PSERC

Reliability Assessment Incorporating Operational Considerations and Economic Aspects for Large Interconnected Grids

Final Project Report

Power Systems Engineering Research Center

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Power Systems Engineering Research Center

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Executive Summary

The *Reliability Assessment Incorporating Operational Considerations and Economic Aspects for Large Interconnected Grids* Project was conceived as an undertaking to bridge the developments in the Markets and the Systems Research Stems of the Power Systems Engineering Research Center (PSERC). The increasing frequency of transmission congestion due to the more intensive use of the grid, brought about by the entry of many new players and by the proliferation in the number of transactions, has created a critical need for the assessment of the reliability of the bulk system. This project's aim was to construct models with appropriate level of detail of the operational procedures and economic aspects, and use them to develop effective tools for evaluating the reliability and the associated economics of large bulk systems such as those of the *RTO*s/*ISO*s currently in formation. The project research team has successfully met this aim and brought about advances in the modeling and the development of tools for reliability evaluation. Furthermore, the project has established a solid basis for linking economics, reliability and security.

This *Reliability* Project focused on some of the pressing needs of the industry in the reliability arena in the restructured environment. Within the scope of this project, we have advanced the state of the art in congestion modeling for reliability and security evaluation. We have developed new detailed models with the explicit representation suitable for the large networks in the restructured environment, constructed new tools for security and reliability assessment, and established a concrete basis for the linkage of reliability and economics. The reliability study in this project is performed in the broader sense of adequacy and security of bulk power systems within the context of uncertainty management. The work explicitly considered the many changes under restructuring and their impacts. In addition, the work is notable for its capability to address the scale of grid reliability issues associated with the push toward grid regionalization.

The objectives of this project were:

- to improve the representation of congestion situations in reliability evaluation;
- to enhance the composite system modeling for reliability analysis through the explicit representation of operational considerations and economic aspects;
- to develop computationally efficient tools for reliability evaluation of large systems; and
- to explicitly couple the reliability assessment with the analysis of the corresponding economics.

We carried out the work on this project as a series of separate and interdependent tasks that resulted in a large body of publications in both conference proceedings and archival journals. Overall, the Project has resulted in:

- an improved understanding of the impacts of congestion on bulk power reliability;

- an explicit evaluation of the impacts on system reliability of remedial actions and protection system hidden failures;
- a useful scheme in security evaluation for the detection of island formation and the identification of causal factors under multiple line outages;
- an explicit evaluation of the impacts of different security criteria on the market performance economics thereby providing the benefit/cost justification for a selected security criterion;
- design of a short-term resource adequacy program which takes into account both the physical and market factors that impact reliability; and
- development of planning tools to optimally site generation resources taking into account congestion impacts.

This report summarizes the key developments in the various tasks that constituted the work. We grouped the results of the project into four key areas:

- development of models incorporating operational considerations for reliability and security assessment;
- the economic dimensions of reliability and security evaluation;
- short-term resource adequacy; and
- system planning: reliability considerations.

We describe the results under each area and provide the relevant reference documents. The PSERC document numbers can be used to locate the documents on the PSERC website (http://www.pserc.org).

Our studies have resulted in some insightful findings and conclusions. Some of the noteworthy aspects are:

- The ability to detect island formation and identify the outaged lines that are the causal factors is a very useful tool in system security assessment online and off-line.
- The demonstrated ability of the quadratized power flow in contingency simulation and effects analysis enabled the development of enhanced tools for reliability study.
- The new approach for the systematic evaluation of economic impacts of a selected security criterion provides the insight that the power systems may be operated under a stricter criterion without adversely impacting the economic efficiency of markets.
- The value of electricity purchased, typically, far exceeds the average price paid; as such, the value of lost load exceeds, by many times, the price paid for electricity.
- The reliability of electricity supplied over a network in terms of unanticipated interruptions and voltage and frequency stability have certain public good attributes, and therefore a central authority must establish their desired level.
- In most cases, the provision of reliability-enhancing services can be decentralized and left to market forces, provided that the proper public values

are reflected in the prices paid to suppliers, either indirectly through mandated levels of reliability or directly through regulatorily-induced supplements.
- A carrots-and-sticks based approach for short-term resource adequacy is able to overcome some key deficiencies in the implemented schemes.
- The importance of including outage costs in expansion planning has been clearly demonstrated with the advances in the location techniques proposed.

The results of this project are also useful in providing fruitful directions for future work. Key areas that are logical extensions of the results reported here are on the topics of:

- the determination of all the nodes of the formed islands under multiple line outages;
- the effective representation of the maintenance scheduling of generating units and transmission equipment/facilities in the modeling of operational considerations for reliability evaluation;
- the extension of the proposed security economic impacts evaluation approach to incorporate the multi-settlement system including the real-time market and the bilateral transactions;
- the incorporation of demand responsiveness to price, multiple strategic sellers interaction, uncertainty in the strategic sellers' information, inter-hour relationships, transmission network effects and generation maintenance into the short-term resource adequacy models; and
- the use of Monte Carlo sampling to derive the estimated objective value by sample-average approximation of the actual expected value for use in the optimization of the location schemes.

We expect that these topics will be addressed in future projects.

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1. Introduction

This project is concerned with the evaluation of reliability in the wider sense of adequacy and security of bulk power systems. The entry of many new players, their decentralized decision making, the proliferation in the number of transactions, the use of the transmission system in a manner very different than for which it was planned, the establishment of new centralized controlling entities, be they *ISO*s or *RTO*s, have changed both the operations and planning in the electricity industry. Impacts such as transmission congestion, provision of ancillary services on an unbundled basis and frequent changes in the nature and origin/destination of transactions have introduced major factors whose consideration is critically important in the evaluation of composite reliability of generation-transmission systems. The frequency of congestion and changes of flow patterns has stressed the power system and resulted in severe demands on the effective deployment of operational procedures in the operation of the system. The increased use of remedial actions and the effective use of the protection system are two key examples of the impacts of these demands. The advent of markets has also put a new emphasis on the quantification of the economic impacts that are entailed in meeting the reliability requirements. This economic evaluation is particularly useful for the *ISO*/*RTO*s, as well as, for the transmission customers and the grid owners. For them, a key consideration in the assessment of reliability is the analysis of the economics of providing reliability at different levels. A critically important aspect of this analysis is the role of direct customer controls. The economic considerations are related to the specification of the list of considered contingencies and to the robustness of the composite system in terms of the capability of responding to the postulated contingencies.

There are numerous challenges in the assessment of reliability and the determination of the associated economics. In addition to the development of models that reflect the changes under restructuring enumerated above, the push toward grid regionalization has created a need to develop models and tools that are capable to address the scale of grid reliability with the considerably larger networks requiring analysis. The modeling work needs to incorporate system operations behavior from the operational procedures to the protective and control devices and to the actions of and demand-side response, including direct customer control. An additional aspect is the representation of multi-area systems to reflect the impacts of the structural characteristics of the network of interconnected regions under the control of a single *ISO/RTO*. The new models necessitate the development of tools that are computationally tractable to compute appropriate indices for reliability. A key aspect of the work is the explicit representation of economic issues in the evaluation of reliability. In particular, the *willingness to pay* of various customer classes and the actions of demand-side response in electricity markets needs to be explicitly modeled. The entire reliability assessment work needs to be carried out within the broader context of uncertainty management in the restructured environment. Issues that are sources of uncertainty, such as weather impacts, load forecasts, fuel availability, fuel prices, and demand-side participation, need to be considered within the context of uncertainty management.

The objectives of this project were:

- to develop an improved representation of congestion situations in reliability evaluation;
- to enhance the modeling of the composite system for reliability analysis through the explicit representation of operational considerations and economic aspects;
- to develop computationally efficient tools for reliability evaluation of large systems; and,
- to explicitly couple the reliability assessment with the analysis of the corresponding economics.

The work performed within the framework of this project consists of a series of separate but interdependent tasks that resulted in a significant number of conference proceedings and Journal publications by the four main investigators – G. Gross, A.P. Meliopoulos, R. Schuler and C. Singh and their students and co-workers. Some of the work reported under this project received only nominal support and so the research work is credited to other PSERC projects.

