Applied Mathematics for Deregulated Electric Power Systems: Optimization, Control, and Computational Intelligence

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1. Introduction

The achievements in system engineering in the analysis and control of power system reliability and security over the last three decades, accomplished by taking full advantages of advances in computer, communication, and control technologies, are truly remarkable. For example, the economic generation commitment and dispatch for large power systems are now routinely solved using efficient Lagrangian-relaxation methods [1] and interior-point methods [2]. State estimation with bad data and topology detection capability [3], has become a mainstay in control room, and has gone from being an advisory tool to being used in real-time energy price calculation [4]. Fast stability analysis has benefited from energy function analysis [5,6,7], which also contributed to enhanced understanding of modes of instability. Tools for analyzing voltage stability, a phenomenon not noted until the 1970's, have been well-developed [8,9] that it is common for control center operators to rely on the power-voltage sensitivity curve in determining admissible power transfer across some major congested interfaces. Small-signal stability has evolved from a power system stabilizer adding damping to the local swing mode to the need to understand interarea mode oscillations based on coherency analysis [10,11], which drives the development of the wide-area monitoring system (WAMS) installed in the western US system [12]. Flexible AC Transmission Systems [13], based on advances in high-voltage power electronics, allow a system operator to control voltage and line power control on transmission systems, as well as provide damping enhancement [14]. More recently, artificial neural network and genetic algorithms have been applied to several power system problems, including damping control design [15-17]. From a public policy viewpoint, the work in [18] was singularly significantly in the restructuring of the power industry organized as regional monopolies [19,20].

Such accomplishments are achieved, in part, due to highly focused university research support by Energy Research and Development Agency (ERDA), Department of Energy (DOE), National Science Foundation (NSF), Electric Power Research Institute (EPRI), and many utilities and manufacturers in the US, as well as their international counterparts. In particular, this very successful research process is driven in two directions: power system problems have motivated the development of new applied mathematical tools, and conversely, advances in applied mathematics are customized to form systematic approaches to complex power system problems.

Although we can point to many successes, the 2003 August 14 Northeast Blackout [21] is a stark reminder that the increasing complexity of interconnected power systems continues to outstrip the preparedness of automatic control and protection systems and power control centers to deal with extreme contingencies. The unprecedented magnitude of overload on a group of transmission lines in Ohio and the subsequent swings in power flow when these lines were tripped resulted in system conditions not foreseen in any system planning and operation studies, causing several interconnected systems to separate within each system and collapse.

Power grid control problems, in normal and emergency operating conditions, need to be continuously studied. The task is particularly challenging in deregulated markets where the basic structure of decision-making has moved from centralization towards decentralization. The objective of this NSF Workshop is to delineate major technical and engineering issues related to reliability and security of power systems arising from growing system complexities, increased transmission congestions, and structural changes for which basic research can contribute. In particular, such fundamental changes in infrastructures require a reevaluation of issues related to information, coordination, and computation in the analysis and control of the system.

Cross-disciplinary fertilization has benefited the development of power system engineering a great deal in the past and will definitely benefit even more in the future. This Workshop is intended to bring authorities in several relevant disciplines to stimulate discussions on how to bring the latest advances in these disciplines to bear on rethinking and reformulating problems of reliability and security in power systems. The following disciplines, in particular, have been identified as potential suppliers of new philosophies and new tools for emerging problems in power systems. They include: Multi-player Game Theory, Distributed Optimization, Global Adaptive Control, Hybrid Systems, Dynamical System Theory, and Distributed Artificial Intelligence. Recent developments in these disciplines have been revolutionary and may bring in fresh ideas and new approaches to problems of information, coordination and computation in power system reliability and security.

To organize the discussion and provide a structure to the workshop, three main themes have been identified: (a) optimization of restructured power system operation, (b) system stability and dynamic performance, and (c) computational intelligence methods. This article on open problems in power system reliability and security is provided before the conference to motivate and focus the invited presentations. The organization will also allow alternative viewpoints, from both power system researchers and applied mathematicians, to the questions posed in this article. The invited presenters are asked to prepare papers before the start of the workshop, which are collected in this monograph. Short articles are also solicited from the workshop attendees to enrich the diversity of the monograph. It is anticipated that this monograph may impact power system reliability and security research for many years to come.

