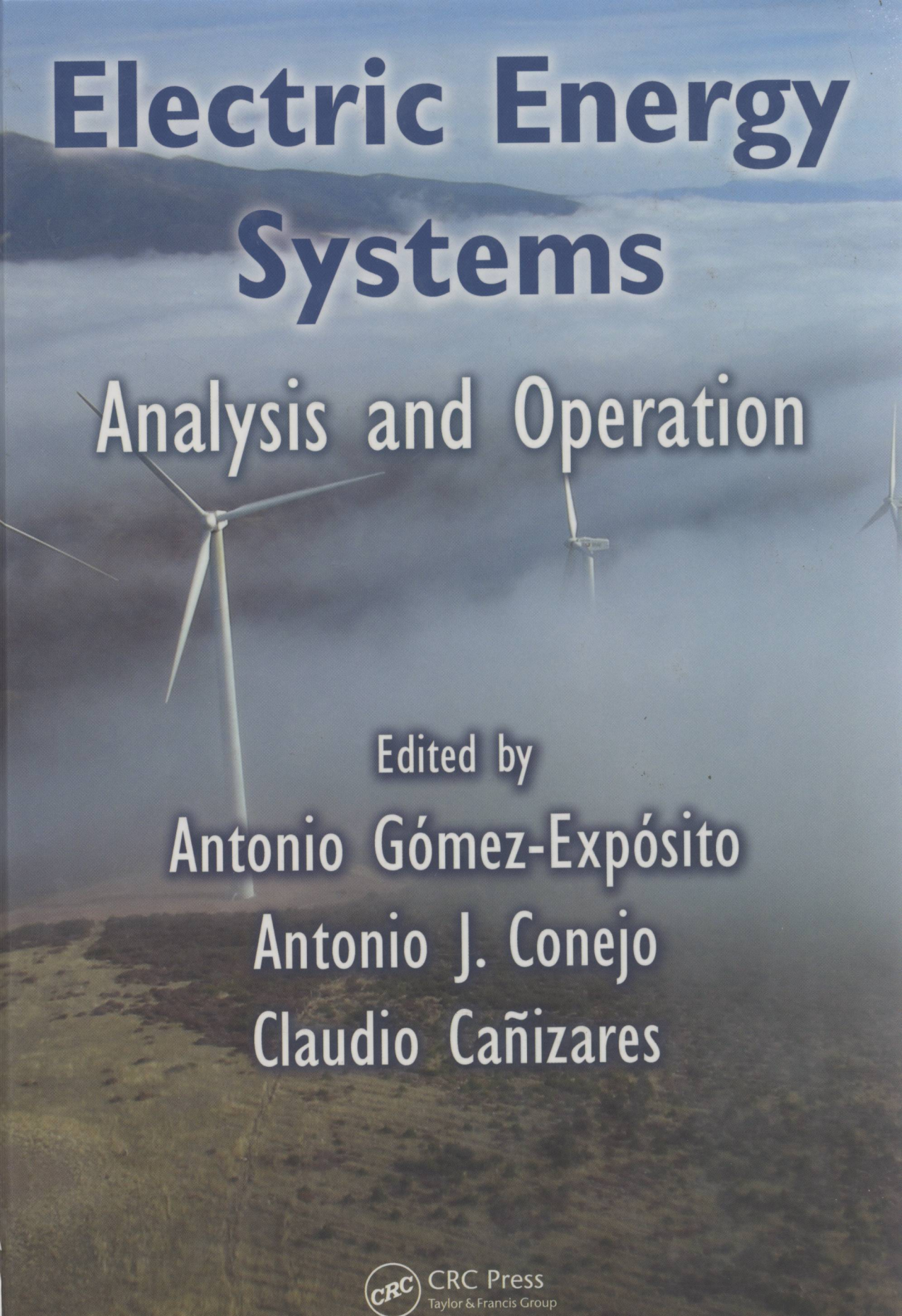
Electric Energy Systems

Analysis and Operation



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Electric Energy Systems

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Antonio Gómez-Expósito, Antonio J. Conejo, and Claudio Cañizares

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Experience is not always the kindest of teachers,
but it is surely the best
—Spanish Proverb

Foreword

The purpose of this book is to merge, update, and extend the material in both classical power system analysis books and power economics books, within the framework of currently restructured electric energy systems. This effort is clearly needed to address the operations and planning problems in nowadays unbundled generation, transmission, and distribution systems.

