1. Operation of Restructured Power Systems

Y.H. Song, X. Wang and J.Z. Liu

There has been a world-wide trend towards restructuring and deregulation of the power industry over the last decade. The competition in the wholesale generation market and the retail market together with the open access to the transmission network can bring many benefits to the end consumers, such as lower electricity prices and better services. However, this competition also brings many new technical issues and challenges to the operation of restructured power systems. In recent years there have been many publications [1−4] devoted to the regulation and policy issues of establishing markets for electricity. This book will focus on the development of computational tools for effectively and efficiently operating such restructured systems.

1.1 System Operation in a Competitive Environment

Regardless of the market structures that may emerge in various parts of the world, one fact that seems always to be true is that transmission and generation services will be unbundled from one another. The generation market will become fully competitive, with many market participants who will be able to sell their energy services (or demand side management). On the other hand, the operation of a transmission system is expected to remain a regulated monopoly whose function is to allow open, non-discriminatory and comparable access to all suppliers and consumers of electrical energy. This function can be implemented by an entity called the Independent System Operator (ISO) [5−13].

Although electricity markets may have many different ISO designs and approaches all over the world, there are nonetheless elements that are necessary to all types of ISOs in order to meet their common basic requirements. Basically, the ISO has responsibility for the reliability functions in its region of operation and for assuring that all participants have open and nondiscriminatory access to transmission services through its planning and operation of the power transmission system. The ISO should conduct all of its functions in an impartial manner so that all participants are treated equitably. The main functions of the ISO can be categorized into reliability-related functions and market-related functions.

1.1.1 Reliability-related Functions

The reliability-related functions include two aspects:

- System operation and coordination. The ISO should perform system security monitoring functions and redispatch generation as necessary to eliminate real-time transmission congestion and to maintain system reliability, including taking all necessary emergency actions to maintain the security of the system in both normal and abnormal operating conditions.
- Transmission planning and construction. The ISO should carry out reliability studies and planning activities in coordination with the transmission owners and other market participants to assure the adequacy of the transmission system. The ISO should publish data, studies and plans relating to the adequacy of the transmission system. Data might include locational congestion prices and planning studies that identify options for actions that might be taken to remedy reliability problems on the grid and cost data for some of these actions.

1.1.2 Market-related Functions

First of all, an ISO must be a market enabler with no commercial interest in the competitive generation market. The market-related functions of an ISO must be carried out according to transparent, understandable rules and protocols. The following operational functions are necessary to enable a competitive generation market:

- Determine Available Transmission Capability (ATC) for all paths of interest within the ISO region.
- Receive and process all requests for transmission service within and through the ISO region from all participants, including transmission owners.
- Schedule all transactions it has approved.
- Operate or participate in an Open Access Same Time Information System (OASIS) for information publishing.
- Establish a clear ranking of transmission rights of all the participants on the ISO transmission system. Facilitate trading of transmission rights on its grid among participants.
- Manage transmission congestion in accordance with established rules and procedures for generation redispatch and its cost allocation.
- Assure the provision of ancillary services required to support all scheduled delivery transactions.
- Market settlement and billing functions.

The minimum functions of the ISO should include the operation and coordination of the power system to ensure security. In this case, a separate market operator (for example, the Power Exchange in California) is needed to perform the market-related functions. On the other hand, the maximum functions of the ISO will include all the reliability-related and market-related functions mentioned above and in addition the ISO is the transmission owner (for example, the National Grid Company of UK). The functions of the ISO at various sizes and time scales are shown in Figure 1.1.

