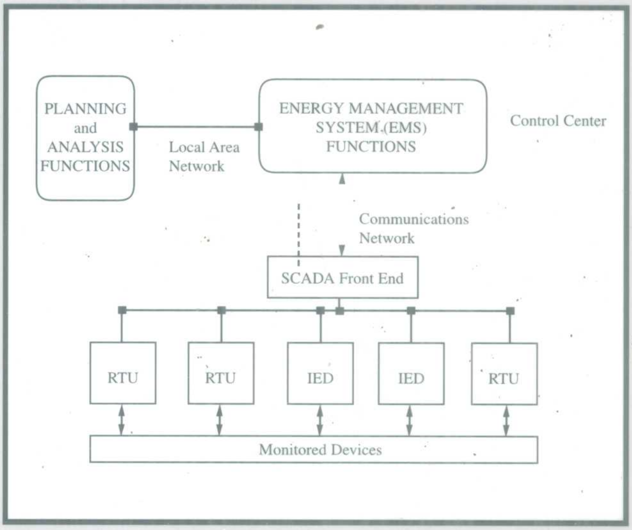
Power System State Estimation

Theory and Implementation



Ali Abur

Antonio Gómez Expósito

Power System State Estimation

Theory and Implementation

Ali Abur

Texas A&M University
College Station, Texas, U.S.A.

Antonio Gómez Expósito

University of Seville
Seville, Spain

MARCEL DEKKER, INC. NEW YORK • BASEL

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress.

ISBN: 0-8247-5570-7

This book is printed on acid-free paper.

Headquarters
Marcel Dekker, Inc., 270 Madison Avenue, New York, NY 10016, U.S.A.
tel: 212-696-9000; fax: 212-685-4540

Distribution and Customer Service
Marcel Dekker, Inc., Cimarron Road, Monticello, New York 12701, U.S.A.
tel: 800-228-1160; fax: 845-796-1772

Eastern Hemisphere Distribution
Marcel Dekker AG, Hutgasse 4, Postfach 812, CH-4001 Basel, Switzerland
tel: 41-61-260-6300; fax: 41-61-260-6333

World Wide Web
http://www.dekker.com

The publisher offers discounts on this book when ordered in bulk quantities. For more information, write to Special Sales/Professional Marketing at the headquarters address above.

Current printing (last digit):

10 9 8 7 6 5 4 3 2 1

PRINTED IN THE UNITED STATES OF AMERICA

POWER ENGINEERING

1. Power Distribution Planning Reference Book, *H. Lee Willis*
2. Transmission Network Protection: Theory and Practice, *Y. G. Paithankar*
3. Electrical Insulation in Power Systems, *N. H. Malik, A. A. Al-Arainy, and M. I. Qureshi*
4. Electrical Power Equipment Maintenance and Testing, *Paul Gill*
5. Protective Relaying: Principles and Applications, Second Edition, *J. Lewis Blackburn*
6. Understanding Electric Utilities and De-Regulation, *Lorrin Philipson and H. Lee Willis*
7. Electrical Power Cable Engineering, *William A. Thue*
8. Electric Systems, Dynamics, and Stability with Artificial Intelligence Applications, *James A. Momoh and Mohamed E. El-Hawary*
9. Insulation Coordination for Power Systems, *Andrew R. Hileman*
10. Distributed Power Generation: Planning and Evaluation, *H. Lee Willis and Walter G. Scott*
11. Electric Power System Applications of Optimization, James A. Momoh
12. Aging Power Delivery Infrastructures, *H. Lee Willis, Gregory V. Welch, and Randall R. Schrieber*
13. Restructured Electrical Power Systems: Operation, Trading, and Volatility, *Mohammad Shahidehpour and Muwaffaq Alomoush*
14. Electric Power Distribution Reliability, *Richard E. Brown*
15. Computer-Aided Power System Analysis, *Ramasamy Natarajan*
16. Power System Analysis: Short-Circuit Load Flow and Harmonics, *J. C. Das*
17. Power Transformers: Principles and Applications, *John J. Winders, Jr.*
18. Spatial Electric Load Forecasting: Second Edition, Revised and Expanded, *H. Lee Willis*
19. Dielectrics in Electric Fields, *Gorur G. Raju*
20. Protection Devices and Systems for High-Voltage Applications, *Vladimir Gurevich*
21. Electrical Power Cable Engineering: Second Edition, Revised and Expanded, *William A. Thue*
22. Vehicular Electric Power Systems: Land, Sea, Air, and Space Vehicles, *Ali Emadi, Mehrdad Ehsani, and John M. Miller*