Our work focused on the following topics:

- Development of Models Incorporating Operational Considerations for Reliability and Security Assessment
- The Economic Dimensions of Reliability and Security Evaluation
- Short-Term Resource Adequacy
- System Planning: Reliability Considerations

This project establishes a solid analytical basis for the development of models capable of capturing the impacts of congestion and operational considerations. These models can play a key role in the construction of effective tools capable of evaluating the reliability of very large-scale networks such as those in the *RTO*s currently being formed. The availability of the new models and computationally efficient reliability evaluation tools provide heretofore unavailable capabilities to operations and planning personnel.

The remainder of the report is organized as follows. The next four sections describe various individual and group contributions to the topics listed above. Because of the rather broad range of topics covered by this project and the diversity of the topics addressed, we will present the various contributions in the form of an annotated review of the contributions under each topic. Each individual contribution is summarized and the key results are given. The final section of this report provides an overall summary of these individual contributions and makes specific suggestions concerning the additional work that remains for the future.

2. Development of Models Incorporating Operational Considerations for Reliability and Security Assessment

This project required the development of various modeling aspects for the analysis of reliability and security. A key focus was on the modeling of congestion impacts on reliability in the development of an integrated model of the bulk system that incorporates the system network, including the physical supply sources, the network operating constraints, the system electric loads, the available generation offers, and the spectrum of ancillary services particularly those associated with capacity-based services and reactive power support. This integrated model serves as the basis for the simulation of the operation of the system by incorporating the principal *RTO*/*ISO* procedures. The operational conditions of the system with all equipment available – the reference or base case – as well as, the operational conditions under the postulated contingencies resulting from independent single facility outages as well as common mode outages need to be considered. The system conditions, be they associated with a base case or with a contingency case, are simulated using an *optimal power flow* methodology. For this project, we made use for the study of security of the framework we developed for congestion analysis in a previous project. We describe the work on system security evaluation of the economic dimensions in the next chapter. In addition, we developed a modified *OPF* tool for the reliability work.

The modified *OPF* tool that we developed permits a three-level simulation of the electric power system operational procedures. The three-level approach provides a realistic modeling of the congestion effects together with more detailed modeling of the bulk power system. This formulation explicitly incorporates the congestion management actions taken by the *RTO*/*ISO*. Specifically, at the first level, an optimal power flow has the objective to minimize the overall costs incurred by the *RTO*/*ISO* in supplying the electric load. The *RTO*/*ISO* costs include the costs of the accepted generation offers as well as the costs of the required ancillary services. The formulation implicitly incorporates the use of ancillary services for remedial actions. If this problem does not have a solution, the *OPF* is applied to the second level formulation with the objective of simply supplying the electric load while satisfying the operational constraints (emergency state) of the system. If this second level problem formulation is also infeasible, the *OPF* is applied to the third level formulation with the objective of minimal load shedding. This third level problem formulation always has a solution and determines the electric loads that cannot be served due to system reliability shortfalls.

The development of this *OPF* tool made use of the prior work of the research team. The *quadratized* power flow formulation was exploited with an emphasis on making the applications of the *OPF* methodology efficient for large-scale systems. We applied the tool to develop contingency simulation methodology and the analysis of contingency effects. The proposed model is well suited to incorporate congestion in reliability analysis through the three-level formulation approach. In addition, the proposed model allows the explicit incorporation of remedial actions for reliability assessment and the inclusion of the impact of system protection devices on reliability. The effort resulted in the improved

analysis of system contingency effects explicitly taking into account the evaluation of the effects of remedial actions on system reliability and d on market performance. In addition, the explicit representation of hidden failures of the protection systems provides new insights into the analysis of protection equipment impacts on reliability. The modeling and tool development work has been tested on various systems including the IEEE 24-bus RTS. For the work on hidden failures of the protection equipment, the test system was appropriately modified to allow assessment of the added modeling capability. Specifically, this system has been converted into a substation-oriented model (i.e., the substation arrangement of breakers, switches, relays, etc. is represented explicitly in the model).

2.1 System Security Assessment

The analysis of the power system security requires tools for the study of networks undergoing multiple line outages. We have developed two basic tools for this specific purpose. We have generalized the concept of line outage distribution factors and we have developed efficient methodology for the detection of island formation. The prominent role of cascading outages in recent blackouts has created a critical need in security applications for the rapid assessment of multiple-line outage impacts. The development of these tools was in response to meet this need.

We developed a closed-form analytic expression for generalized line outage distribution factors or *GLODF*s under multiple-line outages without the need for the reevaluation of post-outage network system parameters. This general expression allows the computationally efficient evaluation of *GLODF*s for security application purposes.

Our focus in the detection of island formation work is on the network topology modifications, which separate the system into islands. We study the causality factors of island formation in the presence of multiple line outages and develop a general methodology for its detection and for the identification of the subset of outaged lines causing island formation. The detection/identification of island formation provides the information needed to be able to deal effectively with the numerous complications that arise. These complications all stem from the singularity of the Jacobian matrix in the Newton power flow. Consequently, the power flow cannot be used without the introduction of a modified Jacobian matrix. Furthermore, the impacts of the Jacobian matrix singularity propagate through all the applications programs that use the Newton power flow, such as state estimation and various network analysis tools. These complications prevent the use of such tools in standard form and require their application to the connected sub networks that are formed. Moreover, separation into two or more islands requires the deployment of different control strategies to ensure system security. For off-line static security analysis studies involving the analysis of numerous *what if* cases, the line outages that lead to island formation are regarded as “most problematic”. Indeed, situations with multiple line outages may require extensive corrective control efforts, ranging from redispatch to load shedding – a last resort. The impacts of such line outages are even more pronounced when stability aspects are included.

For both real-time as well as off-line applications, the rapid detection of island formation and the identification of the causal factors are required to deal with the complications cited above. In cases where several lines are outaged and no island formation occurs, additional network analysis is needed to identify which additional line outage(s) result in system separation into islands.

In this work, we address the need of the rapid identification of island formation in a computationally efficient way in which we make effective use of the connectivity information of a subset of outaged lines in a larger set of outaged lines containing that subset. Specifically, we propose the development of a combined-graph-theoretic-algebraic approach to detect island formation and to identify the causality factors under multiple-line outages. The proposed approach is based on the graph theoretic notion of minimal cutsets and the approximate line flow sensitivities, the so-called power transfer distribution factors or *PTDF*s. The marriage of the purely topological minimal cutset notion – the outages of the elements of the minimal cutset separate the system – with the circuit theory based *PTDF*s embodying both topology and network parameter information, harnesses effectively this information. We use the *PTDF*s to evaluate the impacts of line outages on the non-outaged lines' flows in terms of the so-called line outage distribution factors or *LODF*s. The *LODF* values provide the fractions of the pre-outage flow on the outaged line that are redistributed to the non-outaged lines in the post-outage network. For the study of multiple-line outages, we use the generalized *LODF*s or *GLODF*s and establish a one-to-one relationship between *GLODF*s and the minimal cutset. The *GLODF* values of a set of outaged lines become undefined if and only if the set of outaged lines constitutes one or more minimal cutsets. We use this relationship to detect island formation. Moreover, we can also identify the elements of the minimal cutsets and which terminal nodes of the minimal cutset elements are located in the same island.

A salient feature of the proposed approach is its low computational requirements as the computations are carried out on matrices whose dimension is the number of outaged lines. These computations take advantage of the structural characteristics of the proposed methodology. In this way, we can directly pinpoint the impact of the interactions between the additional line outage and the *k*-line outages as a causal factor for island formation. For this reason, the proposed method is particularly useful in the analysis of appropriate preventive/corrective control strategies in cases involving the *domino effect* of multiple line outages to effectively mitigate the impacts of such a sequence of outages. We illustrate the application of the tool to two large networks – the IEEE 118 bus-system and a 2200 bus network derived from Northeast Power Coordinating Council network.

We described the work in this area in the two publications cited below. The summaries of the contents of the publications are given.

> **Güler, Teoman, Gross, George and Liu, Minghai "Generalized Line Outage Distribution Factors," accepted for publication in *Letters, IEEE Transactions on Power Systems,* vol. 22, no.1, February 2007. (PSERC 06-39)**

Distribution factors play a key role in many system security analysis and market applications. These factors are linear approximations of the sensitivities of specific system variables with respect to changes in nodal injections and withdrawals. The injection shift factors (*ISF*s) are the basic factors that serve as building blocks of the other distribution factors. The line outage distribution factors (*LODF*s) may be computed using the *ISF*s and, in fact, may be iteratively evaluated when more than one line outage is considered. The prominent role of cascading outages in recent blackouts has created a need in security applications for evaluating *LODF*s under multiple-line outages. While the line outage distribution factors (*LODF*s) are well understood, the evaluation of *LODF*s under multiple-line outages has received little attention. In this letter, we present an analytic, closed-form expression for and the computationally efficient evaluation of *LODF*s under multiple-line outages.