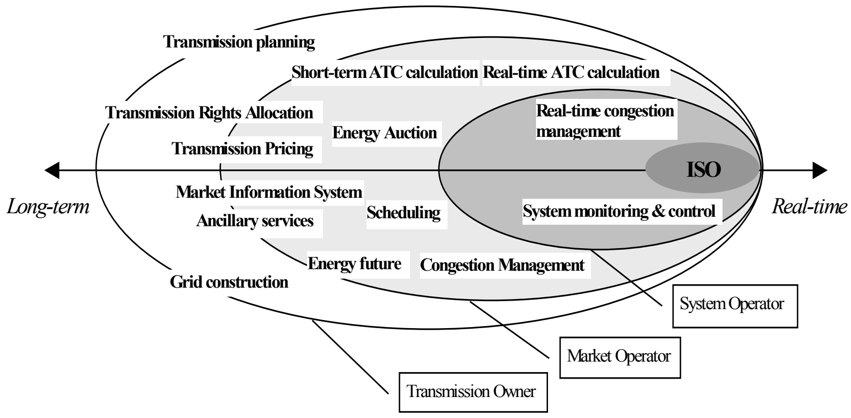

Figure 1.1. Functions of the ISO at various sizes and time scales

1.2 Effects of Industry Restructuring on System Reliability

Maintaining reliability involves two sets of operations: normal operations and emergency operations. Markets can do much to maintain reliability and prevent outages (by preparing resources for use in emergencies) during normal operations. Markets alone may be much less effective during actual emergencies [11].

Response time is the key factor that will determine whether the independent actions of participants in competitive markets can perform some reliability functions or whether technical standards and direct control will be required. Roughly speaking, competition is likely to work well for actions that occur half an hour or more in the future. Given this lead time, buyers and sellers can find the price level for each service that will balance supply and demand. For shorter time periods, however, system control is still likely to be required. Technical standards may be needed to specify the amount of each service that is required and to establish metrics for judging the adequacy of service delivery; markets can then determine the least-cost ways to deliver the required services. Disturbance response and generation planning provide useful examples of the two ends of the temporal spectrum.

The system operator must have the ultimate authority to compel actions needed to maintain reliability in real time and to restore the system quickly and safely after an outage occurs, although after-the-fact disputes may occur over who pays for what. If the system operator deemed it necessary to reduce flows on a particular transmission line, to take a line out of service, to reduce output at a particular generator, or to increase output at another generator, the operators of those pieces of equipment would be required to comply with the orders from the system operator. Such real-time operating authority is necessary to ensure system security in the future, as in the past, although these services may be obtained in a market-based means.

Providing for system adequacy, however, may be different in the future from in the past. For example, generation planning will be entirely different from its past practice. Historically, utilities planned for and built power plants to meet a predetermined reserve criterion, typically a 1-day-in-10-years loss-of-load probability or a minimum installed reserve margin. The regulator then determined the extent to which the utility would recover the costs of these generators through rates charged to the utility's retail customers. In addition, these costs were generally reflected in embedded-cost rates that did not vary from hour to hour. In the future, in a market-based model for providing adequate generation resources, decisions on retirement or repowering of existing generators and the construction of new units are likely to be made by investors with much less regulatory involvement. Of course, governments will still oversee the siting and environmental consequences of these decisions. But with retail choice of generation suppliers, markets (investors and consumers), rather than economic regulators, will decide which supplies are needed and economical.

These decisions will be made on the basis of trends in market prices and projected revenues from the sale of electricity relative to the construction and operating costs of the unit in question. Generators will be built when projected market prices of electricity are high enough to yield a profit. Prices in the future are likely to vary from hour to hour throughout the year, based on the units in operation each hour and the balance between unconstrained demand and supply online. When demand begins to exhaust the available supply, prices will rise, sometimes sharply, which in turn will suppress demand and induce investment in new supply. Spot prices will stop rising only when constrained demand is brought down, supply is increased, or both. Although these spot prices are likely to be quite low for most hours, they may be very high for a few hours each year. It is the level, frequency, and duration of these high prices that will signal markets to build more generating capacity, rather than the decisions of planners in vertically integrated utilities. This price volatility will also signal customers on the benefits of managing their loads in real time.