2. Themes on Reliability and Security in Deregulated Electricity Markets

In this section we provide some motivations to each of the three themes of the workshop. Although we do not expect all the identified issues will be addressed by the presenters at the workshop, we feel that the discussion will provide a focused starting point. Table 1 provides a summary of the topics within the three themes.

Table 1. Summary of Workshop Themes

Themes	Power System Issues	Mathematical Techniques
Optimization of restructured power system operation	Multiple settlement systems, multiple agents, Hedging and arbitrage, distributed generation, storage, transmission rights, transmission investment, FACTS controllers, congestion revenue shortfall, seams, unit commitment, state estimator reliability	Stochastic optimization, risk management, distributed optimization, incomplete information, Nonlinear programming techniques, methods from statistics, game theory
System stability and dynamic performance	Damping control, adaptive control, gain scheduling, voltage stability, reserves, improved generator ramp rates, islanding	Adaptive control, nonlinear control, robust distributed control, hybrid systems
Computational intelligence	Bidding strategies, market power, hedging, market monitoring, price mitigation, real-time system operation	Data mining, artificial intelligence, neural networks

2.1 Optimization of restructured power system operation

A deregulated electricity market comprises of many players such as generator owners, load supply entities (or load aggregators), and transmission owners. Each market has an independent grid operator, known as the ISO (independent system operator), responsible for the day-to-day and, some times, long-term operation of the power system. Our discussion will evolve around power system issues for these players.

Bidding Strategies

A deregulated electricity market primarily functions by accepting supply (generator) and demand (load) bids from various market participants, to determine the operating conditions of a power system. To abate the impact of the uncertainty inherent in load forecasting, many deregulated markets use a two-settlement system, namely, the generators are committed in the day-ahead market according to the bid-in load with the difference between the bid-in and actual in-day load reconciled in the real-time market. Such a system most likely would allow bilateral trades that can be arranged many months prior to further reduce the price uncertainty [22].

Supply and demand bidding in a single settlement market for a multi-agent systems has been studied using various methods, from incremental cost curves [23] to a genetic-algorithm based market auction simulator described in [24,25]. The market clearing price is determined from the intersection of the supply and demand curves. However, the forecast load is a stochastic function of temperature and humidity, among other factors. To reduce the stochastic effect of load, a two-settlement system is used in which the day-ahead unit commitment guarantees the bid loads certainty in supply and the committed generators a fixed amount of income. The in-day load deviation is then accounted for by reconciling the difference between the forecasted and actual real-time load levels.

An electricity market with two or more settlements offers opportunities for market participants, particularly load serving entities (LSE), to hedge their energy positions in order to meet their obligation to serve load in an economic fashion. An optimal LSE position, however, may not lead to a reliable and secure operating system, especially when the committed generating units are not adequate to meet the actual load demand.

Due to various reliability rules and market imperfections, the day-ahead and the real time prices in a two-settlement system may show substantial differences on a regular basis beyond the inaccuracies in the load forecast. In markets allowing virtual transaction bids, that is, supply and demand bids by financial entities which do not own any physical assets, such day-ahead and real-time price discrepancies would allow players to arbitrage the price differential or game the system. In some cases, these virtual transaction bids may further stress the system reliability and security.

In the foreseeable future, distributed generation of various types, such as wind turbines, micro-turbines, fuel cells, and solar cells, may have sufficient penetration to make a financial impact on the system dispatch and become an issue on system reliability. The dispatch of some of these generating units will be stochastic in nature, with their capability dependent on the wind and insolation forecast.

The optimization of storage devices such as the traditional pump-hydro units and the more recent battery parks, with respect to energy peak shaving, load balancing, and stability control would need to be treated in a new light under deregulation. In terms of bidding strategies, it may be useful for pump-hydro turbines to be aggressive in periods when the electricity prices are volatile (such as during summer peak periods) and be conservative when the prices are less volatile (such as during spring and fall periods) [26]. Such operating principles would be helpful to not only generator owners, but also to system operators and dispatchers.