> **Güler, Teoman and Gross, George "Detection of Island Formation and Identification of Causal Factors under Multiple Line Outages," *IEEE Transactions on Power Systems*, vol. 22, no.1, February 2007. (PSERC 06-38)**

The detection of island formation in power networks is prerequisite for the study of security analysis and control. We develop a combined graph-theoretic-algebraic approach to detect island formation in power system networks under multiple line outages. We construct the approach by gaining insights into the topological impacts of outaged lines on system connectivity from the use power transfer distribution factor information. We develop a one-to-one relationship between minimal cutsets and a matrix of the generalized line outage distribution factors for multiple line outages. This relationship requires computations on lower order matrices and so is able to provide rapidly essential information. The proposed approach detects the island formation and identifies the subset of outaged lines that is the causal factor. Furthermore, for cases in which the set of outaged lines does not result in system separation, the method has the ability to identify whether a set of candidate line outages separates the system. Consequently, the need for establishing nodal system connectivity is bypassed. We illustrate the capabilities of the proposed approach on two large-scale networks. The proposed approach provides an effective tool for both real-time and off-line environments for security analysis and control.

2.2 Enhanced Reliability Evaluation

The analysis of the power system security reliability was advanced with the development of the modeling and tools using the *quadratized* power flow model. Three publications have resulted from the work. These are summarized below.

> **Yang, Fang, Meliopoulos, A.P., Cokkinides, George J. and Stefopoulos, George K. "Contingency Simulation Using Single Phase Quadratized Power Flow", *Proceedings of the IX Probabilistic Methods Applied to Power Systems (PMAPS) Conference*, Stockholm, June 11 -15, 2006. (PSERC 06-50)**

This paper proposes advances in contingency simulation techniques for bulk power system reliability assessment. In bulk power system reliability assessment, it is essential

that contingency simulation methods solve the post-contingency situation realistically. Also, because of the large number of system contingencies, simulation methods must be computationally efficient, as well as, provide acceptable accuracy. The proposed techniques meet these requirements by introducing an effective power flow engine and numerically efficient schemes. The approach extensively utilizes the single phase quadratized power flow and the hybrid contingency selection technique. For computational efficiency, detailed advantage is taken of sparse oriented compensation and the quasi-compensation iterative schemes.

We use the single-phase quadratized power flow (*SPQPF*) to overcome the shortcomings of the conventional power flow. Contingency simulation techniques using the conventional power flow (*CPF*) model typically suffer from lack of realism in the modeling and slow convergence. The *SPQPF* allows the incorporation of more realistic generator models and load representation in the quadratized form and has superior performance in converging to the solution. We adapt the *SPQPF* as the basic power flow solution approach. We also use the hybrid contingency technique to efficiently process the contingencies. The hybrid contingency selection technique classifies system contingencies into two distinct groups and applies different selection techniques for each group. The two groups consist of a group with contingencies that cause system linear changes and another with contingencies that cause system nonlinear changes or discontinuities. This classification is attained by means of contingency stiffness and performance indices to identify contingencies that cause system nonlinearities and discontinuities. The first group includes the majority of contingencies. A performance based approach is used to select the contingencies that impact system reliability for this group. The second group contains only a small portion of the contingencies.

The contingency classification serves to allow the use of efficient solution schemes for the simulation of the contingencies. We implement the sparse oriented compensation scheme for the contingencies in the first group by using the pre-contingency system matrix to minimize the computational burden for post contingency analysis and taking full advantage of sparsity. This scheme provides accurate results more efficiently than the procedure of reformulating and re-factorizing the post contingency system matrix, typically employed. We use the quasi-compensation iterative scheme for the small number of contingencies in the second group. The scheme uses effective updating of the mismatch vectors without the need to update the pre-contingency system matrix. We integrate this scheme into the *SPQPF* to efficiently solve the iterations of *SPQPF* to obtain results with the desired accuracy.

We have tested the proposed technique on a number of systems and illustrate the application on the IEEE 24-bus reliability test system (RTS) and the IEEE 96-bus RTS. For the IEEE 24-bus RTS, the hybrid contingency selection technique is first used to classify the system contingencies into two groups. Contingencies in the first group are solved using the sparse-oriented compensation scheme. The results are exactly the same as the results of the first *SPQPF* iteration. For the second group of contingencies, the quasi compensation iterative scheme is applied. The iteration numbers of this method are determined by the pre-defined *SPQPF* mismatch tolerance. In addition, the effectiveness

of sparse techniques in improving solution efficiency is also tested. For the relatively small IEEE 24-bus RTS, the solution time is reduced by 10% from the conventional approach when using sparsity techniques in the proposed compensation method. The improvement in the solution speed increases to 40% for the IEEE 96-bus RTS. This trend shows that as the system size increases, the improvement in the solution speed using the proposed method becomes more significant. The contingency simulation results for the two reliability test systems demonstrate the capability of the proposed approach for contingency simulation.

Yang, Fang, Meliopoulos, A.P., Cokkinides, George J. and Stefopoulos, George K. "Security-Constrained Adequacy Evaluation of Bulk Power System Reliability", *Proceedings of the IX Probabilistic Methods Applied to Power Systems (PMAPS) Conference,* Stockholm, June 11 -15, 2006. (PSERC 06-49)

This paper proposes a security-constrained adequacy evaluation (*SCAE*) methodology to assess bulk power system reliability in the competitive electricity market environment. The proposed *SCAE* methodology is based on a systematic framework and incorporates a variety of schemes for the computationally efficient evaluation of the metrics used to quantify the ability of the bulk power system to meet the demands without violating the security constraints.

The three major components of the proposed SCAE framework are the critical contingency selection, the effects analysis and the evaluation of reliability indices. The objective of the critical contingency selection is to identify rapidly, in an approximate way, those contingencies that may cause system loss of load. The most critical contingencies are then evaluated by effects analysis to obtain their impacts on system operations. The reliability indices are calculated to measure the system reliability level. We make extensive use of the single-phase quadratized power flow (*SPQPF*) for the contingency selection and effects analysis.

We next provide a brief description of the salient characteristics of the three components. The critical contingency selection consists of two parts – the enumeration of all possible system contingences using a wind-chime enumeration scheme for different outage levels and the ranking of all the contingencies at each level in terms of performance index (*PI*) changes. We use a state linearization approach to rank system contingencies in the *SPQPF* approach. As the nonlinearities in the *SPQPF* approach are milder, the use of an indirect differentiation procedure to compute the higher order sensitivity terms for calculating the performance index changes from the pre–to the post–contingency state. Results of the state linearization method have shown promising performance in improving contingency ranking accuracy when compared to the conventional performance index linearization method.

The effects analysis is the most computationally demanding part of the procedure. To overcome the problems encountered in effects analysis using the conventional power flow such as lack of realism in the modeling and possible divergence when the system is

severely stressed, we propose a non-divergent optimal quadratized power flow (*NDOQPF*) algorithm. We integrate the *SPQPF* into the *NDOQPF* algorithm and use it to simulate contingencies. The ability to incorporate major operational controls and security constraints into the resulting optimization problem provides good realism in the contingency simulation and, in addition, computational efficiency. The non-divergence of power flow is achieved by introducing fictitious bus injections that are driven to zero as the solution progresses. This scheme guarantees convergence if a solution exists; if a solution does not exist, a suboptimal solution, that may include load shedding, is provided. An important aspect of the *NDOQPF* algorithm is its ability to effectively represent congestion constraints in *RTO/ISO* operations.

We incorporate probability information on the contingencies to carry out the evaluation of the reliability indices. The set of contingencies that result in a loss of load is identified in the effects analysis. The probabilities of the contingencies in this set and the transition rates from any contingency within the set to other contingencies outside the set are used to calculate three reliability indices to determine probability, frequency, and duration.