In electricity markets, customer response to real-time pricing signals could also help to improve reliability. High prices will encourage the construction of new generating units and the prompt restoration to service of existing units that are off-line. Similarly, with real-time price information, consumers can decide whether they want to conserve or reduce their usage at times of high prices. Together, these supply and demand responses to price will reduce the need to maintain expensive generating capacity that is only rarely used. Thus, economics can substitute for engineering to maintain real-time reliability when demand would otherwise exceed supply. The challenge of restructuring the electricity industry is to find an appropriate mix of economic incentives and performance standards that maintain reliability at the lowest reasonable cost.

1.3 New Requirement for Computation Tools and Software Systems in Electricity Markets

New computational tools and software systems are needed for generators, retailers, the ISO and other market participants to meet the operating, scheduling, planning, and financial requirements in the emerging competitive market environment. For example, generation companies may need new bidding systems to decide their bidding strategies and to communicate their bidding information with the market operator; the retailers and distribution companies may need new billing systems and new load management system to meet the time varying spot prices.

The most complex requirement on software systems will come from the ISO, who is in charge of the secure operation of the power system and may even run a few markets for energy auction, ancillary services procurement, and transmission rights auction, etc. Historically, the main software system in the control centre of the power system is the well-known Energy Management System (EMS), which consists of four major elements [11–13]:

- Supervisory Control and Data Acquisition (SCADA), including data acquisition, control, alarm processing, online topology processor, etc.
- Generation scheduling and control applications, including Automatic Generation Control (AGC), Economic Dispatch (ED), Unit Commitment (UC), hydrothermal coordination, short term load forecast, interchange scheduling, etc.
- Network analysis application, including topology processor, state estimator, power flow, contingency analysis, Optimal Power Flow (OPF), security enhancement, voltage and reactive power optimisation, stability analysis, etc.
- Dispatch Training Simulator (DTS), including all the three above components but in a separate off-line environment.

The EMS is still needed by the ISO in the electricity market, but some of its functions will change to meet the new requirement. For example, some generation scheduling applications might be removed or redesigned to be something like energy market trading applications while some other network analysis application, like OPF, should be extended to be able to perform new functions. DTS is also facing significant changes. It must include all the market applications and power system applications.

Besides EMS, some new software systems will be needed in the ISO. These new systems may include:

- Market long-term planning subsystem, including applications like a plan for future transmission expansion, long-term ATC determination, maintenance of transmission facilities, etc. This subsystem needs coordination between the ISO and transmission owners.
- Market trading subsystem, including all the possible functions associated with market administration roles of the ISO or a separate market operator. These functions could be a day-ahead energy auction to match supply offers and demand bids (a spot market), electricity futures trading, ancillary services procurement, transmission rights auction, etc.
- Market operation planning subsystem, including power system scheduling function, short-term ATC determination, short-run transmission-related services pricing, congestion management, etc.
- Market real-time dispatching subsystem, including power system dispatch function, system balancing, real-time ATC determination, real-time congestion management, etc.
- Market settlement and billing subsystem, determining deviations from the schedules and bilateral contracts, determining payments to suppliers and ancillary services providers, determining payments to financial instrument holders.
- Market information subsystem. All ISOs are expected to provide a system of open communication for information related to power system operations. In the US, some of this information will be published on the FERC mandated OASIS. The Information that would assist with the efficiency and security of system operation should include: system information on transmission congestion, locational market clearing prices, need and bid for ancillary services and their prices, and all applicable ATCs, etc.

These new software subsystems are linked tightly with each other and must coordinate with the existing systems in the control room to support the implementation of electricity market. Therefore, besides the development of new applications, there is still enormous work on software system integration to be done. An overview of possible software systems in the competitive market environment and the relationship between them are given in Figure 1.2.