A common thread through these bidding strategies is that they are stochastic optimization and risk management problems. They can be further characterized as distributed multi-agent problems with incomplete information as each player can only estimate the actions of the other players. Research advances in these areas will be helpful in providing new ideas to improve the bidding competitiveness in the energy market.

Market and Operation Optimization

In a open-access deregulated electricity market, an Independent System Operator (ISO) is responsible for the scheduling of the generation and load and for maintaining system security. An ISO faces many complex issues, some of which are discussed here.

One of the primary functions of an ISO is to manage the use of the transmission assets in its system according to the market rules [27]. In an open-assess electricity market, loads may be served by generation from anywhere in the interconnected system as long as in doing so, the system security is not compromised. As a result, available transmission capacity (ATC) [28] is computed to establish transmission rights, which are known by several names, such as transmission congestion contracts (TTC) and financial transmission rights (FTR). For a power system with congestion, under the locational marginal pricing (LMP) scheme, loads in congested area holding the transmission rights can import less expensive generation without paying for the more expensive local generation.

The transmission rights are, in general, assigned to the owners of the specific transmission facilities, which can be auctioned off. The more severe the congestion, the more the congestion rights are worth, because of the higher energy price difference between the congested and non-congested areas. This trend creates for transmission owners a disincentive to invest in new facility to relieve the overload, because to do so would reduce congestion rent [29, p. 176]. Furthermore, transmission enhancement increases consumer prices in less expensive areas and reduce revenues for generators in congested areas [30, p. 317], and thus is not universally welcome by all consumers and generators.

In view of this quandary, the SMD recently issued by NERC includes provisions for ISO or RTO (Regional Transmission Organizations, formed by merging several ISOs) to determine necessary transmission enhancements and the means to build the new transmission. The justification of investments may require new analysis and siting tools, as these investments involve not only transmission lines, but also new devices such as flexible AC transmission system (FACTS) controllers [13].

Although ATC is a system-configuration dependent quantity, transmission rights in a deregulated market are often calculated assuming no transmission line outages, that is, they are fully funded. Thus if one or more critical transmission lines are out of service, there will be a shortfall in congestion revenue, which sometimes can be significant, to pay the transmission rights. At issues here are how to share the shortfall equitably and how to avoid the shortfall to begin with.

The transmission capacity of neighboring ISOs is also an important issue. External supply into a control area can be curtailed for various reasons even though the external supply is cheaper. Although this seams issue [31] can be prevented by merging several ISOs to form a single RTO, in the interim other optimization method needs to be considered, such that the energy production cost can be reduced.

Techniques that can be used to resolve some of the above transmission rights issues will be useful to explore. Of particular interests are techniques that can address the variation of available transfer with respect to the system configuration and how the resolve the seams issue. Techniques to site and maximize the use of FACTS controllers in power systems should also be considered.

Another primary function of an ISO is to operate an electricity market efficiently. In a deregulated market, the unit commitment problem of meeting the forecasted load will be based on the supply and demand bids submitted by the generators and load serving entities, in which the supply bids will most likely not be the generator cost curves. In addition, the optimization problem would need to co-optimize the energy and reserve requirements to achieve an optimal security-constrained solution [28]. Such a large-scale optimization problem with multiple passes needs to be solved in a limited amount of time to allow the timely posting of the generator schedule. The unit commitment solution obtained in such an environment is usually only suboptimal. Thus any new, more efficient algorithm or an improved means of using an existing algorithm that can improve the solution optimality even by fractions of a percent would result in billions of dollars of energy and reserve payments annually.