We apply the proposed *SCAE* methodology to the IEEE 24-bus reliability test system (RTS). In this system, the peak load level results in highly stressed system conditions. The major operational controls include real power economic dispatch, reactive power proportional dispatch, and the remedial actions such as real and reactive generation rescheduling, reactor/capacitor bank switching and load shedding. The critical contingency selection using state linearization method provides more accurate contingency ranking than the conventional *PI* method. Effects analysis results indicate if any constraint violations are caused by a contingency, and if constraint violations exist, the required remedial actions are implemented. Any contingencies that require load shedding to maintain operations are recorded to evaluate the system reliability indices. In addition, a detailed solution procedure for an example contingency is provided to illustrate the non-divergence feature of the proposed *NDOQPF* algorithm. Finally, the three reliability indices of probability, frequency, and duration indices are computed for the system.

Meliopoulos, A.P., Yang, Fang, Cokkinides, George J. and Dam, Q.B. "Effects of Protection System Hidden Failures on Bulk Power System Reliability", *to be submitted.* (PSERC 06-51)

This paper proposes a methodology to evaluate the effects of protection system hidden failures on bulk power system reliability. Protection system hidden failures are recognized as a contributing factor to cascading outages. However, in typical current bulk power system reliability assessment studies, protection systems are assumed to be perfectly available, and the impacts of protection system hidden failures are not taken explicitly into account. In the proposed methodology, a breaker-oriented substation model is developed to represent the detailed substation configuration and the protection system scheme. In addition, the impacts of the detection of protection system hidden failures, uncovered by system monitoring, are analyzed. We develop the effects analysis for hidden failures in the circuit breaker trip mechanism (*CBTM*) and formulate

contingencies that result from such hidden failures. We extend the proposed security-constrained adequacy evaluation methodology to evaluate these contingencies so as to explicitly include the effects of protection system hidden failures on system reliability. The contributions of this paper are in the development of the modeling of the hidden failures and the associated analytic approach. We provide a brief overview of these contributions.

System substations are generally simplified and represented simply as buses. To consider protection system hidden failures, we employ a breaker-oriented substation model that provides the physical substation configuration with specific bus arrangements. The breaker-oriented substation model adds a new level of detail in the network representation. Such a model allows the introduction of the protection system schemes for various power system components. The use of this detailed substation and protection system model makes possible study of the impacts of protection system hidden failures on bulk power system reliability.

Each protection system component, such as the instrumentation, relays, and circuit breakers, may have hidden failures, which may be detected by the real-time monitoring function through the application of intelligent electronic devices (*IEDs*) in the substations. While the monitoring is unable to detect hidden failures of some non-monitored components such as the trip coil of circuit breakers, the *IEDs* allow the detection of hidden failures in the instrumentation and relays. In this work, the consideration of protection system hidden failures concentrates on hidden failures in the non-monitored components such as the circuit breaker trip mechanism.

We use probabilistic models of both independent and common-mode *CBTM* hidden failures. For independent hidden failures, each *CBTM* is able to transition between normal and hidden failure states. This transitioning process is modeled as a two-state Markov chain. The independent hidden failure model of *CBTM*s, however, prevents considering common-mode failures that involve simultaneous hidden failures of two or more *CBTM*s. Mathematical models for both independent and common mode hidden failures are derived in terms of the associated differential equations. The solution to such differential equations gives the probability of each substation state at each instant of time.

CBTM hidden failures can cause the trip of intact equipment following system disturbances. Specifically, when an initial fault occurs to a system component, the circuit breakers that have hidden failures in their trip mechanisms that should open to isolate this component cannot do so. As a result, adjacent circuit breakers will open, which may result in the outages of equipment that should remain intact in the network. Such effects analysis procedure can be repeated for all system substations under various initial system faults. As a result, all contingencies resulting from *CBTM* hidden failures and the corresponding conditional probabilities, given the occurrence of initial system disturbances, can be obtained. We have extended the *SCAE* methodology to allow the assessment of bulk power system reliability, which explicitly includes the effects of protection system hidden failures, contingencies resulting from *CBTM* hidden failure outages along with other system contingencies.

The proposed approach is demonstrated on a breaker-oriented 24-substation reliability test system. This breaker-oriented system model is derived from the original IEEE 24-bus reliability test system (*RTS*). Each node (bus) of the original system is replaced with a substation that has specific bus arrangement (ring, breaker and a half, and so on). As a result, the bus arrangement at each node and the location of each circuit breaker becomes the explicit part of the system network model. Based on the breaker-oriented system model, the effects analysis of *CBTM* hidden failures is performed for each substation. We consider three different levels of *CBTM* hidden failure probabilities to illustrate the impacts of different *CBTM* hidden failure probability levels on bulk power system reliability. After all the contingencies resulting from *CBTM* hidden failures are identified, the extended security-constrained adequacy evaluation methodology is applied to evaluate all contingencies. Evaluation results show that hidden failures in protection systems can substantially downgrade the system reliability level and such influence increases as the *CBTM* failure probabilities become larger.

3. The Economic Dimensions of Reliability and Security Evaluation

Security and reliability management is a highly challenging task, and even more so with the prominence of electricity markets. As system and market operations strongly interact, any change in the system security or reliability impacts the economics and vice-versa. While the nature of these interactions is well understood on a qualitative basis, the quantification of the system security or reliability impacts on the overall economics of electricity markets is, typically, not performed. In this work, we develop an approach to quantify the interactions between system security and the performance of electricity commodity markets. This approach provides meaningful measures of the financial, as well as, the resource dispatch impacts of a change in the security criterion. Moreover, we also provide some important insights into the estimates of the value of reliability. The research demonstrates what markets can and cannot do in identifying and achieving the desired level of reliability, and it also demonstrates through system simulations of experimentally derived behavior how markets, particularly those with RTP, can enhance the operability of existing systems and reduce the capacity requirements of emerging ones.

3.1 The Economic Impacts of System Security

The wide geographic spread and large-scale nature of the new regional transmission organizations, or *RTO*s, or of the earlier independent system operators, or *ISO*s, require the explicit representation of the areas that make up the system as well the tie lines that interconnect them in the studies aimed to assess system security aspects. We use the generic term of independent grid operator or *IGO* to refer to such central entities. The *IGO*'s responsibilities include both system and market operations, with a strong focus on system reliability. The *IGO* must maintain and ensure the security of the multi-area system by the effective balancing of the interconnected areas' generation and demand while maintaining the frequency of the system within acceptable bounds, the voltages within the required ranges and the operation of each component within its appropriate rating under both base case and the postulated contingency case conditions. System security is defined as the ability of the interconnected system to provide electricity with the appropriate quality under normal and contingency conditions. Security is a time-dependent phenomenon and is a function of the robustness of the system with respect to imminent disturbances – the so-called contingencies. For the operating state corresponding to a snapshot of the system, the security assessment analyzes whether the occurrence of any of the postulated contingencies results in the violation of any operational constraints, and whether such violations may be removed by dispatching appropriate preventive or corrective security control actions. A preventive control action associated with a postulated contingency entails the modification of the pre-contingency – base case – state, to eliminate any potential violation, were that contingency to occur. On the other hand, an associated corrective control action involves the deployment of generation redispatch/load curtailment to modify the post-contingency state only after the contingency actually occurs. For certain contingencies, such as a generator outage or a sudden change in load, the *IGO* may take only corrective control actions.

Security assessments are, typical, based on a deterministic criterion, such as ($n-1$) or ($n-2$) security. We associate with each security criterion a specific contingency list and a specified control action for every contingency on that list. For example, the contingency list of the ($n-1$) criterion consists of all single element contingencies while that of the ($n-2$) criterion considers all double element contingencies in addition to the single element contingencies. Since all the contingencies on the ($n-1$) list are also included in the ($n-2$) contingency list, the ($n-2$) is considered to be the stricter criterion. Virtually every system operator uses, at the very least, some modified ($n-1$) list of single line outages and preventive control to deal with their impacts. But, in many instances, a stricter criterion is imposed, such as a modified version of the ($n-2$) criterion with only a subset of all the double element contingencies considered. The elements of this subset are carefully selected to include contingencies that are particularly critical for the multi-area structure of the system, such as the outages of pairs of tie lines interconnecting an export and an import area. In this paper, we consider a wide range of security criteria, which are representative of the practices of various *IGO*s. But, the situation is more complicated because of the need to consider the markets managed by the *IGO*.

