Restructured Electric Power Systems

Analysis of Electricity Markets with Equilibrium Models

XIAO-PING ZHANG

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Mohamed E. El-Hawary, *Series Editor*

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EDITED BY

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PREFACE

Electricity market deregulation is driving the power energy production from a monopolistic structure into a competitive market environment. The liberalization of the energy production has brought the issue of market equilibrium into the electricity power industry. Many studies have been performed in order to adjust the available equilibrium analysis methods to fit to the electricity market rules and sensitivities. With the development of electricity markets, one of the challenging and yet important task is to analyze the electricity market behavior and market power in order to improve the efficiency of electricity markets.

Special contributions of this book are to overview the latest developments in analyzing and assessing electricity market behavior and market power, that is, the electricity market equilibrium models, and discuss the application of such models in practical analysis of electricity markets. The topics of this book reflect the recent research and development of the electricity market equilibrium models, and foresee the future applications of such models and computational techniques in electricity market analysis:

- Fundamentals of electric power systems such as system structure and evolution, analytical techniques for system operation and control, and their consequence in electricity market environments.
- State-of-the-art electricity market design, and operations drawn from the real electricity markets.
- Problems of electricity market behavior and market power are reviewed and electricity market equilibrium models for analyzing market behavior, and market power are outlined.
- Mathematical programs with equilibrium constraints (MPEC) and equilibrium problems with equilibrium constraints (EPEC) are presented, the state of the art techniques for computing the electricity market equilibrium problems are discussed, and the challenges and recent advances in solving the electricity market equilibrium problems are discussed.
- Applications of the electricity market equilibrium models in electricity market modeling and analysis are presented.

Chapter 1 discusses the fundamentals of electric power systems. The structure and evolution of electric power systems are outlined. New developments include the integration of renewable generation sources into electric power systems, new operating and control paradigm such as microgrids, virtual power plants, plug-in hybrid electric vehicles, and the development of super power grids, which will have a significant impact on the operation of electric power systems as well as electricity markets. Then the concepts, analytical methods, and tools for operation and control of electric power systems are presented where the implications of these in electricity market environments are also briefly discussed. Finally real-time control of electric power systems via SCADA/EMS systems and the future trend of system operation and control are discussed, which is closely related to the development of future electricity markets.

In Chapter 2, the history of electric power systems deregulation is reviewed while the structure and the evolution of electricity markets are discussed. Then Chapter 2 addresses the key market design objectives and fundamental market design principles, especially the state-of-the art standard market design (SMD) framework, and also the operation of electricity markets and the criteria for its success. In addition, computational tools for electricity markets operations are presented. The treatment in this chapter reflects the current practice of electricity market structure, design, and operations, drawn from design and operation of the real electricity markets.

In Chapter 3, in connection with the electricity market development, the implication of market power is discussed. Then different electricity market equilibrium models for analyzing market behavior of participants and market power, which are related to the development of mathematical programs with equilibrium constraints (MPEC) and equilibrium problems with equilibrium constraints (EPEC) in mathematical programming, are overviewed; the challenges in the computing electricity market equilibrium are outlined; and recent advances in solving the electricity market equilibrium problems are discussed, and future research needs are also presented.

As in most fields, any attempt to develop a tractable model must abstract away from at least some of the detail. However, the choices in electricity markets are particularly difficult in part because experience with electricity markets is still accumulating and in part because there are several features of electricity markets are not features of other markets. Chapter 4 discusses the formulation of electricity market equilibrium models, distinguishing the physical, commercial, and economic models. It outlines the uses of such models, qualified in the light of the many assumptions that must be made for them to be tractable.

Most existing Nash-Cournot models of competition among electricity generators assume that firms behave purely *a la* Cournot or Bertrand with respect to transmission decisions by the independent system operator. Such models are unrealistic for markets in which interfaces connecting subnetworks are frequently saturated but the congestion pattern within individual subnetworks is less predictable. In order to deal with such situations, Chapter 5 proposes two approaches for dealing with them. The first is a hybrid Bertrand-Cournot model of these markets in which firms are assumed to behave *a la* Cournot regarding inter-subnetwork transmission quantities, but *a la* Bertrand regarding intra-subnetwork transmission prices. A second approach is a Bertrand-type model where transmission lines that are congested most of the time are designated as "common knowledge constraint" and treated as equality constraints by all market participants including the ISO and all generation firms. Under affine demand functions and quadratic costs, the market equilibrium of these models becomes mixed linear complementarity problems with bisymmetric positive semi-definite matrices.

In Chapter 6, the electricity market equilibrium analysis is performed with the aid of a nonlinear primal-dual interior point algorithm to solve the linear SFE bid-based electricity market model with a full AC network representation. This algorithm is based upon the AC transmission model, fully taking into consideration all the operating aspects such as the generation capacity limits, bus voltage limits, transmission line constraints, network losses, transformer tap-ratio control, and especially the effect of the reactive power. In the market equilibrium algorithm proposed, the impact of the electricity network control such as voltage control, transformer tap-ratio control on the market equilibrium is examined.

In Chapter 7, in response to the new requirements that restructured power markets place upon transmission planning, a method for assessing the economic benefits of transmission upgrades has been proposed by the California Independent System Operator (CAISO). Economic effects considered include reductions in the cost of building and operating power plants along with changes in market prices. The methodology accounts for how transmission upgrades mitigate market power by increasing the size of a supplier's geographic market, considering historical patterns of bidding behavior. Five principles underlie the methodology: consideration of multiple perspectives (consumers, generators, transmission operators, and society at large); full network representation; market-based pricing, accounting for strategic behavior by generators; modeling of uncertainty, including the value of transmission as insurance against extreme events; and recognition of how supply, demand-side, and transmission resources can substitute for each other. The methods used in the first full-scale application, to the proposed Palo Verde-Devers 2 (PVD2) upgrade, are summarized, along with results. Novel methods for modeling market power and for specifying probabilities of future scenarios and analyzing the effect of uncertainty are summarized and applied. Mitigation of market power accounts for a substantial portion of the benefits of that project.

The materials are derived mainly from the research and industrial development in which the authors have been heavily involved. The book will be a very useful reference for electrical power engineers, university professors, and undergraduate and postgraduate students in the subject area of electrical power systems, power system economics, and energy policy. The book can be used for postgraduate courses and industry courses as well.

Finally I am most grateful for the timely cooperation of all the contributors, in particular Ross Baldick, Benjamin Hobbs, Shmuel Oren, and David Sun for their enthusiasm in this book and their timely inputs. Without them, this book would not exist. I very much appreciate the staff from the IEEE Press and Wiley for their patience and good-natured support during the preparation of the book. I would also like to thank very much Dr. Mohamed El-Hawary, Series Editor of Power Engineering, for his kind advice and suggestions during the process of preparing this book. Last but not at least, I thank very much my wife, Zhong, my daughter, Dorothy, and my son, George for their patience, understanding and support during the development of the book.

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