Beside the day-ahead unit commitment optimization which is based on the forecast load, a critical operation of a deregulated electricity market is the real time dispatch to balance the system operation against actual load. Such real time operation is meaningful only if the real-time system data is using in the dispatch program. As a result, ISOs in Ontario and New England are using the state estimator results in their real-time dispatch. State estimators have been available for many years [3], and their solutions are mostly used only as advisory information in power system control centers. The reliability of state estimators has been addressed by many researchers [32,33]. There are, however, still some areas not fully addressed, especially reliability with respect to system models. In the past, system model data errors have been tracked off line so that the model data and topology can be corrected in the master database. In a deregulated market where real time energy prices are determined as often as every 5 minutes, a model data error due to whatever reason needs to be detected and corrected by the state estimator in real time. Otherwise, the dispatch solution may produce spikes in energy prices, which are detrimental to an efficient and equitable electricity market. Single-settlement markets based on real time prices are particularly vulnerable to such a reliability issue, which would severely undermine the market efficiency.

For the unit commitment problem, we should explore the applicability of new optimization techniques to solve large-scale nonlinear programming problems. For the state estimator reliability issue, we need to examine techniques that can monitor the anomaly occurring in the state estimator solution and then hypothesize the origin of the anomaly, such as a breaker status error or a model data error. Some statistics and artificial intelligence based techniques could be useful.

2.2 System stability and dynamic performance

The August 14, 2003 Northeast Blackout showed the importance of having proper stability control. Although the evolution of the upset is still under investigation, it is certain that the largest blackout in this nation was caused by a cascade of events, many of which were system oscillations and voltage collapse, and relay actions to isolate these problems. The system frequencies and voltages recorded in several control areas showed enormous transients, a result of several power systems splitting apart internally. The analysis of the blackout will no doubt point out the need for more advanced control, as well as other issues such as relay settings and operator control for system separation.

Power system control in the future will be shaped by recently developed new technologies. In addition to traditional generator and excitation system control, power electronics based control known generally as flexible AC transmission system (FACTS) controllers have been shown in studies to provide damping to interarea modes [14,34], thus improving the power transfer in systems that are small-signal stability limited. Synchronized phasor measurement networks have also been prototyped, such that actuators can use additional signals to improve the effectiveness of the damping control algorithm [35].

With advanced tools and more detailed models, many existing controllers can be redesigned for improved performance. For example, a 10-year old operating problem in a small interconnected power system due to the instability of the deflector governor in a Pelton turbine was resolved using a combined feedforward-feedback control [36]. The feedforward part provides a fast response to prevent turbine overspeed, so that the feedback gain for frequency regulation can be reduced to avoid destabilizing the interarea swing mode. Such variable or adaptive gain designs that switch from nominal to high gains in order to counter disturbances may be helpful in many power system scenarios. Other more complex adaptive structures including change of input signals may also be useful. The main challenge is to determine when adaptation should be turned on, and more important, when it should be turned off.

In systems that transfer large amounts of power over long distances, voltage stability may be the determining factor in calculating the available transmission capacity. The measured data of the August 14 blackout showed that the voltage in the load area actually collapsed, as predicted by theory. In some regions, the ATC is determined based on second contingencies in which the network is severely weakened. It is well-known that reactive power does not "travel" far from the point of injection even in nominal system configuration. Network disruptions will further reduce the effectiveness of reactive power injections. Thus fast acting reactive power devices such as SVC and STATCOM can be used to "prime" the system against the worst contingencies. The effectiveness of series devices such as the TCSC and SSSC for reactive power support is less obvious. The use of controllers such as UPFC and IPFC that can circulate active power, for optimal voltage stability enhancement is not entirely obvious, in terms of how the flow setpoints and power circulation should be specified for maximum power transfer. New techniques in these investigations will be tremendously helpful.

In a deregulated electricity market, part of the system reliability is dependent on having adequate generation reserve in the system. The reserves are classified into regulation, 10-minute spinning reserves, and 10- and 30-minute non-synchronous reserves, depending on the ramping capability of the available generators. Many generators are operated quite conservatively because they have to observe temperature and pressure constraints. However, with the availability of advanced sensors, it is possible to use additional feedback control to reduce transients internal to turbines such that they can be more responsive and at the same time, operated more reliably. For example, if the pressure variable in the penstock of a hydro turbine is measured, then a pressure feedback loop can be implemented on the turbine valve to reduce the water column oscillations in the penstock, thus allowing the hydro turbine to have a faster ramp rate. Having faster generator response rates will generally result lower energy and reserve prices, allowing a power system to operate more efficiently.

