Zhaoyang Dong
Pei Zhang
et al.

Emerging Techniques in Power System Analysis

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With 67 Figures

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Preface

Electrical power systems are one of the most complex large scale systems. Over the past decades, with deregulation and increasing demand in many countries, power systems have been operated in a stressed condition and subject to higher risks of instability and more uncertainties. System operators are responsible for secure system operations in order to supply electricity to consumers efficiently and reliably. Consequently, power system analysis tasks have become increasingly challenging and require more advanced techniques. This book provides an overview of some the key emerging techniques for power system analysis. It also sheds lights on the next generation technology innovations given the rapid changes occurring in the power industry, especially with the recent initiatives toward a smart grid.

Chapter 1 introduces the recent changes of the power industry and the challenging issues including, load modeling, distributed generations, situational awareness, and control and protection.

Chapter 2 provides an overview of the key emerging technologies following the evolvement of the power industry. Since it is impossible to cover all of emerging technologies in this book, only selected key emerging technologies are described in details in the subsequent chapters. Other techniques are recommended for further reading.

Chapter 3 describes s the first key emerging technique: data mining. Data mining has been proved an effective technology to analyze very complex problems, e.g. cascading failure and electricity market signal analysis. Data mining theories and application examples are presented in this chapter.

Chapter 4 covers another important technique: grid computing. Grid computing techniques provide an effective approach to improve computational efficiency. The methodology has been used in practice for real time power system stability assessment. Grid computing platforms and application examples are described in this chapter.

Chapter 5 emphasizes the importance of probabilistic power system analysis, including load flow, stability, reliability, and planning tasks. Probabilistic approaches can effectively quantify the increasing uncertainties in power systems and assist operators and planning in making objective decisions... Various probabilistic analysis techniques are introduced in this chapter.

Chapter 6 describes the application of an increasingly important device, phasor measurement units (PMUs) in power system analysis. PMUs are able to provide real time synchronized system measurement information which can be used for various operational and planning analyses such as load modeling and dynamic security assessment. The PMU technology is the last key emerging technique covered in this book.

Chapter 7 provides information leading to further reading on emerging techniques for power system analysis.

With the new initiatives and continuously evolving power industry, technology advances will continue and more emerging techniques will appear., The emerging technologies such as smart grid, renewable energy, plug-in electric vehicles, emission trading, distributed generation, UVAC/DC transmission, FACTS, and demand side response will create significant impact on power system. Hopefully, this book will increase the awareness of this trend and provide a useful reference for the selected key emerging techniques covered.

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August 2009

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1 Introduction

Zhaoyang Dong and Pei Zhang

With the deregulation of the power industry having occurred in many countries across the world, the industry has been experiencing many changes leading to increasing complexity, interconnectivity, and uncertainties. Demand for electricity has also increased significantly in many countries, which resulted in increasingly stressed power systems. The insufficient investment in the infrastructure for reliable electricity supply had been regarded as a key factor leading to several major blackouts in North America and Europe in 2003. More recently, the initiative toward development of the smart grid again introduced many additional new challenges and uncertainties to the power industry. In this chapter, a general overview will be given starting from deregulation, covering electricity markets, present uncertainties, load modeling, situational awareness, and control issues.

1.1 Principles of Deregulation

The electricity industry has been undergoing a significant transformation over the past decade. Deregulation of the industry is one of the most important milestones. The industry had been moving from a regulated monopoly structure to a deregulated market structure in many countries including the US, UK, Scandinavian countries, Australia, New Zealand, and some South American countries. Deregulation of the power industry is also in the process recently in some Asian countries as well. The main motivations of deregulation are to:

- increase efficiency;
- reduce prices;
- improve services;
- foster customer choices;
- foster innovation through competition;
- ensure competitiveness in generation;

- promote transmission open access.

Together with deregulation, there are two major objectives for establishing electricity markets. They are (1) to ensure a secure operation and (2) to facilitate an economical operation (Shahidehpour et al., 2002).

1.2 Overview of Deregulation Worldwide

In South America, Chile started the development of a competitive system for its generation services based on marginal prices as early as the early 1980s. Argentina deregulated its power industry in 1992 to form generation, transmission, and distribution companies into a competitive electricity market where generators compete. Other South America countries followed the trend as well.