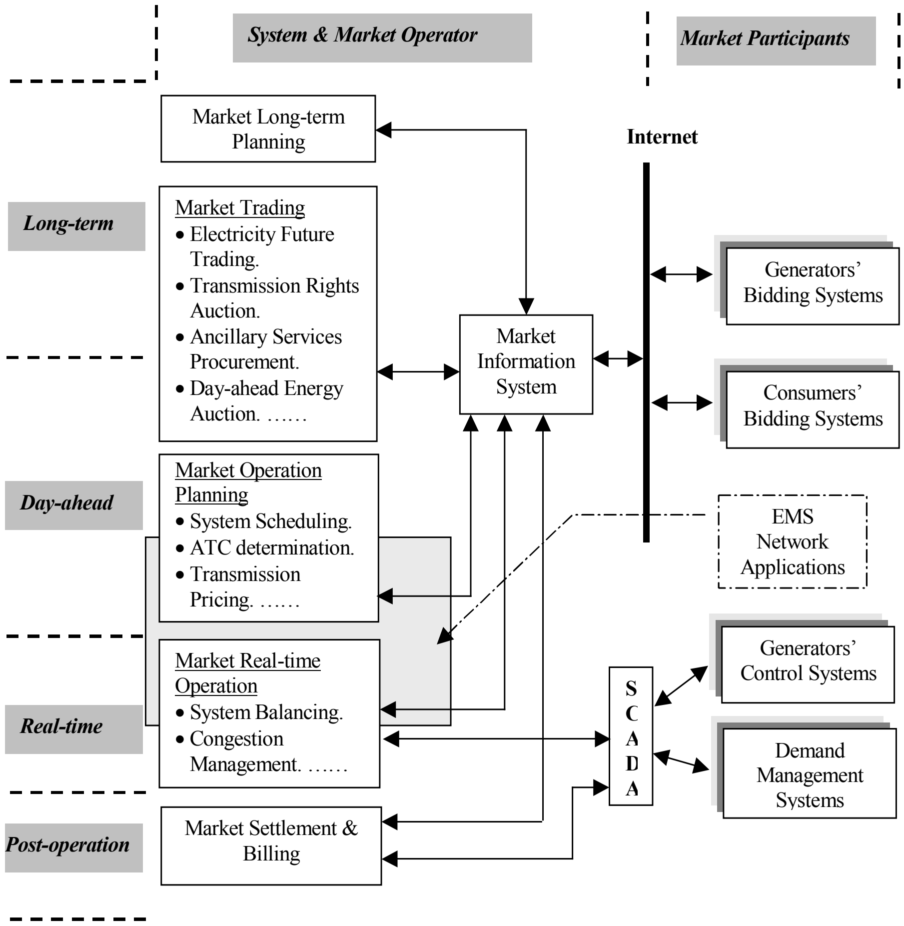

Figure 1.2. Overview of software systems in the competitive electricity market

1.4 Outline of the Book

In recent years, there have been many books published on deregulation of the power industry but most of them placed emphasis on the market structure and policy issues. From an engineering point of view, how to develop effective computational tools for efficiently operating restructured power systems is a big challenge. Several books [5–7] have been published recently on this topic. During the past several years, with funding from both research council and industry, we have been working on different computational models and methods for operation and control of such systems. The book is based on our recent PhD theses and over 30 papers published in IEEE and IEE journals/conferences. It covers all the major operational issues, such as scheduling and dispatch, congestion management, available transfer capability calculation, price forecasting and optimal bidding strategies. In addition, a review of international research and world-wide industry practice is covered in each chapter before presenting our methods so as to give the readers a broader state-of-the-art in this exciting field. The contents of the book are described in more detail in this section.

The main issue addressed in Chapter 2 is the investigation of the oligopolistic aspects of an electricity market as market structure is critically important in any industry. In this respect, a mathematical model is proposed for a wholesale electricity spot market, which takes into account the oligopolistic aspect of the market. The model is developed on the basis of the Cournot paradigm for the analysis of oligopolistic markets and allows the presence of private contracts (bilateral agreements) to be easily taken into account to assess their influence on profits and on the market-clearing price. The proposed methodology allows several features, typical of oligopolistic competition in the hourly market of electricity, to be analysed. The effectiveness of the proposed methodology is tested on the IEEE 30-bus system, assuming that the relative marketplace is composed of three different generating companies.