A comprehensive approach to system security needs to include controls against cascading failures. The large amount of uncontrolled flow that is diverting from one transmission corridor to another transmission path needs to be minimized to prevent oscillation and voltage instability. Mechanically adjusted phase-shifters, such as those installed around New York City to control the balance of flows into the city, are intended for steady-state operation. They are too slow to react to cascading failures. New power electronic devices such as FACTS Controllers would be able to provide rapid control actions. Furthermore, an islanding scheme following a major system disruption needs to be determined to prevent a power system splitting internally into unsustainable islands, which was the case for the August 14 Blackout. Instead of a fixed islanding scheme, an adaptive approach to balance the generation, reserve, and load in the resulting islands would be most beneficial [37]. Further investigations should be conducted in this area.

New advances in control theory and design methods will allow the development of improved control for enhancing power system operation. For example, adaptive control and nonlinear control may allow optimal performance of the actuators to deal with disturbances without destabilizing other dominant system dynamics. Distributed control schemes taking into account time delays in the controller input would require some robustness design. A comprehensive assessment of these new techniques needs to be carried out to prevent future blackouts.

2.3 Computational intelligence

The complexity of a deregulated electricity market is substantial in many respects. The market participants, such as generator owners and load supplying entities, are provided only with limited information to prevent them from gaming. For the ISOs, the issues are not only to operate the system efficiently, but also to ensure that the competition is fair. In such an environment requiring the analysis of large amounts of data, some model-independent methods from computation intelligence can be most useful.

In the early days of deregulation, some market participants adjusted their bids based on a correlation of their past bids and the corresponding daily profits until they arrive at the desired strategies, a process known as experimental economics [38,39]. Despite the intention of some market participants to be competitive to ensure an efficient electricity market, there are other market participants, namely the generators and the owners of TCCs (who are not necessary transmission line owners), who will resort to gaming to increase their profits, if they can find a way to do so.

As an example, consider market power as evident by the generators' ability to set market clearing prices. Indices of market power have been proposed by many researchers and used to predict the impact of market power on electricity prices. When transmission constraints are present, even a small generator can exercise market power as it becomes the price setter in the congested area [40]. Market power takes on a new facet when in several electricity markets, virtual supply and demand biddings not backed by physical assets are accepted in the day-ahead market. An unusually large virtual load bid on the receiving end of a radial bus and a correspondingly large virtual supply bid at the sending end would artificially create congestion on the radial line, resulting in increased energy prices on the load bus.

Up to now most market power analysis is focused only on generators. A more complete market power analysis should include a portfolio analysis, such that the aggregate profit from a market participant, which owns generators and transmission rights and submits virtual bids, should be monitored to determine whether losing positions are more than compensated by profits from other positions.

In general, market power analysis should also be based on actual market clearing prices and the resulting security of the system so dispatched and operated [41]. ISOs have been charged with monitoring the system security to keep market power in check. Entities which have planned to game the system would cause disruptions to the market prices and system operations if they are successful. Thus control center operators have to continually monitor the system inputs and examine their impacts to detect gaming behaviors. Analysis methods such as data characterization and data mining would perhaps offer new insights into how market monitoring and mitigation could be done most effectively.

The other application of interest is the use of intelligence to prevent cascaded outages such as the August 14 Blackout. As an example, in the August 14 Blackout, the New York Control Center was not aware of the operation problems outside of its control area. Some external line trips had caused a small shift in power flows, but not at a magnitude to alarm the system operators. Once the external system started to split up, the operators observed large swings of power throughout the transmission grid in New York, at magnitudes that were unfamiliar to them. Within a span of a few seconds, many major transmission lines were tripped, leading to a loss of service in most of the system.

Unquestionably, preventing such large-scale cascaded blackouts requires efforts in many areas. One possibility is to add more intelligence to the control center, to provide an evolving security assessment function to alert the operator to potential cascading problems. Such a function would monitor both internal and external disturbances of a control area, even for small changes in flow conditions.