In this paper, we consider the typical day-ahead market, or *DAM*, structure widely adopted in North American markets in which uniform price auctions are used for market clearing side by side with the provision of transmission services to the bilateral transactions. Such a situation represents the ISO New England (ISO-NE), the PJM-ISO and the New York ISO (NY-ISO). In these markets, the sellers and the buyers submit their offers and bids, respectively, indicating their willingness to sell or to buy specified quantities of electricity at specific locations. The bilateral transactions requesting transmission service from the *IGO* also provide their willingness to pay for the service. The *IGO* then determines the market clearing and transmission service provision so as to maximize the social welfare, subject to the operational constraints for the base and the contingency cases under the security criterion.

As power system operations must comply with the security criterion, a change in the security criterion typically results in changes in the market outcomes brought about by to the changes in the contingency list and associated control action for each postulated contingency. Consider the case in which the *IGO* operates the system under ($n-1$) security. The power flows associated with the provision of transmission services to the bilateral transactions and the market clearing are such that no violations occur for the loss of a single element in the system making full use of the preventive control capability. But, under a stricter security criterion, which includes double element outages in the contingency list, a decrease in the transfer capabilities between export to import areas from those in the ($n-1$) criterion may result. Consequently, the power flows must respect the decreased transfer capabilities. As such, the various market participants in the export and the import areas may be impacted differently in terms of financial and dispatch results. For the case with all the demands fixed, the purchases of the import areas' buyers reflect the decreased import capabilities. Consequently, the buyers increase purchases from the native resources, typically, at higher prices. Hence, the overall costs to supply electricity increase with respect to the costs in the ($n-1$) security, and therefore the market efficiency decreases. When the demand is price responsive, and so no longer

fixed, some buyers in the import areas may procure less energy whenever their willingness to pay is exceeded by the offer prices of the sellers of the area's native resources. In a similar vein, some of the export area buyers, who have low willingness to pay, may nevertheless procure more energy when their willingness to pay exceeds the prices offered by the export area sellers whose sales decrease due to the lowered transfer capabilities. As a result, the market efficiency changes from that of the $(n-1)$ security case. In either the fixed or the price responsive demand case, some market participants may gain and others may lose as a result of the change in the security criterion. The basic thrust of this study is to quantify the changes in the electricity market performance due to a change in the security criterion.

In this work, we explicitly consider the system security from the point of view of the *IGO*. We emulate the way the *IGO* currently operates both the system and the markets under a specified security criterion. We ignore the probability of any contingency in the studies that replicate the *IGO* actions. We develop an approach to quantify the interactions between the specified system security criterion and the *DAM* outcomes taking explicitly into account the outages of tie lines interconnecting the multi-area system. The quantification provides measures of the financial and resource dispatch impacts of a change in security criterion vis-à-vis those corresponding to a reference security criterion. For a specified security criterion, we use the snapshot representation of the system for an hour and solve the so-called security constrained *OPF* (*SCOPF*) problem to maximize social welfare while satisfying the operational constraints for each contingency case and the base case. The solution of the *SCOPF* serves to compute the values of a set of metrics that evaluate the market performance under the specified security criterion. These metrics include the financial impacts and resource dispatch impacts on both a system and an area basis. We evaluate the changes in the values of the metrics under each security criterion considered with respect to those under the reference criterion. We extend the hourly snapshot analysis to a longer period to observe the diverse market outcomes due to changes in the unit commitment decisions, network parameters, the set of resources, the market participants' behavior and the exogenous parameters, such as fuel and emission costs. We illustrate the proposed approach to quantify the impacts of different system security criteria on the *ISO-NE DAM* performanc*e* for representative days in 2005 period. The study establishes an explicit link between the system security criterion and the market efficiency impacts. The results of this study indicate that the power system may be operated under a stricter criterion without adversely impacting the economic efficiency of electricity markets when price responsive demand and appropriate control actions are present.

We have prepared a publication that summarizes the scope of the work on this topic. The summary appears below.

Güler, Teoman, Gross, George, Litvinov, Eugene, and Coutu, Ron "Multi-Area System Security: The Economic Impacts of Security Criterion Selection," submitted for review to *IEEE Transactions on Power Systems.* (PSERC 06-52)

The increasing attention paid to reliability in regional transmission organizations provides the impetus for the investigation of stricter security criteria in the operation of the large-scale multi-area systems. However, as system and market operations strongly interact, a change of the system security criterion impacts the economics and vice-versa. While the nature of the interactions between system and market operations is well understood qualitatively, the quantification of the system security impacts on the overall economics of electricity markets is, typically, not performed. In this paper, we develop a general approach to quantify the impacts of different security criteria on market performance using the day-ahead markets. The quantification provides meaningful measures of the financial and the resource dispatch impacts on both a system and an area basis. We illustrate the proposed approach on the *ISO-NE* system in the quantification of the comparative impacts of two different security criteria for the 2005 day-ahead markets. Through this study, we gain insights that the power systems may be operated under a stricter criterion without adversely impacting the economic efficiency of electricity markets.

3.2 The Economic Impacts of System Reliability

From surveys of the existing literature, the use of optimization models of simplified electricity networks, the experimental analyses of buyer and seller behavior and the numerical calibrations and simulations of these results, the following conclusions can be drawn:

- The value of electricity purchased, typically, far exceeds the average price paid. Therefore, the value of lost load exceeds, by many times, the price paid for electricity.
- The reliability of electricity supplied over a network in terms of unanticipated interruptions and voltage and frequency stability have certain public good attributes, and therefore a central authority must establish their desired level.
- In most cases, the provision of reliability-enhancing services can be decentralized and left to market forces, provided that the proper public values are reflected in the prices paid to suppliers, either indirectly through mandated levels of reliability or directly through regulatory induced supplements.
- The value lost through interruptions is a function not only of their frequency, but also of their duration and the number of contiguous neighbors affected.
- The provision of real-time prices of electricity to customers can reduce both the installed generation capacity and the transmission line capacities. For example, we have shown for a particular system a reduction in peak generation capacity of 7.5% and the capacity of individual transmission lines of from 6 to 7%, based on a Monte Carlo simulation using experimentally derived buyer and seller behavior.

Some results concerning the value of reliability and of its constituent components, plus their public goods aspects, are derived jointly from this project and through analytic work and numerical simulations carried out and extended from a separate PSERC project M-12, "Reliability, Electric Power and Public vs. Private Goods". The results are detailed in a number of publications. We provide a brief summary of each of these publications.

> **Toomey, David, Schulze, William, Schuler, Richard, Thomas, Robert and Thorp, James "Reliability, Electric Power, and Public versus Private Goods: A New Look at the Role of Markets",** ***Proceedings of the 38th Hawaii International Conference on System Sciences,*** **January 2005. (PSERC 05-72)**

Adopting the perspective of an all-knowing system planner, the model determines the optimal generation capacity, transmission line capacity and size and location of capacitors that need to be installed and operated in order to maximize the net benefits to society of providing electricity service. Prior analyses of customers' willingness to pay for electricity and damage functions from high or low voltage and over or under frequency are combined in the objective, and the physical laws governing the transportation of electricity, together with generators' capability curves to provide energy and/or *VAr*s, are used as constraints in this model that endogenously determines the optimal level of reliability for the system. This approach still understates the full value of reliability since it only reflects the value of lost load and estimated damage to user equipment, and not the cost of added uncertainty borne by customers every time there is an unanticipated outage. Nor does the analysis reflect explicitly the added external costs of extended outages or the social interaction/dependency costs of contiguous customers being interrupted.

Nevertheless, the qualitative aspects of the analysis demonstrate that from a customer's viewpoint, freedom from unanticipated outages, and voltage and frequency stability all have public goods aspects when these services are provided jointly to nearby customers off of the same network. Although different customers may have different demands for these services, they all receive the same level in a given neighborhood. Thus individuals have incentives to over- or under-state their true preferences in order to "free ride" on the average cost of the service actually provided. Therefore, it is up to a central authority to set the standard for the desired levels of these components of reliability, but having done that, the actual provision of the services that together comprise reliability (*kWhs*, *Var*s, and installed generation, line and capacitor capacity, by location), can be decentralized and provided efficiently through market-like mechanisms, provided that there are sufficient suppliers to make those markets behave competitively.

