

POWER GENERATION OPERATION AND CONTROL

Allen J. Wood

Bruce F. Wollenberg

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**POWER GENERATION,
OPERATION, AND
CONTROL**

POWER GENERATION, OPERATION, AND CONTROL

SECOND EDITION

Allen J. Wood

*Power Technologies, Inc. and
Rensselaer Polytechnic Institute*

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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 home-work 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.

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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 Bonnalynne 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.

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