In the UK, the National Grid Company plc was established on March 31, 1990, as the owner and operator of the high voltage transmission system in England and Wales.

Prior to March 1990, the vast majority of electricity supplied in England and Wales was generated by the Central Electricity Generating Board (CEGB), which also owned and operated the transmission system and the interconnectors with Scotland and France. The great majority of the output of the CEGB was purchased by the 12 area electricity boards; each of which distributed and sold it to customers.

On March 31, 1990, the electricity industry was restructured and then privatized under the terms of the Electricity Act 1989. The National Grid Company plc assumed ownership and control of the transmission system and joint ownership of the interconnectors with Scotland and France, together with the two pumped storage stations in North Wales. But, these stations were subsequently sold off.

In the early 1990s, the Scandinavian countries (Norway, Sweden, Finland and Denmark) created a Nordic wholesale electricity market – Nord Pool (www.nordpool.com). The corresponding Nordic Power Exchange is the world's first international commodity exchange for electrical power. It serves customers in the four Scandinavian countries. Being the Nordic Power Exchange, Nord Pool plays a key role as a part of the infrastructure of the Nordic electricity power market and thereby provides an efficient, publicly known price of electricity of both the spot and the derivatives market.

In Australia, the National Electricity Market (NEM) was first commenced in December 1998, in order to increase the transmission efficiency and reduce electricity prices. NEM serves as a wholesale market for the supply of electricity to retailers and end use customers in five interconnected regions: Queensland (QLD), New South Wales (NSW), Snowy, Victoria (VIC), and

South Australia (SA). Tasmania (TAS) joined the Australian NEM on May 29, 2005, through Basslink. The Snowy region was later abolished on July 1, 2008. In 2006 – 2007, the average daily demands in the current five regions of QLD, NSW, VIC, SA, and TAS are 5 886 MW, 8 944 MW, 5 913 MW, 1 524 MW, and 1 162 MW, respectively. The NEM system is one of the world's longest interconnected power systems connecting 8 million end use consumers with AUD 7 billion of electricity traded annually (2004 data) and spans over 4 000 km. The Unserved Energy (USE) of the NEM system is 0.002%.

In the United States, deregulation occurred in several regions. One of the major electricity markets is the California electricity market, which is part of the PJM (Pennsylvania-New Jersey-Maryland) market. The deregulation of the California electricity market followed a series of stages, starting from the late 1970s, to allow non-utility generators to enter the wholesale power market. In 1992, the Energy Policy Act (EPACT) formed the foundation for wholesale electricity deregulation.

Similar deregulation processes have occurred in New Zealand and part of Canada as well (Shahidehpour et al., 2002).

1.2.1 Regulated vs Deregulated

Traditionally the power industry is a vertically integrated single utility and a monopoly in its service area. It normally is owned by the government, a cooperative of consumers, or privately. As the single electricity service provider, the industry is also obligated to provide electricity to all customers in the service area.

With the electricity supply service provider's monopoly status, the regulator sets the tariff (electricity price) to earn a fair rate of return on investments and to recover operational expenses. Under the regulated environment, companies maximize profits while being subject to many regulatory constraints. From microeconomics, the sole service provider of a monopoly market has the absolute market power. In addition, because the costs are allowed by the regulator to be passed to the customers, the utility has fewer incentives to reduce costs or to make investments considering the associated risks. Consequently, the customers have no choices for their electricity supply service providers and have no choices on the tariffs (except in case of service contracts).

As compared with a monopoly market, an ideal competitive market normally has many sellers/service providers and buyers/customers. As a result of competition, the market price is equal to the cost of producing the last unit sold, which is the economically efficient solution. The role of deregulation is to structure a competitive market with enough generators to eliminate market power.

With the deregulation, traditional vertically integrated power utilities are split into generation, transmission, and distribution service providers to form a competitive electricity market. Accordingly, the market operation decision model also changes as shown in Figs. 1.1 and 1.2.