In the emerging electricity market, which relies on price-based competition, an unambiguous, transparent and predictable pricing framework of electricity for both active and reactive power is one of the major issues. Chapter 3 describes the development of an Integrated Optimal Spot Pricing (IOSP) model after reviewing various existing models. The proposed model includes the detailed derivation of optimal nodal specific real-time prices for active and reactive powers, and the method to decompose them into different components corresponding to generation, loss and many selected ancillary services such as spinning reserve, voltage control and security control. The features of the proposed model are discussed in relationship to existing pricing models and classical economic dispatch. The model is then implemented by extending the IPOPF method developed in the previous chapters. Insight is given by the case studies on a 5-bus, IEEE 30-bus and IEEE 118-bus systems.

It is well known that the generation and consumption of electricity must occur essentially at the same time. Therefore, real-time (minute-to-minute) operations and the associated markets and pricing approaches are crucial to design and implement a successful competitive wholesale electricity market. In Chapter 4, real-time dispatch methodologies for deregulated power systems are reviewed. An efficient dispatch framework for unbundled electricity markets through a real-time balancing mechanism is then presented. This framework is able to meet the real-time energy imbalance caused by unexpected contingencies and unpredictable load fluctuation with all the available adjustment bids in the real-time balancing market. Test results demonstrate that the proposed coordinated dispatch method implemented with a modified OPF can deal with system imbalance and network congestion simultaneously and successfully.

With the recent advent of world-wide power industry deregulation, measuring and modelling transmission system transfer capability is assuming greater importance. In Chapter 5, first of all, to give the reader some insight into the terms, history of standard terms of transfer capability of transmission networks is reviewed, together with the definitions and analysis of their weaknesses. To get accurate and dependable available transfer capability (ATC) measures, major uncertain factors associated with ATC estimation are identified and analysed. For short-term operational planning purposes, this chapter focuses on the development of a practical approach to evaluate the steady-state ATC of interconnected systems. To reflect the physical realities of the transmission network, a stochastic model is formulated for ATC calculation, where the key uncertainties affecting the level of ATC are modeled explicitly. To deal with the complex problem with both discrete random variables and continuous random variables involved efficiently, the solution methodology rests on a novel hybrid stochastic programming formulation. The results on the IEEE 118-bus system are encouraging, and clearly illustrate the effectiveness and efficiency of the proposed methodology.

Chapter 6 deals with congestion management. To find out what is going on in the real world, the congestion management approaches of five typical electricity markets in the world are investigated. A new scheme for an augmented LR-based regionally decomposed OPF is presented in this chapter. Applying the regionally decomposed OPF algorithm to active power congestion management across interconnected regions through the RBM, presented in Chapter 4, provides an efficient redispatch method to relieve the inter/intra-regional congestion without exchanging too much information between regional ISOs. The proposed method is of particular interest to a multi-utility or a multi-national interconnected system, such as the USA and Europe, where the independence of regional dispatching should be retained. Case studies based on the three-region IEEE RTS-96 are presented to illustrate the proposed method.

Chapter 7 analyses the dynamic security issue in the restructuring power market. A general framework is proposed to manage this issue in combination with the market mechanism and the power system intrinsic characteristics. Under this framework, the Security Management Market has been specially set up and categorized into several markets based on the market nature of the participants. By bidding into the respective market with their offers, different market participants provide their own control measures for utilization under emergency. Based on the available resources in this market, ISO would secure the system in the most economic way. Thus, power system security can be ensured under the market mechanism. Mathematically, the problem is formulated as an optimal control problem.