> **Adilov, Nodir, Light, Thomas, Schuler, Richard, Schulze, William, Toomey, David and Zimmerman, Ray "Differences in Capacity Requirements, Line Flows and System Operability under Alternative Deregulated Market Structures: Simulations Derived from Experimental Trials",** ***Proceedings of IEEE Power Systems Conference and Exposition,*** **San Francisco, June 12-16, 2005. (PSERC 05-38)**

What has been shown in subsequent experimental analyses is that by providing customers with the ability to be active participants in the market, either through pre-arranged demand-reduction programs (DRP), where upon announcement, a specified credit is provided for each reduction in usage below a benchmark, or through real-time pricing (RTP) initiatives, customers can reduce price spikes and improve the competitiveness of those markets, even in cases where only 20% of the buyers are active participants. The behavioral results from this previous PSERC project (M-7), "Structuring Markets for Demand Response", were extended by simulating the effects on the operation of the IEEE 30-bus grid used in PowerWeb exercises. While the locations of generators were maintained at the identical six separate busses for each simulation, thirty different randomly selected assignments of buyers who had widely different consumption patterns were made in order to infer the consequences for a range of possible system characteristics. Each simulation had separate demand patterns for day and for night, and 11 day/nite pairs of experimental results were available for each of the thirty configurations, or a total of 22 flow patterns for each assignment.

Then, under each of the market clearing structures, DRP and RTP were compared with a simulated cost-based regulatory dispatch in response to fixed, constant average-cost-based prices that have been typical in any regulated regimes. Both the maximum flows on each line and the maximum generation demanded were taken as a surrogate for the determinants of installed line and generation capacities under each regime. This analysis suggests that under both DRP and RTP, on average a 6 to 7% reduction in required line capacity would have been obtained, as compared to the regulated regime with fixed prices. Furthermore, the RTP regime required 7.5% less generating capacity as compared to the regulated regime with fixed prices. These implied reductions were derived despite the fact that under the active demand participation regimes, there were no restrictions on the generators' behavior (no prohibitions of withholding capacity from the market, nor price caps), whereas under the regulated regime, all suppliers offered all of their capacity at its marginal cost. The results can lead to inferences either about reductions in required capacity, and therefore reductions in costs to the buyers, or about possible improvements in reliability.

Schuler, Richard "Two-Sided Electricity Markets: Self-Healing Systems", in H. Richardson, P. Gordon, and J. Moore II, eds., *Economic Costs and Consequences of Terrorist Attack*, E. Elgar, Cheltenham, U.K. (forthcoming 2007). (PSERC 05-50)

This paper summarizes some of the above results and also draws on actual operational experience in Australia suggesting that since real-time prices are inversely correlated with system frequency, that under widespread use of RTP, many customers might install frequency-sensing devices which could lead to self-correcting automatic demand responses to sudden drops in supply capability.

4. Short-Term Resource Adequacy

The electric system is said to be reliable when consumers receive all the electricity they demand with the desired quality. The study of electric system reliability consists of the investigation of system security and system adequacy. Security is the ability of the system to withstand sudden disturbances. Adequacy is the ability of the system to meet the aggregate customer demand. Resource adequacy addresses the need to have "sufficient" resources in place to meet the forecasted demand taking into account the uncertainty of the environment and the salient characteristics of electricity, including the lack of large-scale storage and the limited demand responsiveness of load to price. Under the conventional vertically integrated structure, the reliability decisions were the responsibility of the utility that owned and operated the resources and the transmission network. In the market environment, an independent entity, which we refer to by the generic term independent grid operator, or IGO, is responsible for system reliability. Our focus is on the resource adequacy of the system over a short period of the order of months. For such periods, the resource mix remains fixed and the only decision variables for ensuring resource adequacy are the offered capacities of the existing supply sources and demand bids of price responsive buyers in electricity markets.

Under restructuring, resource adequacy assurance has become very complex, as seen in the 2000–2001 California electricity crisis. Capacity is at the heart of both the energy and the capacity-based ancillary services markets. Since sellers need not offer all their capacity to serve the demand, they may engage in so-called *physical capacity withholding* or *capacity gaming*. Any withholding action impairs the reliability, and consequently the short-term resource adequacy depends on market player behavior. In fact, absent the formulation of specific rules, withholding may result in capacity deficiency, which has become a concern in various jurisdictions. FERC's attempts to guide market design recognize the importance of the resource adequacy issue to well functioning markets.

Current resource adequacy tools fail to explicitly consider the interactions between market design, the behavior of market players and system reliability. To overcome this deficiency, we construct an analytical framework for short-term resource adequacy that explicitly considers the interactions between markets and reliability. The framework models both the physical world by representing the contribution of the resources and the load demand to reliability, and the market world, by including the market design, the market players' behavior and their interactions with the physical world. In this way, we can develop explicit relationships between economics and resource adequacy. We illustrate the capabilities of the framework by using it to assess the impacts of market player behavior on reliability on various test systems.

We make use of the framework to propose a design of a short-term resource adequacy program for electricity markets. The proposed design harnesses market forces to provide short-term resource adequacy and in doing so establishes an *explicit linkage between*

reliability and economics. The design aims to overcome some of the key deficiencies identified in the programs implemented for the short-term period of our focus.

The results of the work are summarized in two papers that were prepared to address the needs for analysis tools for the design and implementation of resource adequacy programs for the short-term period of our focus.

> **Ruiz, Pablo A. and Gross, George "An Analytical Framework for Short-Term Resource Adequacy in Competitive Electricity Markets," *Proceedings of the IX Probabilistic Methods Applied to Power Systems (PMAPS) Conference*, Stockholm, June 11 -15, 2006. (PSERC 06-09)**

Short-term resource adequacy, a key component of system reliability, is the ability of a system with a fixed resource mix to meet the load at all times. In the competitive environment, the interaction of markets and reliability has raised this issue to new prominence. Market design influences significantly the behavior of market players, which, in turn, impacts the capacity adequacy of the system. Current resource adequacy tools fail to explicitly consider the interactions between the market design, the behavior of market players and system reliability. We construct an analytical framework for short-term resource adequacy that explicitly considers the interactions between markets and reliability. The framework models both the physical world by representing the resources and the load demand, and the market world, by including the market design, the market players' behavior and their interactions with the physical world. We explicitly represent the strategic behavior of market participants to make the results realistic. We use the framework to assess the impacts of market player behavior on various test systems. Representative results are provided from the simulation studies to illustrate that the impacts of market factors on resource adequacy can be very significant.

> **Ruiz, Pablo A. and Gross, George "A Proposed Design for a Short-Term Resource Adequacy Program," submitted to *IEEE Transactions on Power Systems*. (PSERC 06-37)**

Short-term resource adequacy is the ability of a system with a set of given resources to meet the load over the short term. In the aftermath of the 2000–2001 California crisis, focus on resource adequacy has come to the forefront of market design issues. Various approaches, such as capacity requirements, capacity payments and financial options requirements, have been proposed to ensure resource adequacy in electricity markets. We propose a design of a short-term resource adequacy program based on capacity requirements expressed in terms of a price sensitive demand curve. A "carrots and sticks" approach is used to give incentives for providing capacity to markets and mete out penalties for non-performance situations. The probabilistic modeling of the uncertainty in the availability of generating resources and in the load allows the evaluation of reliability in terms of well-known metrics. Through the explicit representation of the strategic behavior of market players, capacity withholding impacts are directly measurable. The analysis of the proposed design and the simulation of a simple implementation show that the program results in improved reliability. Reduction of the total system costs results

when key program parameters are appropriately selected. We have tested the proposed design via simulation on test systems ranging from 10 to 100 generators, and under different conditions. In every case on each tested system, the implementation of the design results in reliability improvements. Extensive sensitivity studies in which various parameter values are widely varied indicate that reduced total system costs can be attained with the proposed program when the parameter values are judiciously selected. We illustrate the impacts of the program with representative results on different sized test systems. The design and analysis work of this paper serves as a useful tool in the assessment and the enhancement of short-term resource adequacy programs. As such, it constitutes a contribution in reliability economics and furthers the state of the art in electricity market design.