23. Power Distribution Planning Reference Book: Second Edition, Revised and Expanded, *H. Lee Willis*
24. Power System State Estimation: Theory and Implementation, *Ali Abur and Antonio Gómez Expósito*

ADDITIONAL VOLUMES IN PREPARATION

To Our Parents

Foreword

One of the major causes of the New York power outage of 1987 was ultimately traced to incorrect information about the status of a circuit in the system. The operation of a major new market, such as the PJM market, would be nearly impossible without the capabilities afforded by state estimation. It is not yet known to what extent the blackout of 2003 may have been in part caused by missing information. Undoubtedly, thus, the theme of this book is an important one. From its origins as a mathematical curiosity in the 1970's to its limited use during the 1980's to its expanded but not yet central role in the operation of the system in 1990's, nowadays state estimation has become nothing less than the cornerstone upon which a modern control center for a power system is built. Furthermore, to the extent that markets must be integrated with reliable system operation, state estimation has acquired a whole new role: it is the foundation for the creation and operation of real time markets in power systems, and thus the foundation for all markets, real time or not, since ultimately all markets must derive their valuations from real time information. Among the most important properties of a properly operated market is something that I shall call "auditability," that is, the ability to go back and verify why certain things were done the way they were. Without an accurate and ongoing knowledge of the status of every flow and every voltage in the system at all times, it would be impossible to "go back" and explain why, for example, prices were what they were at a particular time.

This book, written by two of the most prominent researchers in the field, brings a fresh perspective to the problem of state estimation. The book offers a blend of theory and mathematical rigor that is unique and very exciting. In addition to the more traditional topics associated with weighted least squares estimation (including such *de rigueur* topics as bad data detection and topology estimation), this book also brings forth several new aspects of the problem of state estimation that have not been presented in a systematic manner prior to this effort. Most notable among these are the chapters on robust estimation and the work on ampere measurements, to name just two. In this sense the book distinguishes itself from the other state estimation book known to this writer, the book by the late great Alcir Monticelli. In such way this book is a great complement to the efforts of Monticelli.

The readers of the book will also find it quite pleasing to have a nice review of a number of topics relating to efficient computation. The book provides excellent material for those wishing to review the topic of efficient computation and sparsity in general. Proper attention is paid throughout the book to computational efficiency issues. Given that computational efficiency is the key to making state estimation work in the first place, the importance of this topic cannot be understressed.

Although the bibliography associated with every chapter and with the appendix is short, it is all quite pertinent and very much to the point. In this sense, the readers can get focused and rapid access to additional original material should they wish to investigate a topic further.

I am particularly pleased to have had the opportunity to comment on both the theme of the book and the book itself, since the authors of this book are unquestionably respected leaders in the field and are themselves the originators of many of the ideas that are in present use throughout the field of state estimation and beyond. I am sure readers will share with me these sentiments after reading this book.

Fernando L. Alvarado

Preface

Power system state estimation is an area that matured in the past three decades. Today, state estimators can be found in almost every power system control center. While there have been numerous papers written on many different aspects of state estimation, ranging from its mathematical formulation to the implementation and start-up issues at the control centers, relatively few books have been published on this subject.

This book is the product of a long-term collaboration between the authors, starting from the summer of 1992 when they worked at the University of Seville on a joint project that was sponsored by the Ministry of Science and Education of the Spanish Government. Since then, they have spent two summers working together on different projects related to state estimation and continued their collaboration. They each taught regular and short courses on this topic and developed class notes, which make up most of the material presented in this book.