In Chapters 4 and 6, congestion management in the real-time operation of the electricity markets is discussed. A framework was proposed and implemented, in which the Independent System Operator (ISO) can balance its system and relieve transmission congestion efficiently through a real-time balancing market. This chapter is about how to avoid and manage transmission congestion during short-term (day-ahead to hour-ahead) scheduling of electricity markets. In this chapter, the concepts of two typical financial instruments, CfDs and FTRs, and how they have been used to hedge against price risks, are introduced. the basic model of optimal dispatch in the spot market and the fundamentals of LMP theory are presented. In particular, the impact of limits of bus generation and load on nodal prices are emphasised from the analysis of different forms of nodal price. After that, on the basis of the typical spot market dispatch model, some new individual revenue adequacy constraints are added to produce a more reasonable result for bilateral contract delivery in transmission congestion situations. An iterative procedure is employed to solve the formulated complex problem with dual variables in constraints. A 5-bus system and the IEEE 30-bus system are analysed to illustrate the proposed approach.

Ancillary services, a new terminology, are those services necessary to provide security and reliability issues that can be applied to dispatching and scheduling problem. Furthermore, ancillary services are required to maintain system reliability and to effect commercial transactions. Chapter 9 introduces the concept of ancillary services and the various ancillary service markets. In particular, we discuss the procurement and pricing of reserves in electric power markets. A joint dispatch model for energy and reserve with regards to real-time and day-ahead markets is presented. Finally, development of option pricing model is described.

Chapter 10 focuses on voltage security as a function of ancillary services that can be described in the context of reactive power markets and associated pricing mechanisms. First, an introduction to voltage security and reactive power management is presented and the consequences of recent electricity industry restructuring in the UK are highlighted. Second, an overview of recently developed reactive power markets is presented and several examples are discussed in detail. Finally, several recently developed algorithmic techniques are presented. The techniques introduce the concepts of transition-optimisation and congestion management in the context of a complete framework for the monitoring, assessment and control of voltage security.

Short-term load forecasting (STLF) plays an important role in the operational planning and the security functions of an energy management system. The STLF is aimed at predicting electric loads for a period of minutes, hours, days or weeks for the purpose of providing fundamental load profiles to the system. On the other hand, the electricity supply industry is undergoing unprecedented restructuring world-wide and there is a growing interest in the prediction of system marginal price (SMP) under the competitive market structure of deregulated power systems. The prediction of SMP improves the financial performance of an independent power producer bidding in the day-ahead market. Chapter 11 reviews conventional forecasting techniques in brief followed by novel load and price forecasting techniques via wavelet transform and neural networks with case studies to aid comprehension. The wavelet transform is a recently developed mathematical tool for signal analysis. A novel composite technique for short-term load forecasting using the Kohonen neural network and wavelet transform is described in this chapter. Practical examples on the South Korea system are reported. Then similar techniques are applied to the prediction of system marginal prices.

Chapters 12 and 13 are devoted to the generating sector. In Chapter 12, a methodology to simulate the strategic behaviour of generating companies in an oligopolistic electricity market, by using strategic supply functions, is proposed. In particular, electricity producers are supposed to bid in a pool-based electricity market. In order to simulate strategic competition among producers in the electricity market, the bidding process is expressed using linear supply functions. Another important aspect to be taken into account when analysing electricity market, as already mentioned in the previous chapter, is the presence of private contracts between generating companies and customers. In the developed tween generating companies and customers. In the developed methodology, the general case of an asymmetric oligopoly is analysed and the strategic behaviour of producers is investigated, assuming linear supply functions. The results of the analysis are expressed in terms of market clearing price, profit-maximizing value of the supply functions' slope, and hence real power output sold and profit made, of each producer sharing the market. Moreover, the proposed methodology allows the presence of private contracts, set up as Contracts for Difference (CfDs), to be taken into account, evaluating their effects on the market equilibrium conditions.