In addressing the aforementioned issues, we realized that the challenges were significant. First of all, we had to provide added value to the reference books on the topic. Fortunately, achieving this goal was facilitated by the economic and technical revolution that the electric sector has been undergoing during the last two decades. This revolution has dramatically changed or made obsolete many important concepts as they are considered in existing books. Another difference between this and earlier books lies in the addition of some advanced chapters, which are usually covered in specialized monographs, as well as in the deeper treatment of certain classical topics.

The second and perhaps more difficult challenge was the need to avoid an *encyclopedic* approach, both in scope and content. A book coauthored by 24 researchers, each one writing on his own area of expertise, can easily degenerate into a voluminous collection of disconnected papers, which might only be useful for a minority of specialists. Being aware of this risk, the authors have made a significant effort to begin with the basic principles, paying attention to the topics any power engineer should know, including many solved examples, and directing the reader to other chapters if necessary. Some redundant material has been intentionally left out in order not to distract the reader's attention by cross referencing. An added advantage of the approach used here is that many chapters become self-sufficient for those readers with a certain background in power systems who simply desire to keep themselves updated.

Our objective was to keep the spectrum of readers to whom this book is directed fairly broad. On the one hand, instructors and undergraduate students of engineering schools can use it as a textbook, with the material being possibly fully covered in two terms. Depending on the particular context, the instructor may have to pick up only a subset of chapters, discarding those that are covered in other subjects of the curriculum. This may be the case of protections, overvoltages, synchronous machines, etc. On the other hand, considering the advanced level of certain chapters, and the inclusion, for the first time in a textbook of this breadth and depth, of the regulatory issues, which are changing the electric sector, this volume can also serve as a handbook for graduate students and practicing professionals who lack the time to search for original sources (papers and technical reports). These readers will surely welcome the large number of references at the end of each chapter, which will allow them to acquire a deeper knowledge on the topics of their own interest.

It is assumed here that the reader has a minimum background in algebra (matrices, complex numbers, etc.), calculus (linear differential equations, Laplace and Fourier transform, etc.), physics (electromagnetic fields, rotating mass dynamics, etc.), circuits (nodal equations, three-phase circuits, etc.) and, if possible, electric machines and microeconomics. This is usually the case of those undergraduate students who enroll for the first time in a course on power system analysis.

Owing to space limitations, the book is mainly focused on the operation of generation and transmission systems, although part of the material (e.g., certain component models, three-phase and harmonic load flows, reliability indices and protections) is of application also in the analysis of distribution networks. For the same reason, the long-term planning problem has not been explicitly dealt with; nevertheless, several chapters and parts of others (e.g., load flow, generation scheduling, security, reliability, and stability) present essential tools for network expansion studies, design and comparison of alternatives, etc., which are directly linked with the short-term planning problem.

The book has been organized in 12 chapters and 3 appendices, which could have been arranged in several ways. A possibility could have been to begin with the most classical chapters (load flow, frequency regulation, economic dispatch, short circuits, and transient stability), and then continue with what could be labeled advanced topics (market issues, state estimation, electromagnetic transients, harmonics, etc.). However, it is difficult in many cases to place the division between basic and advanced material properly speaking, particularly in those chapters specifically dealing with the operation of generation and transmission systems. The scheme adopted in this book is based instead on the different working regimes of the power system, which are crucial to determine the techniques and tools needed to study the time scales involved.

The five chapters following the introductory one cover what is essentially the balanced sinusoidal steady-state regime, which, rigorously speaking, should be called quasi-steady-state because of the slow but continuous variation of the loads. In this context, mainly related to the real-time operation of power systems, phasors and complex power constitute the basic tools on which the different analytical and computational methods are built. On the other hand, the last six chapters are devoted to the transient and nonsinusoidal states of a power system, including both balanced and unbalanced conditions. The system under transients originated by faults is first dealt with, followed by the slower electromechanical oscillations, to end with the faster electromagnetic transients.

Chapter 1 makes an original presentation of what power systems have been in the past and what they have become nowadays, from the technical, economical and regulatory points of view. It constitutes by itself very valuable material to be disseminated among those young students who erroneously believe that professional challenges can only be found in computer engineering and communications.

Besides conventional components, Chapter 2 briefly deals with cables and asynchronous machine modeling, of renewed interest in view of the growth of distributed generation. An introduction to load forecasting techniques is also presented.

In Chapter 3, which is devoted to the classic power flow or load flow problem, the section on large-scale systems, complemented by Appendix A, stands out. The reader may find interesting the discussion about the simplifications behind the fast decoupled load flow. Power flow and voltage regulating devices are presented, starting from a common framework, in an original manner.