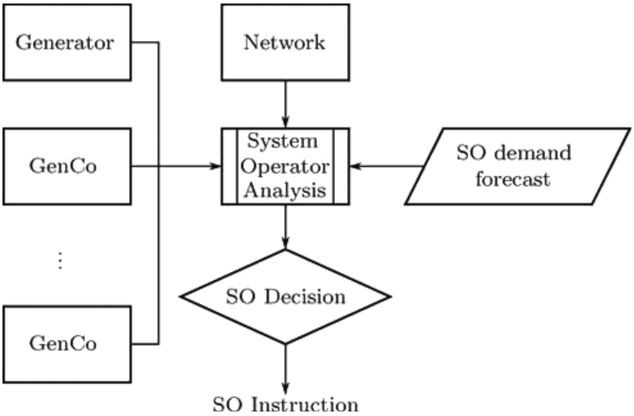

Fig. 1.1. Market Operation Decision Model for the Regulated Power Industry – Central Utility Decision Model

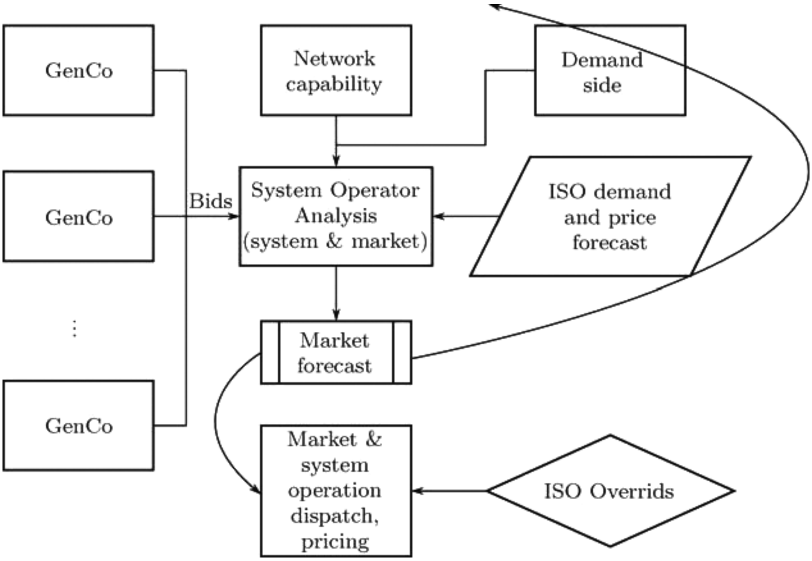

Fig. 1.2. Market Operation Decision Model for the Deregulated Power Utility – Competitive Market Decision Model

In the deregulated market, the economic decision making mechanism responds to a decentralized process. Each participant aims at profit maximization. Unlike that of the regulated environment, the recovery of the investment in a new plan is not guaranteed in a deregulated environment. Consequently, risk management has become a critical part of the electricity business in a market environment.

Another key change resulted from the electricity market is the introduction of more uncertainties and stake holders into the power industry. This helps to increase the complexity of power system analysis and leads to the need for new techniques.

1.2.2 Typical Electricity Markets

There are three major electricity market models in practice worldwide. These models include the PoolCo model, the bilateral contracts model, and the hybrid model.

1) PoolCo Model

A PoolCo is defined as a centralized marketplace that clears the market for buyers and sellers. A typical PoolCo model is shown in Fig.1.3.

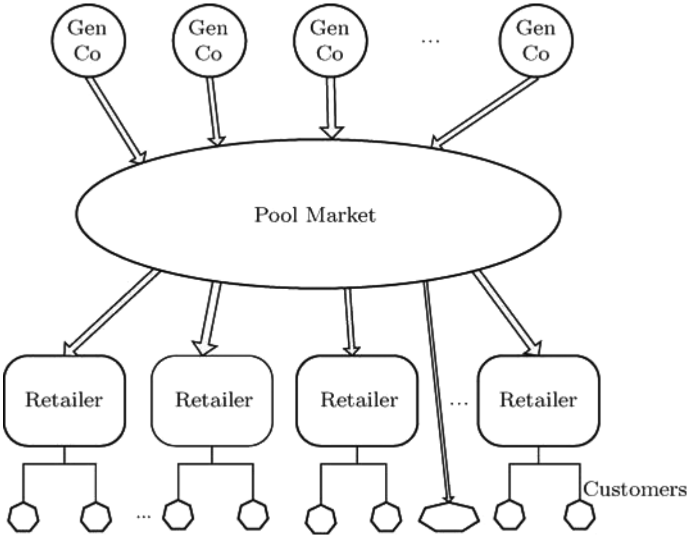

Fig. 1.3. Spot Market Structure (National Grid Management Council, 1994)