Chapter 13 presents the research work on bidding strategies of generators in electricity markets. Under deregulation, it is a common practice that generators produce and submit the bids to system operator/market operator based on market-oriented self-scheduling with the objective function of maximizing their own profits while considering the whole market situations such as system demands, network constraints, competitors' bidding behaviors and market prices. Four sets of bids sensitivities are defined and derived based on IPOPF model assuming each generator submits a linear bidding curve. They are bids-output sensitivity, bids-market price sensitivity, bids-profit sensitivity, and bids-line power flower sensitivity, which are valuable indexes and information in a pool-based electricity market. A single-period pool-based bidding model is then proposed based on bids sensitivities with the assumption that multi-round bidding and discriminatory pricing scheme are accepted as basic bidding rules. This model takes interactions among generators into consideration. The optimal bids (the coefficients of linear bidding curves) are obtained when the system reaches Nash equilibrium. Generators temporal constraints and demand-side bidding are not considered in this single-period bidding problem. Furthermore, the model is extended to take coalition into account. It allows the considered generator to make any potential coalition with other generators (grand coalition is not allowed). The algorithm is presented to find the optimal bids for the coalition subgroup.

Chapter 14 describes the aspect of transmission service improvement. Generally speaking, transmission services should be provided in a way to support all the required functions of transmission systems reliably. The advent of Flexible AC Transmission Systems (FACTS) technology has coincided with the major restructuring of the electric power industry. By the use of power electronics-based controllable components to control line impedance, magnitude and phase angle of nodal voltage individually and simultaneously, FACTS can provide benefits in increasing system transmission capacity and power flow control flexibility and rapidity. Therefore, it is able to play an important role in transmission services improvement. Taking the two important applications of FACTS control, ATC enhancement and FTR auction, as examples, this chapter addresses this issue with the intention of giving deeper insights into the ability of FACTS technology to facilitate electricity market operation and transaction.

1.5 References

[1] F.C. Schweppe, M.C. Caramanis, R.D. Tabors, and R.E. Bohn: “Spot Pricing of Electricity” (Kluwer Academic Publishers, 1988)
[2] M. Ilic, F. Galiana, and L. Fink: “Power System Restructuring: Engineering and Economics” (Kluwer Academic Publishers, 1998)
[3] M. Einhorn, and R. Siddiqui: “Electricity Transmission Pricing and Technology” (Kluwer Academic Publishers, 1996)
[4] S. Stoft: “Power Systems Economics”, IEEE and Wiley-Interscience, 2002
[5] K. Bhattacharya, M. Bollen, and J.E. Daalder: “Operation of restructured Power Systems”, Kluwer Academic Publishers, 2001
[6] M. Shahidiehpour, H. Yamin, and Z. Li: “Market Operations in Electric Power Systems”, IEEE and Wiley-Interscience, 2002
[7] Y.H. Song: “Modern Optimisation Techniques in Power Systems”(Kluwer Academic Publishers, 1999)
[8] T.J. Overbye: “Reengineering the Electric Grid”, American Scientist, May-June 2000, pp. 220-229
[9] S. Hunt, G. Shuttleworth: “Unlocking the Grid”, IEEE Spectrum, July 1996, pp.20-25
[10] P.G. Harris: “Impacts of Deregulation on the Electric Power Industry”, IEEE Power Engineering Review, October 2000, pp.4-6
[11] Secretary of Energy Advisory Board, U.S. Department of Energy: “Maintain Reliability in a Competitive U.S. Electricity Industry”, September 29, 1998
[12] F.A. Rahimi, A. Vojdani: “Meet the Emerging Transmission Market Segments”, IEEE Computer Application in Power, January 1999, pp. 26-32
[13] R. Hakvoort: “Technology and Restructuring the Electricity Market”, Proceedings of the International Conference on Electric Utility Deregulation

http://www.springer.com/978-1-85233-670-7

Operation of Market-oriented Power Systems
Song, Y.-H.; Wang, X.-F. (Eds.)
2003, XVIII, 443 p., Hardcover
ISBN: 978-1-85233-670-7