5. System Planning: Reliability Considerations

Adequacy planning of interconnected power systems is important to avoid congestion and consequent lack of reliability. Therefore it is important that the ISOs guide the process of adding generation and transmission facilities, so that the new units are located in a way that they can provide the highest reliability benefits at the least cost. Thus economic considerations and reliability constraints both need to be included in such planning. Although tools have been proposed in the past for expansion planning, they do not include explicit considerations of reliability considerations. Since reliability represents a probabilistic constraint, its incorporation renders the problem of optimization more complex. Since optimization may require repeated calculation of reliability indices for various scenarios, development of efficient reliability analysis techniques is important. Also, there exists a need to translate reliability into equivalent costs, therefore development of interruption cost method logic is also important. Therefore this research effort has focused on the following activities:

- development of an efficient evaluation technique for reliability;
- development of an efficient optimization procedure for expansion; and,
- methodology to explicitly include the interruption costs.

The method used for reliability evaluation is an enhanced version of the decomposition process that partitions the state space of the interconnected system into disjoint subsets of failure and non-failure states. The enhanced procedure is called the global decomposition and is based on the observation that decomposition is governed by state capacities and not by probabilities. This allows the development of a more generic state space to include all possible scenarios from which information for various scenarios may be extracted for the given reliability data. The various optimization techniques investigated are dynamic programming, smart scenario comparison, meta-heuristic techniques, and combination of dynamic programming and meta-heuristics. These optimization techniques have been appropriately integrated into the global decomposition procedure. The interruption cost calculation is deployed to translate the effects of failures into cost. The idea of customer damage function curves this purpose using both the frequency and duration of failure states. A method has been developed to compute these values for a randomly sampled state.

Thus the focus on adequacy planning has led to the development of efficient reliability evaluation tools, interruption cost calculation methodology, and optimization techniques for the explicit inclusion of the uncertainty-based reliability constraint. The efforts in this area have resulted in four publications. We provide their titles and respective summaries below.

Jirutitijaroen, Panida and Singh, Chanan "Reliability and Cost Trade-Off in Multi-Area Power System Generation Expansion Using Dynamic Programming and Global Decomposition", *IEEE Transactions on Power Systems*, vol. 21, no. 3, August 2006. (PSERC 06-32)

To avoid congestion problems, it is important that the additional generation and transmission facilities be planned and implemented considering reliability in addition to cost considerations. In the new restructured environment, the ISO/*RTO*s may guide this process of adequacy planning but need suitable tools. This paper proposes dynamic programming to determine the location of generators in multi-area power systems with global decomposition as a reliability evaluation tool. This paper introduces a powerful reliability analysis tool where a single round of decomposition may be used as the basis of reliability computations when additional generators are considered. The original generation probability distribution in each area is modified to incorporate additional generators. An equation relating the number of additional units in each area to generation probability distribution is developed in this paper. After global decomposition, an equation for reliability is derived and approximated. The problem structure is transformed and solved by dynamic programming.

Jirutitijaroen, Panida and Singh, Chanan "A Global Decomposition Algorithm for Reliability Constrained Generation Planning and Placement", *Proceedings of the IX Probabilistic Methods Applied to Power Systems (PMAPS) Conference*, Stockholm, June 11 -15, 2006. (PSERC 06-33)

Adequacy planning of multi-area systems avoids congestion problems leading to inadequate levels of reliability of power supply. This paper develops a comparison algorithm for selecting the *best* generation placements utilizing global decomposition method for reliability index calculation. A smart scenario analysis algorithm is proposed to determine the *best* generation combination. In this algorithm comparison is made concurrently with global decomposition process to improve computational efficiency and reduce memory requirements. The proposed comparison algorithm is validated by application to a 12-area system.

Jirutitijaroen, Panida and Singh, Chanan "A Hybrid Method for Multi-Area Generation Expansion using Tabu-search and Dynamic Programming", *Proceedings of the 2006 International Conference on Power System Technology*, Chongqing, China, October 2006. (PSERC 06-34)

Both classical and heuristic optimization techniques have been applied to solve the generation expansion problem but these do not generally include explicit consideration of reliability considerations. Recently, the application of dynamic programming to optimally locate the prospective generators in multi-area power systems while utilizing global decomposition as a reliability evaluation tool has been proposed. However, in this approach the optimization is applied to a subset of the state space and may not guarantee global optimality since the reliability index is simplified and approximated. Tabu search is one of many heuristic techniques applied to the generation expansion problem. It has

been recognized as an efficient method for combinatorial optimization problems. The algorithm is powerful due to the flexible forms of memory in the search space. The search performance, however, depends on a good starting solution. This paper combines Tabu search with the solution from dynamic programming to obtain optimal solution. The comparison between using randomly generated starting solutions and solution from dynamic programming is made. The method is then implemented for an actual 12-area power system.

Jirutitijaroen, Panida and Singh, Chanan "Multi-Area Generation Adequacy Planning Using Stochastic Programming", *Proceedings of the 2006 IEEE PES Power Systems Conference and Exposition*, Atlanta, Georgia, October 2006. (PSERC 06-35)

Optimization methods have been previously applied to solve generation expansion planning but these do not explicitly include system reliability considerations. The formulation accounting for the uncertainty in generation capacities and load has appeared in the stochastic programming literature but the consideration of reliability indices is not included. In the past, the problem was formulated as a two-stage recourse model where the first stage decision variables are the additional capacity units and the second stage decision variables are the network flows. The objective is simply to minimize the expansion costs in the first stage and operation costs in the second stage without considering the reliability indices.

In this paper, the problem is also formulated as a two-stage recourse model but unlike the previous methods, this formulation does not require generation to meet the demand at every instant. Instead, the problem formulation maximizes the reliability with the available resources, i.e., minimizes the expected loss of load costs subject to the available expansion budget. We note that this reliability index is also a stochastic variable and minimizing this index makes the problem more challenging than incorporating the uncertainties in system capacities and load. The overall objective is to minimize expansion costs in the first stage and at the same time to minimize expected loss of load costs in the second stage. The L-shaped algorithm is applied to solve the problem. This paper also introduces a technique of including the cost of interruptions within the framework of sampling. The problem is implemented on a three-area power system.

6. Conclusions

This section recaps the accomplishments of the project and outlines directions for future work. The broad range of topics investigated in this project has engendered considerable contributions to advance the state of the art in the reliability and security modeling and tool development areas and to provide a concrete linkage between reliability and economics. The research results obtained from this project provide members with a number of specific benefits. These include:

- an improved understanding of the impacts of congestion on bulk power reliability;
- an explicit evaluation of the impacts on system reliability of remedial actions and protection system hidden failures;
- a useful scheme in security evaluation for the detection of island formation and the identification of causal factors under multiple line outages;
- an explicit evaluation of the impacts of different security criteria on the market performance economics thereby providing the benefit/cost justification for a selected security criterion;
- design of a short-term resource adequacy program, which takes into account both the physical and market factors that impact reliability; and,
- the development of planning tools to optimally site generation resources taking into account congestion impacts.

In the following paragraphs, we state the summary results for each of the topics and provide suggested directions for future work.

In the area of reliability and security assessment modeling, we made major thrusts in the creation of new methodologies and tools. We developed a closed-form analytic expression for generalized *LODF*s under multiple-line outages without the reevaluation of post-outage network system parameters. This general expression allows the computationally efficient evaluation of *LODF*s under multiple-line outages for security application purposes and is particularly useful for the study of blackouts impacting large geographic regions. The development is important in light of the prominent role of cascading outages in recent blackouts, which has created a critical need in security applications for the rapid assessment of multiple-line outage impacts. We further applied the notion of generalized *LODF*s to construct a combined graph-theoretic-algebraic approach to detect island formation in power system networks under multiple line outages. The ability of the new method to detect island formation and to identify the causal factors is very useful in both on-line and off-line environments so as to effectively deal with the many complications that arise from island formation. When the outages of multiple lines result in the formation of two or more islands, the method is able to identify which outaged lines cause the system separation. In cases where several lines are outaged and no island formation occurs, the method can identify whether a set of candidate line outages separates the system into islands. Such identification provides the information needed for the deployment of appropriate tools for security analysis and

control. A salient characteristic of the proposed approach is the low computing requirements. The extension of the work to the determination of all the nodes of the formed islands is a topic worth investigating in future work.

The work on the incorporation of remedial action effects and the explicit representation of hidden failures of the protection system made possible the development of new computationally efficient tools for contingency simulation and effect analysis. The results of the approach that incorporates hidden failures indicate that the impacts of hidden failures on the reliability of the system and congestion are rather substantial. This work has identified a number of additional modeling and research issues that need to be addressed in future research projects. These are detailed in the publication prepared. In the modeling work, an important issue that needs to be investigated is the effective representation of the maintenance scheduling of generating units and transmission equipment/facilities. The complexity of this issue arises from the decentralized decision-making associated with the diverse ownership of generating units and the strategic aspects of scheduling the maintenance under competitive electricity market conditions.