The chapters of the book are written in such a way that it can be used as a textbook for a graduate-level course on the subject. However, it may also be used as a supplement in an undergraduate-level course in power system analysis. Professionals working in the field of power systems may also find the chapters of the book useful as self-contained references on specific issues of interest.

The book is organized into nine chapters and two appendices. The introductory chapter provides a broad overview of power system operation and the role of state estimators in the overall energy management system configurations. The second chapter describes the modeling of electric networks during steady state operation and formulates one of the most commonly used state estimation methods in power systems, namely the weighted least squares (WLS) method. Application of the WLS method to power system state estimation presents several challenges ranging from numerical instabilities to the handling of measurements with special constraints. Chapter 3 presents various techniques for addressing these problems. Network observability is analyzed in Chapter 4, where a brief review of networks and graphs is followed by the description of alternative methods for network observability determination. Chapter 5 is concerned with detecting and identifying incorrect measurements. In this chapter, it is assumed that the WLS method is used for state estimation and bad data processing takes place after the convergence of the WLS state estimator. In Chapter 6, the topic of robust estimation is introduced and some robust estimation methods which have already been investigated for power system applications are presented. Chapter 7 is about different methods of estimating transmission line parameters and transformer taps. These network parameters are typically assumed to be perfectly known, despite the fact that errors in them significantly affect the state estimates. The problem of topology error identification is the topic of Chapter 8. Topology errors cause state estimators to diverge or converge to incorrect solutions. The challenges in detecting and identifying such errors and methods of overcoming them are presented in this chapter. Finally, Chapter 9 discusses the use of ampere measurements and various issues associated with their presence in the measurement set. The book also has two appendices, one on basic statistics and the other on sparse linear equations.

All chapters, except for the first one, end with some practice problems. These may be useful if the book is adopted for teaching a course at either the graduate or undergraduate level. The first five chapters are recommended to be read in the given order since each one builds on the previously covered material. However, the last four chapters can be covered in any arbitrary order.

Parts of the work presented in this book have been funded by the United States National Science Foundation projects ECS-9500118 and ECS-8909752 and by the Spanish Government, Directory of Scientific and Technical Investigations (DGICYT) Summer Research Grants No. SAB 95-0354 and SAB 92-0306, and Research Project No. PB94-1430.

It has been a pleasure to work with our many graduate students who have contributed to the development and implementation of some of the ideas in this book. Specifically, we are happy to acknowledge the contributions made by Esther Romero, Francisco González, Antonio de la Villa, Mehmet Kemal Çelik, Hongrae Kim, Fernando Hugo Magnago and Bei Gou in their respective research projects.

Finally, we are also grateful for the constant encouragement and support that we have received from our spouses, Ayşen and Cati, during the preparation of this book.

Ali Abur
Antonio Gómez Expósito

Contents

Chapter 1

Introduction

Power systems are composed of transmission, sub-transmission, distribution and generation systems. Transmission systems may contain large numbers of substations which are interconnected by transmission lines, transformers, and other devices for system control and protection. Power may be injected into the system by the generators or absorbed from the system by the loads at these substations. The output voltages of generators typically do not exceed 30-kV. Hence, transformers are used to increase the voltage levels to levels ranging from 69-kV all the way up to 765-kV at the generator terminals for efficient power transmission. High voltage is preferred at the transmission system for different reasons one of which is to minimize the copper losses that are proportional to the ampere flows along lines. At the receiving end, the transmission systems are connected to the sub-transmission or distribution systems which are operated at lower voltage levels ranging from 115-KV to 4.16-KV. Distribution systems are typically configured to operate in a radial configuration, where feeders stretch from distribution substations and form a tree structure with their roots at the substation and branches spreading over the distribution area.

1.1 Operating States of a Power System

The operating conditions of a power system at a given point in time can be determined if the network model and complex phasor voltages at every system bus are known. Since the set of complex phasor voltages fully specifies the system, it is referred to as the static state of the system. According to [1], the system may move into one of three possible states, namely normal, emergency and restorative, as the operating conditions change.

A power system is said to operate in a normal state if all the loads in the system can be supplied power by the existing generators without violating