In a PoolCo market, buyers and sellers submit bids to the pool for the amounts of power they are willing to trade in the market. Sellers in an electricity market would compete for the right to supply energy to the grid and not for specific customers. If a seller (normally a generation company or GENCO) bids too high, it may not be able to sell. In some markets, buyers also bid into the pool to buy electricity. If a buyer bids too low, it may not be able to buy. It should be noted that in some markets such as the Australian NEM, only the sellers bid into the pool while the buyers do not, which means that the buyers will pay at a pool price determined by the market clearing process. There is an independent system operator (ISO) in a PoolCo market to implement economic dispatch and produce a single spot price for electricity. In an ideal competitive market, the market dynamics will drive the spot price to a competitive level equal to the marginal cost of the most efficient bidders provided the GENCOs bid into the market with their marginal costs in order to get dispatched by the ISO. In such a market low cost generators will normally benefit by getting dispatched by the ISO. An ideal PoolCo market is a competitive market where the GENCOs bid with their marginal costs. When market power exists, the dominating GENCOs may not necessarily bid with their marginal costs.

2) Bilateral Contracts Model

Bilateral contracts are negotiable agreements on delivery and receipt of electricity between two traders. These contracts set the terms and conditions of agreements independent of the ISO. However, in this model the ISO will verify that a sufficient transmission capacity exists to complete the transactions and maintain the transmission security. The bilateral contract model is very flexible, as trading parties specify their desired contract terms. However, its disadvantages arise from the high costs of negotiating and writing contracts and the risk of creditworthiness of counterparties.

3) Hybrid Model

The hybrid model combines various features of the previous two models. In the hybrid model, the utilization of a PoolCo is not obligatory, and any customer will be allowed to negotiate a power supply agreement directly with suppliers or choose to accept power at the spot market price. In the model, PoolCo will serve all participants who choose not to sign bilateral contracts. However, allowing customers to negotiate power purchase arrangements with suppliers will offer a true customer choice and an impetus for the creation of a wide variety of services and pricing options to best meet individual customer needs (Shahidehpour et al., 2002).

1.3 Uncertainties in a Power System

Uncertainties have existed in power systems from the beginning of the power industry. Uncertainties from demand and generator availability have been studied in reliability assessment for decades. However, with the deregulation and other new initiatives happening in the power industry, the level of uncertainty has been increasing dramatically. For example, in a deregulated environment, although generation planning is considered in the overall planning process, it is difficult for the transmission planner to access accurate information concerning generation expansion. Transmission planning is no longer coordinated with generation planning by a single planner. Future generation capacities and system load flow patterns also become more uncertain. In this new environment, other possible sources of uncertainty include (Buygi et al., 2006; Zhao et al., 2009):

- system load;
- bidding behaviors of generators;
- availability of generators, transmission lines, and other system facilities;
- installation/closure/replacement of other transmission facilities;
- carbon prices and other environmental costs;
- market rules and government policies.

1.3.1 Load Modeling Issues

Among the sources of uncertainties, power system load plays an important role. In addition to the uncertainties coming from forecast demand, load models also contribute to system uncertainty, especially for power system simulation and stability assessment tasks. Inappropriate load models may lead to the wrong conclusion and possibly cause serious damage to the system. It is necessary to give a brief discussion of the load modeling issues here.

Power system simulation is the most important tool guiding the operation and control of a power grid. The accuracy of the power system simulation relies heavily on the model reliability. Among all the components in a power system, the load model is one of the least well known elements; however, its significant influences on the system stability and control have long been recognized (Concordia and Ihara, 1982; Undrill and Laskowski, 1982; Kundur 1993; IEEE 1993a; IEEE 1993b). Moreover, the load model has direct influences on power system security. On August 10, 1996, WSCC (Western Systems Coordinating Council) in the USA collapsed following power oscillations. The blackout caused huge economic losses and endangered state security. However, the system model guiding the WSCC operation had failed to predict the blackout. Therefore, the model validation process, following this outage, indicated that the load model in WSCC database was not adequate to reproduce the event. This strongly suggests that a more reliable load model is desperately needed. The load model also has great effects on economic operation of a power system. The available transfer capability of the transmission corridor is highly affected by the accuracy of the load models used. Due to the limited understanding of load models, a power system is usually operated very conservatively, leading to the poor utilization of both the transmission and the generation assets.