Chapter 4 provides many more details than it is usual in textbooks about advanced topics related to state estimation, like nonquadratic estimators and topology error identification.

Chapter 5 starts with a rigorous and general treatment of the economic dispatch problem, paying special attention to transmission loss coefficients, and finishes with the formulation of the optimization problems currently faced by producers, consumers, and other agents of electricity markets.

The presence of Chapter 6, entirely devoted to the operation of the transmission subsystem, is new in textbooks of this nature, but we believe it is fundamental to provide a comprehensive view of all the problems and tasks involved at this level. The new paradigm under which transmission networks are operated, based on open and nondiscriminatory access, and the resulting challenges are presented and discussed in this chapter.

The second part of the book starts with Chapter 7, which is devoted to a general treatment of three-phase linear and nonlinear models of power system components, including power electronics components, such as filters, voltage-source converters, etc. Several of the models described here are used in the following chapters.

Chapter 8 comprises two closely related subjects, namely fault analysis, including a brief reference to grounding systems, and protections. More attention than usual is paid to the matrix-based systematic analysis of short circuits in large-scale systems.

Automatic regulation and control of voltages and frequency is dealt with in Chapter 9 from a broader perspective, beginning with local or primary control strategies and ending with the region-wide secondary and tertiary control schemes. These controls and associated concepts, such as hierarchical and wide-area control, are presented and discussed within the context of practical grid requirements in Europe and North America, and in view of their role in competitive electricity markets, particularly in relation to ancillary services.

Power system stability analysis is discussed in Chapter 10 in a novel and up-to-date manner. This chapter assumes that the reader is familiar with basic system element models and controls, particularly those associated with the synchronous machine, as discussed in Chapters 7 and 9 and Appendix C. Each stability subtopic, that is, angle, voltage, and frequency stability, is first defined and the main concepts and analysis techniques are then explained using basic and simple system models. This is followed by a discussion of practical applications, analysis tools and measures for stability improvement, closing with a brief description of a real instability event, which is a unique feature of this book with respect to other textbooks in the topic.

Chapters 11 addresses again the power flow problem but under nonsinusoidal and unbalanced conditions. This chapter presents advanced topics whose relevance is steadily increasing, given the growing portion and size of electronic converters connected to power systems.

Ignored or superficially covered in most textbooks, in Chapter 12 analytical and computational techniques for the study of electromagnetic transients are explained in detail, as well as some related applications, like propagation and limitation of overvoltages.

The book closes with three appendices covering the solution of large-scale sparse systems of linear equations (Appendix A), the fundamentals of optimization (Appendix B), and the modeling of induction and synchronous machines (Appendix C).

The analytical and computational techniques covered in this book have been selected taking into account that the speed of response in the analysis of very large nonlinear systems is often crucial for the results to be of practical use. In this sense, electric energy systems constitute a unique case, because of their size, complexity, and strict control requirements.

We are thankful to all the colleagues, students, and institutions who have helped us in the complex endeavor of editing and partly writing this book. We hope that this book will be helpful for the new generations of power engineering students and professionals, which is the sole motivation for this project.

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Editors

Antonio Gómez-Expósito received a six-year Industrial Engineering degree, major in Electrical Engineering, with honors, in 1982, and a Doctor of Engineering degree in 1985, both from the University of Seville, Spain. He is currently a full professor at the University of Seville, where he is chairing the Department of Electrical Engineering, the Post-Graduate Program on Electrical Energy Systems and the recently created Endesa Cathedra. In the late eighties, he created and is leading a research group with over twenty researchers, including fourteen doctors. Previously he was also a visiting professor in California and Canada.

Prof. Gómez-Expósito has coauthored several textbooks and monographs about Circuit Theory and Power System Analysis, of which the one published by Marcel Dekker, *Power System State Estimation: Theory and Implementation*, stands out. He is also coauthor of nearly 200 technical publications, many of them in IEEE Transactions. In addition to his regular consulting activity, he has been principal investigator of over forty research projects, funded by public institutions and all major Spanish utilities. Practical results of those projects are power system state estimators, expert systems, digital relays, fault locators, training simulators, etc.

Prof. Gómez-Expósito is a member of the Editorial Board of the IEEE Latin America Transactions and has been involved in the organizing and technical committees of nearly twenty international conferences. Among other recognitions, he received in 2005 the "City of Seville Award" for his research activities in electric energy efficiency, as well as the "Novare Award" in 2007, granted by Endesa to fund a 0.5 Meuros research project. He is a Fellow of the IEEE.

