



POWER GENERATION, OPERATION, AND CONTROL

Third Edition



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



WILEY

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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

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.

BRUCEF. WOLLENBERG
GERALDB. 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 latest, 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

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.

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: $10^7 \text{ kW} \times 8760 \text{ h/year} \times 0.60 = 5.256 \times 10^{10} \text{ kWh}$

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

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

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