Nevertheless, it is also widely known that modeling the load is difficult due to the uncertainty and the complexity of the load. The power load consists of various components, each with their own characteristics. Furthermore, load is always changing, both in its amount and composition. Thus, how to describe the aggregated dynamic characteristic of the load has been unsolved so far. Due to the blackouts which occurred all around the world in the last few years, load modeling has received more attention and has become a new research focus.

The state of the art for research on load modeling is mainly dedicated to the structure of the load model and algorithms to find its parameters.

The structure of the load model has great impacts on the results of power system analysis. It has been observed that different load models will lead to various, even completely contrary conclusions on system stability (Kosterev et al., 1999; Pereira et al., 2002). The traditional production-grade power system analysis tools often use the constant impedance, constant current, and constant power load model, namely the ZIP load model. However, simulation results by modeling load with ZIP often deviate from the field test results, which indicate the inefficiency of the ZIP load model. To capture the strong nonlinear characteristic of load under the recovery of the voltage, a load model with a nonlinear structure was proposed by (Hill, 1993). Load structure in terms of nonlinear dynamic equations was later proposed by (Karlsson, Hill, 1994; Lin et al., 1993) identified two dynamic load model structures based on measurements, stating that a second order transfer function captures the load characteristics better than a first order transfer function. The recent trend has been to combine the dynamic load model with the static model (Lin et al., 1993; Wang et al., 1994; He et al., 2006; Ma et al., 2006; Wang et al., 1994) developed a load model as a combination of a RC circuit in parallel with an induction motor equivalent circuit. Ma et al. (Ma et al., 2006; He et al., 2006; Ma et al., 2007; Ma et al., 2008) proposed a composite load model of the ZIP in combination with the motor. An interim composite load model that is 80% static and 20% induction motor model is proposed by (Perira et al., 2002) for WSCC system simulation. Except for the load model structure, the identification algorithm to find the load model parameters is also widely researched. Both linear and nonlinear optimization algorithms are applied to solve the load modeling problem. However, the identification algorithm is based on the model structure and it cannot give reliable results without a sound model structure.

Although various model structures have been proposed for modeling load for research purposes, the power industry still uses very simple static load models. The reason is that some basic problems on composite load modeling are still open, which mainly include three key points: First, which model structure among proposed various ones is most appropriate to represent the dynamic characteristic of the load and is it the model with the simplest structure? Second, can this model structure be identified? Is the parameter set given by the optimization process really the true one, since optimization may easily stick into some local minima? Third, how is the generalization capability of the proposed load model? Load is always changing; however, a model can only be built on available measurements. So, the generalization capability of the load model reflects its validity. Theoretically, the first point involves the minimized realization problem, the second point addresses the identification problem, and the third point closely relates to the statistic distribution of the load.

A sound load model structure is the basis for all other load modeling practice. Without a good model structure, all the efforts to find reliable load models are in vain. Based on the Occam's razor principle, which states that from all models describing a process accurately, the simplest one is the best (Nelles, 2001). Correspondingly, simplification of the model structure is an important step in obtaining reliable load models (Ma et al., 2008). Currently, ZIP in combination with a motor is used to represent the dynamic characteristic of the load model. However, there are various components of a load. Take motors as an example, there are big motors and small motors, industry motors and domestic motors, three-phase motors and single-phase motors. Correspondingly, different load compositions are used to model different loads or loads at different operating conditions. Once the load model structure is selected, proper load model parameter values are needed. Given the variations of the actual loads in a power system, a proper range of parameter values can be used to provide a useful guide in selecting suitable load models for further simulation purposes.

Parameter estimation is required in order to calculate the parameter values for a given load model with system response measurement data. This often involves optimization algorithms and linear/nonlinear least squares estimation (LSE) techniques, or a combination of both approaches.

A model with the appropriate structure and parameters usually has good performance when fitting the available data. However, it does not necessarily mean it is a good model. A good load model must have good generalization capability. Since a load is always changing, the model built on the available data must also have the strong capability to describe the unseen data. Methodologies used for generalization capability analysis include statistical analysis and various machine learning methods. Even if a model with good generalization capability has been obtained, cross validation is still needed because it is still possible that the derived load model may fail to present the system dynamics in some system operating conditions involving system transients. It is worth noting that both research and engineering practice in load modeling are still facing many challenges. There are many complex load modeling problems causing difficulties to the power industry; consequently, static load models are still used by some companies in their operations and planning practices.