Antonio J. Conejo received an MS degree from MIT, Cambridge, Massachusetts and a PhD degree from the Royal Institute of Technology, Stockholm, Sweden. He is currently a full professor of Electrical Engineering at the Universidad de Castilla-La Mancha, Ciudad Real, Spain. A coauthor of *Decomposition Techniques in Mathematical Programming: Engineering and Science Applications*, professor Conejo has authored or coauthored over ninety papers in refereed journals, and has been the principal investigator of many research projects. His research interests include control, operations, planning and economics of electric energy systems, as well as statistics and optimization theory and its applications. Professor Conejo is a member of the editorial board of the IEEE Transactions on Power Systems and an IEEE Fellow.

Claudio A. Cañizares received an Electrical Engineering degree in April 1984 from the Escuela Politécnica Nacional (EPN), Quito-Ecuador, where he held various teaching and administrative positions from 1983 to 1993. His MSc (1988) and PhD (1991) degrees in Electrical Engineering are from the University of Wisconsin-Madison. He is currently a full professor at the University of Waterloo, Department of Electrical and Computer Engineering, and was the associate chairman of Graduate Studies (2000–2003), deputy chair (2003–2004), and acting chair (July–August 2004) of the Department. In the 1999–2000 academic year, he was a Visiting Professor at the Dipartimento di Elettrotecnica of the Politecnico di Milano, and worked as a research consultant for ENEL-Ricerca and CESI in Milan. During his 2006–2007 sabbatical leave, he was an invited professor at each of the following institutions: ETH, Zurich, Switzerland (September–October 2006); University of Castilla-La Mancha, Ciudad Real, Spain (November–December 2006); and University of Seville, Seville, Spain (January–February 2007). His research activities concentrate mostly on the study of nonlinear systems stability, modeling and computational issues in ac/HVDC/FACTS power systems, and more recently in the areas of price forecasting, demand side management/demand response and

multicarrier energy systems, all within the context of competitive electricity markets. In these areas, he is continuously collaborating with industry and university researchers in Canada and abroad, supervising multiple research fellows and graduate students, some of whom have received awards at important international conferences, and several hold leadership positions in industry and academia. Of his multiple teaching activities, in 2003, his leadership role in the proposal and development of a very successful Power Engineering online program for industry professionals, with strong support and significant funding from Hydro One Networks Inc., should be highlighted.

Dr. Cañizares has authored and coauthored over 170 journal and conference papers, as well as various technical reports, book chapters and a popular computer program for bifurcation analysis of power systems. He has been invited to make keynote presentations at various seminars and conferences throughout the world, as well as participate in several technical IEEE and CIGRE committees and special publications. He is an active member of various IEEE and CIGRE committees, working groups and task forces, and currently holds, and has held in the past, several leadership appointments in some of these committees, which have led to IEEE-PES Working Group Recognition awards. In January 2007, he was granted the IEEE Fellow rank for contributions to voltage stability of power systems. He is also a registered professional engineer in the province of Ontario, Canada.

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1 Electric Energy Systems—An Overview

Ignacio J. Pérez-Arriaga, Hugh Rudnick, and Michel Rivier Abbad

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1.1 A FIRST VISION

1.1.1 The Energy Challenges in Modern Times

Energy is a fundamental ingredient of modern society and its supply impacts directly on the social and economic development of nations. Economic growth and energy consumption go hand-in-hand. The development and quality of our lives and our work are totally dependent on a continuous, abundant, and economic energy supply. This reality is being faced worldwide as basic energy resources have become scarce and increasingly costly. While coal remains an abundant resource, oil and natural gas supply face restrictions, concerns arising on declining volumes in the long term. This reliance on energy for economic growth has historically implied dependence on third parties for energy supply, with geopolitical connotations, as energy resources have not been generally in places where high consumption has developed. Energy has transformed itself into a new form of international political power, utilized by owners of energy resources (mainly oil and natural gas).

Within that framework, electricity has become a favorite form of energy usage at the consumer end, with coal, oil, gas, uranium, and other basic resources used to generate electricity. With its versatility and controllability, instant availability and consumer-end cleanliness, electricity has become an indispensable, multipurpose form of energy. Its domestic use now extends far beyond the initial purpose, to which it owes its colloquial name ("light" or "lights"), and has become virtually irreplaceable in kitchens—for refrigerators, ovens, and cookers or ranges, and any number of other appliances—and in the rest of the house as well, for air conditioner, radio, television, computers, and

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