalation in fuel prices, electric utilities in the United States spent about 20% of their total revenues on fuel for the production of electrical energy. By 1980, that figure had risen to more than 40% of the total revenues. In the 5 years after 1973, U.S. electric utility fuel costs escalated at a rate that averaged 25% compounded on an annual basis. The efficient use of the available fuel is growing in importance, both monetarily and because most of the fuel used represents irreplaceable natural resources.

An idea of the magnitude of the amounts of money under consideration can be obtained by considering the annual operating expenses of a large utility for purchasing fuel. Assume the following parameters for a moderately large system:

Annual peak load: 10,000 MW

Annual load factor: 60%

Average annual heat rate for converting fuel to electric energy: 10,500 Btu/kWh

Average fuel cost: \$3.00 per million Btu (MBtu), corresponding to oil priced at 18\$/bbl

With these assumptions, the total annual fuel cost for this system is as follows:

Annual energy produced: 10^7 kW $\times$ 8760 h/year $\times$ 0.60 = 5.256×10^{10} kWh

Annual fuel consumption: 10,500 Btu/kWh $\times$ 5.256×10^{10} kWh = 55.188×10^{13} Btu

Annual fuel cost: 55.188×10^{13} Btu $\times$ 3×10^{-6} \$/Btu = \$1.66 billion

To put this cost in perspective, it represents a direct requirement for revenues from the average customer of this system of 3.15 cents/kWh just to recover the expense for fuel.

A savings in the operation of this system of a small percent represents a significant reduction in operating cost as well as in the quantities of fuel consumed. It is no wonder that this area has warranted a great deal of attention from engineers through the years.

Periodic changes in basic fuel price levels serve to accentuate the problem and increase its economic significance. Inflation also causes problems in developing and presenting methods, techniques, and examples of the economic operation of electric power generating systems.

1.4 DEREGULATION: VERTICAL TO HORIZONTAL

In the 1990s, many electric utilities including government-owned electric utilities, private investor–owned electric utilities were "deregulated." This has had profound effects on the operation of electric systems where implemented. This topic is dealt with in an entire chapter of its own in this text as Chapter 2.

1.5 PROBLEMS: NEW AND OLD

This text represents a progress report in an engineering area that has been and is still undergoing rapid change. It concerns established engineering problem areas (i.e., economic dispatch and control of interconnected systems) that have taken on new importance in recent years. The original problem of economic dispatch for thermal systems was solved by numerous methods years ago. Recently there has been a rapid growth in applied mathematical methods and the availability of computational capability for solving problems of this nature so that more involved problems have been successfully solved.

The classic problem is the economic dispatch of fossil-fired generation systems to achieve minimum operating cost. This problem area has taken on a subtle twist as the public has become increasingly concerned with environmental matters, so "economic dispatch" now includes the dispatch of systems to minimize pollutants and conserve various forms of fuel, as well as to achieve minimum costs. In addition, there is a need to expand the limited economic optimization problem to incorporate constraints on system operation to ensure the "security" of the system, thereby preventing the collapse of the system due to unforeseen conditions. The hydrothermal coordination problem is another optimum operating problem area that has received a great deal of attention. Even so, there are difficult problems involving hydrothermal coordination that cannot be solved in a theoretically satisfying fashion in a rapid and efficient computational manner.

The post–World War II period saw the increasing installation of pumped-storage hydroelectric plants in the United States and a great deal of interest in energy storage systems. These storage systems involve another difficult aspect of the optimum economic operating problem. Methods are available for solving coordination of hydroelectric, thermal, and pumped-storage electric systems. However, closely associated with this economic dispatch problem is the problem of the proper commitment of an array of units out of a total array of units to serve the expected load demands in an "optimal" manner.

A great deal of progress and change has occurred in the 1985–1995 decade. Both the unit commitment and optimal economic maintenance scheduling problems have seen new methodologies and computer programs developed. Transmission losses and constraints are integrated with scheduling using methods based on the incorporation of power flow equations in the economic dispatch process. This permits the development of optimal economic dispatch conditions that do not result in overloading system elements or voltage magnitudes that are intolerable. These "optimal power flow" techniques are applied to scheduling both real and reactive power sources as well as establishing tap positions for transformers and phase shifters.

In recent years, the political climate in many countries has changed, resulting in the introduction of more privately owned electric power facilities and a reduction or elimination of governmentally sponsored generation and transmission organizations. In some countries, previously nationwide systems have been privatized. In both these countries and in countries such as the United States, where electric utilities have been owned by a variety of bodies (e.g., consumers, shareholders, as well as government agencies), there has been a movement to introduce both privately owned generation companies and larger cogeneration plants that may provide energy to utility customers. These two groups are referred to as independent power producers (IPPs). This trend is coupled with a movement to provide access to the transmission