1.3.2 Distributed Generation

In addition to those uncertainty factors discussed previously, another important issue is the potential large-scale penetration of distributed generation (DG) into the power system. Traditionally, the global power industry has been dominated by large, centralized generation units which are able to exploit significant economies of scale. In recent decades, the centralized generation model has been the focus of concern on its costs, security vulnerability, and environmental impacts, while DG is expected to play an increasingly important role in the future provision of a sustainable electricity supply. Large-scale implementation of DG will cause significant changes in the power industry and deeply influence the transmission planning process. For example, DG can reduce local power demand; thus, it can potentially defer investments in the transmission and distribution sectors. On the other hand, when the penetration of DG in the market reaches a certain level, its suppliers will have to get involved in the spot market and trade the electricity through the transmission and distribution networks, which may need to be further expanded. Reliability of some types of DGs is also of a concern for the transmission and distribution network service providers (TNSPs and DNSPs). Therefore, it is important to investigate the impacts of DG on power system analysis, especially in the planning process. The uncertainties DG brings to the system also need to be considered in power system analysis.

1.4 Situational Awareness

The huge impact in economic terms as well as interruptions of daily life from the 2003 blackouts in North America and the following blackouts in UL and Italy clearly showed the need for techniques to analyze and prevent such devastating events. According to the Electricity Consumers Resource Council (2004), the blackout in August 2004 in America and Canada had left 50 million people without power supply and with an economic cost estimated at up to $10 billion. The many studies of this major blackout concluded that a lack of situational awareness is one of the key factors that resulted in the wide spread power system outage. It has been concluded that the lack of situational awareness was composed of a number of factors such as deficiencies in operator training, lack of coordination and ineffectiveness in communications, and inadequate tools for system reliability assessment. This lack of situational awareness also applies to other major system blackouts as well. As a result, operators and coordinators were unable to visualize the security and reliability status of the overall power system following some disturbance events. Such poor understanding of the system modes of operations and health of the network equipments also resulted in the Scandinavian blackout incident of 2003. As the complexity and connectivity of power systems continue to grow, for the system operators and coordinators, situational awareness becomes more and more important. New methodologies needed for better awareness of system operating conditions can be achieved. The capability of control centres will be enhanced with better situational awareness. This can be partially promoted by development of operator and control centre tools which allows for more efficient proactive control actions as compared with the conventional preventative tools. Real time tools, which are able to perform robust real time system security assessment even with the presence of system wide structural variations, are very useful in allowing operators to have the better mental model of the system's health. Therefore, prompt control actions can be taken to prevent possible system wide outages.

In its report for blackouts, NERC Real-Time Tools Best Practices Task Force (RTTBPTF) defined situational awareness as "knowing what is going on around you and understanding what needs to be done and when to maintain, or return to, a reliable operating state." NERC's Real-Time Tools Survey report presented situational awareness practices and procedures, which should be used to define requirements or guidelines in practice. According to the article by Endsley, 1998, there are three levels for the term situational awareness or situation awareness: (1) perception of elements, (2) comprehending the meaning of these elements, and (3) projecting future system states based on the understanding from levels 1 and 2. For level 1 of situational awareness, operators can use tools which provide real time visual and audio alarm signals which serve as indicators of the operating states of the power system. According to NERC (NERC 2005, NERC 2008) there are three ways of implementing such alarm tools which are being within the SCADA/EMS system, external functions, or a combination of the two.

NERC Best Practices Task Force Report (2008) summarized the following situational awareness practice areas in its report: reserve monitoring for both reactive reserve capability and operating reserve capability; alarm response procedures; conservative operations to move the system from unknown and potentially risky conditions into a secure state; operating guides defining procedures about preventive actions; load shed capability for emergency control; system reassessment practices, and blackstart capability practices.

1.5 Control Performance

This section provides a review of the present framework of power system protection and control (EPRI, 2004; EPRI, 2007; SEL-421 Manual; ALSTOM, 2002; Mooney and Fischer, 2006; Hou et al., 1997; IEEE PSRC WG, 2005;