We also remark that artificial intelligence based techniques have also been applied to control design such as the work in [15-17].

3. Synopses of the Articles in this Monograph

To be written latter

References

[1] S. Virmani, E. C. Adrian, K. Imhof, and S. Mukherjee, "Implementation of a Lagrangian Relaxation Based Unit Commitment Problem," *IEEE Transactions on Power Systems*, vol. 4, pp. 1373 -1380, 1989.

[2] J. A. Momoh and J. Z. Zhu, "Improved Interior Point Method for OPF Problems," *IEEE Transactions on Power Systems*, vol. 14, pp. 1114 -1120, 1999.

[3] A. Monticelli, *State Estimation in Electric Power System: a Generalized Approach*, Boston: Kluwer Academic Publishers, 1999.

[4] NYISO Market Structure Working Group, RTS Concept of Operations, June 3, 2002 meeting, available from www.nyiso.com.

[5] H.-D. Chiang, M. W. Hirsch, and F. F. Wu, Stability Regions of Nonlinear Autonomous Dynamical Systems," IEEE Transactions on Automatic Control, vol. 33, pp. 16-27, 1988.

[6] J. Zaborszky, G. Huang, B. Zheng, and T.-C. Leung, "On the Phase Portrait of a Class of Large Nonlinear Dynamic Systems such as the Power System," IEEE Transactions on Automatic Control, vol. 33, pp. 4-15, 1988.

[7] M. A. Pai, *Energy Function Analysis for Power System Stability*, Kluwer Acadamic Publishers, 1989.

[8] C. W. Taylor, *Power System Voltage Stability*, McGraw Hill, 1994.

[9] T. Van Cutsem and C. Vounas, *Voltage Stability of Electric Power Systems*, Kluwer Acadamic Publishers, 1998.

[10] R. Podmore, "Identification of Coherent Generators for Dynamic Equivalents," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-97, pp. 1344-1354, 1978.

[11] J. H. Chow, G. Peponides, P. V. Kokotovic, B. Avramovic, and J. R. Winkelman, *Time-Scale Modeling of Dynamic Networks with Applications to Power Systems*, Lecture Notes in Control and Information Sciences, 46, Springer-Verlag, New York, 1982.

[12] J. Hauer, D. Trudnowski, G. Rogers, B. Mittelstadt, W. Litzenberger, and J. Johnson, "Keeping an Eye on Power System Dynamics," *IEEE Computer Applications in Power*, vol. 10, issue 4 , pp. 50-54, October 1997.

[13] N. G. Hingorani and L. Gyugyi, *Understanding FACTS*, IEEE Press, 2000.

[14] E. V. Larsen and J. H. Chow, “SVC Control Design Concepts for System Dynamic Performance,” in IEEE Power Engineering Society Publication 87TH0187-5-PWR *Application of Static Var Systems for System Dynamic Performance*, 1987.

[15] A. L. B. Do Bomfim, G. N. Taranto, and D. M. Falcao, “Simultaneous Tuning of Power System Damping Controllers using Genetic Algorithms,” *IEEE Transactions on Power Systems*, vol. 15, pp. 163 -169, 2000.

[16] J.-W. Park, G. K. Venayagamoorthy, and R. G. Harley, “Adaptive Critic Designs and their Implementations on Different Neural Network Architectures,” *Proceedings of the International Joint Conference on Neural Networks*, vol. 3, pp. 1879 -1884, 2003.

[17] A. I. Megahed and O. P. Malik, “Experimental Testing of a Neural Network Based Digital Differential Relay for Synchronous Generators,” *IEEE Transactions on Power Delivery*, vol. 15, pp. 80-85, 2000.

[18] F. C. Schweppe, M. C. Caramanis, R. D. Tabors, and R. E. Bohn, *Spot Pricing of Electricity*, Kluwer Academic Press, 1988.

[19] M. Ilic, F. Galiana, and L. Fink, *Power System Restructuring: Engineering and Economics*, Boston: Kluwer Academic Publishers, 1998.

[20] M. Shahidehpour and M. Alomoush, *Restructured Electrical Power Systems: Operation, Trading, and Volatility*, New York: Marcel Dekker, 2001.

[21] “Blackout, Can It Happen Again?” *Time*, August 25, 2003.

[22] M. Denton, A. Palmer, R. Masiello, and P. Skantze, “Managing Market Risk in Energy,” *IEEE Transactions on Power Systems*, vol. 18, pp. 494-502, 2003.

[23] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation, and Control*, 2nd edition, New York: John Wiley & Sons, 1996.

[24] J. Kumar and G. Sheble, “Auction Market Simulator for Price Based Operation,” *IEEE Transactions on Power Systems*, vol. 13, pp. 250-255, 1998.

[25] C. W. Rechter and G. Sheble, “Genetic Algorithm Evolution of Utility Bidding Strategies for the Competitive Marketplace,” *IEEE Transactions on Power Systems*, vol. 13, pp. 256-261, 1998.

[26] N. Lu and J. H. Chow, “Pumped-Storage Hydro-Turbine Bidding Strategies in a Competitive Electricity Market,” Proceedings of the 2003 IEEE General Power Meeting, Toronto.

[27] X. Ma, D. I. Sun, and K. W. Cheung, “Evolution Toward Standard Market Design,” *IEEE Transactions on Power Systems*, vol. 18, pp. 460-469, 2003.

[28] S. Grijalva, P. Sauer, and J. D. Weber, “Enhancement of Linear ATC Calculations by Incorporation of Reactive Power Flows,” *IEEE Transactions on Power Systems*, vol. 18, pp. 619-624, 2003.

[39] R. Masiello, “Practical Requirements for ISO Systems,” Chapter 5 in [19].

[30] R. Coxe and M. Ilic, “System Planning Under Competition,” Chapter 8 in [19].

[31] N. R. Rau, “Issues in the Path Toward an RTO and Standard Markets,” *IEEE Transactions on Power Systems*, vol. 18, pp. 435-443, 2003.

[32] A. Monticellli and A. Garcia, “Reliable Bad Data Processing for Real-Time State Estimation,” *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-102, pp. 1126-1139, 1983.

[33] A. Abur, “A Bad Data Identification Method for the Linear Programming State Estimation,” *IEEE Trans. on Power Systems*, vol. 5, pp. 894-901, 1990.

[34] E. V. Larsen, J. J. Sanchez-Gasca, and J. H. Chow, “Concepts for Design of FACTS Controllers to Damp Power Swings,” *IEEE Transactions on Power Systems*, vol. 10, pp. 948-956, 1995.

[35] H. Wu, H. Ni, and G. T. Heydt, “The Impact of Time Delay on Robust Control Design in Power Systems,” *Proc. 2002 Power Engineering Society Winter Meeting*, vol. 2, pp. 1511 -1516.

[36] R. M. Johnson, J. H. Chow, and M. V. Dillon, “Pelton Turbine Deflector Overspeed Control in Small Power Systems,” presented at the IEEE General Power Meeting 2003.

[37] H. You, V. Vittal, and Z. Yang, “Self-healing in Power Systems: an Approach using Islanding and Rate of Frequency Decline-based Load Shedding,” *IEEE Transactions on Power Systems*, vol. 18, pp. 174-181, 2003.

[38] K. A. McCabe, S. J. Rassenti, and V. L. Smith, “Auction Design for Composite Goods: the Natural Gas Industry,” *Journal of Economic Behavior and Organization*, vol. 14, pp. 127-149, 1900.

[39] K. A. McCabe, S. J. Rassenti, and V. L. Smith, “Experimental Research on Deregulated Markets for Natural Gas Pipeline and Electric Power Transmission Networks,” *Research in Law and Economics*, vol. 13, pp. 161-189, 1991.

[40] Z. Younes and M. Ilic, “Transmission Networks and Market Power,” Chapter 9 in [19].

[41] A. F. Rahimi and A. Y. Sheffrin, “Effective Market Monitoring in Deregulated Electricity Markets,” *IEEE Transactions on Power Systems*, vol. 18, pp. 486-487, 2003.