The work on economic impacts of system security provides a concrete basis for the linkage of economics to reliability. The proposed approach for the assessment of market performance under a specified security criterion and for the quantification of the impacts of a system security criterion change on the performance of the electricity markets represents a very valuable tool to entities such as *RTO*/*ISO*s. The proposed approach quantifies the *MW* as well as the market efficiency impacts of the security criterion change and has a wide range of applications. These include the studies for the justification by the *RTO*/*ISO* to modify its decision for the selected security criterion and for the cost/benefit analysis of network improvements to mitigate the impacts of specific contingencies. Our investigations on the application of the approach provide important insights into the role of price responsive demand and that of the security control actions. In fact, we conclude that the power systems may be operated under a stricter criterion without adversely impacting the economic efficiency of the day-ahead markets when price responsive demand and appropriate control actions are present.

As the real-time energy markets, or *RTM*, become more prominent, the comparative assessments of a security criterion change have to be broadened to include the impacts on *RTM*. To be able to accomplish this broadened scope, the incorporation of a multi-settlement system involving the *DAM* and the *RTM*, is required. In addition, the growing impacts of bilateral transactions also need to be explicitly considered in the quantification of security criterion change impacts. The studies extending the proposed approach to incorporate the multi-settlement system and the bilateral transactions need to be part of the future work in this area.

The work on the economic impacts of system reliability provides estimates of the value of reliability, it demonstrates what markets can and cannot do in identifying and achieving the desired level of reliability, and it also demonstrates through system simulations of experimentally derived behavior how markets, particularly those with real-time pricing, can enhance the operability of existing systems and reduce the capacity

requirements of emerging ones. Thus, if implemented, these results can lead to greater system reliability, ease of operation and reduced cost. One extension of these analyses is to examine further the translation between the socially optimal system configuration and particular reliability-based regulations and rules, both in form and level (e.g., system-wide reserve margin vs. locational designations). A second analysis consists of explicitly accounting for customer demand response in establishing operating and reliability rules that might vary with the fraction of customer (load) participation by location.

In the area of short-term resource adequacy, we have developed a framework, which takes into account both the physical and market factors that impact reliability. We explicitly represent the strategic behavior of market participants to make the results realistic. The simulation studies indicate that the impacts of market factors on resource adequacy can be very significant. The work serves as a useful aid in resource adequacy assessment in electricity markets and in the design and enhancement of short-term resource adequacy programs. We apply the framework to propose a design of a short-term resource adequacy program. In the analysis and simulation of the program, we explicitly assessed the impacts of the strategic behavior of market participants. The program implementation improves reliability with respect to the case without a resource adequacy program. Moreover, the total system costs can be reduced if the tunable program parameters are appropriately chosen. The proposed design with the ability to evaluate the linkage between reliability and markets contributes to the developing area of electricity market design.

The extensions of the work include the incorporation of demand responsiveness to price, multiple strategic sellers' interaction, uncertainty in the strategic sellers' information, inter-hour relationships, transmission network effects and generation maintenance into the models. In addition, the incorporation of models for generation investment would allow the study of long-term resource adequacy, which remains a critical need for the industry in the competitive environment.

The proposed design can also be extended in various useful directions. Some key areas are the incorporation of demand responsiveness to price, multiple seller interactions, inter-hour relationships and transmission network effects into the models. With the extended modeling, the basic design can be further extended to include the capacity credits providers' geographic location and the price responsiveness characteristics of the various demand-side players. Another area for further research is the formulation, analysis and comparison of different *(i)* capacity requirements that appropriately account for the benefits capacity provides to the system, *(ii)* effective penalty schemes that provide the desired disincentives for non-compliance, and *(iii)* market compatible short-term resource adequacy programs, using forward contracts and call options, for example. Also, there is a need to investigate the market power opportunities arising with the design implementation and their impact on resource adequacy, and to devise effective mitigation schemes to discourage/ prevent them, whenever applicable. In particular, we will investigate the impacts of double price caps in the optimization of the tunable parameters, so as to gain insights into the relationship between market power mitigation rules and

reliability. Finally, the extension of the work to long-term resource adequacy can provide a basis for solving a critical need for the industry in the competitive environment.

The research on the consideration of reliability in system planning has led to more efficient reliability evaluation techniques for multi-area models, development of optimization techniques including reliability constraints, and development of methodology to incorporate the effect of costs of interruptions. This output of the research effort relates to all the four objectives of the proposed research. These techniques may be used by the industry and particularly by the *ISO*/*RTO*s to reduce the impacts of congestion on reliability.

So far the reliability technique used with optimization is analytical. The direction of future research needs to study the use of Monte Carlo sampling where expected cost of load loss is approximated by considering only sampled scenarios and evaluated in the optimization. The estimated objective value is called sample-average approximation of the actual expected value. The investigation of the usability of such an approach in bigger networks and the more detailed modeling of networks and other flow calculation techniques will be the topics for future work.

List of Project Publications Summarized in this Report

Adilov, Nodir, Light, Thomas, Schuler, Richard, Schulze, William, Toomey, David, and Zimmerman, Ray. "Differences in Capacity Requirements, Line Flows and System Operability under Alternative Deregulated Market Structures: Simulations Derived from Experimental Trials", *Proceedings of IEEE Power Systems Conference and Exposition*, San Francisco, June 12-16, 2005. (PSERC 05-38)

Güler, Teoman and Gross, George. "Detection of Island Formation and Identification of Causal Factors under Multiple Line Outages," *IEEE Transactions on Power Systems*, vol. 22, no.1, February 2007. (PSERC 06-38)

Güler, Teoman, Gross, George and Liu, Minghai. "Generalized Line Outage Distribution Factors," accepted for publication in *Letters, IEEE Transactions on Power Systems*, vol. 22, no.1, February 2007. (PSERC 06-39)

Güler, Teoman, Gross, George, Litvinov, Eugene, and Coutu, Ron. "Multi-Area System Security: The Economic Impacts of Security Criterion Selection," submitted for review to *IEEE Transactions on Power Systems.* (PSERC 06-52)

Jirutitijaroen, Panida and Singh, Chanan. "A Global Decomposition Algorithm for Reliability Constrained Generation Planning and Placement", *Proceedings of the IX Probabilistic Methods Applied to Power Systems (PMAPS) Conference*, Stockholm, June 11 -15, 2006. (PSERC 06-33)

Jirutitijaroen, Panida and Singh, Chanan. "A Hybrid Method for Multi-Area Generation Expansion using Tabu-search and Dynamic Programming", *Proceedings of the 2006 International Conference on Power System Technology*, Chongqing, China, October 2006. (PSERC 06-34)

Jirutitijaroen, Panida and Singh, Chanan. "Multi-Area Generation Adequacy Planning Using Stochastic Programming", Proceedings of the 2006 IEEE PES Power Systems Conference and Exposition, Atlanta, Georgia, October 2006. (PSERC 06-35)

Jirutitijaroen, Panida and Singh, Chanan. "Reliability and Cost Trade-Off in Multi-Area Power System Generation Expansion Using Dynamic Programming and Global Decomposition", *IEEE Transactions on Power Systems*, vol. 21, no. 3, August 2006. (PSERC 06-32)

Meliopoulos, A. P., Yang, Fang, Cokkinides, George J. and Dam, Q.B. "Effects of Protection System Hidden Failures on Bulk Power System Reliability", *to be submitted.* (PSERC 06-51)

Ruiz, Pablo A. and Gross, George. "A Proposed Design for a Short-Term Resource Adequacy Program," submitted to *IEEE Transactions on Power Systems.* (PSERC 06-37)

Ruiz, Pablo A. and Gross, Gross. “An Analytical Framework for Short-Term Resource Adequacy in Competitive Electricity Markets,” *Proceedings of the IX Probabilistic Methods Applied to Power Systems (PMAPS) Conference*, Stockholm, June 11 -15, 2006. (PSERC 06-09)

Schuler, Richard. “Two-Sided Electricity Markets: Self-Healing Systems”, in Richardson, H., Gordon, P., and Moore II, J., eds., *Economic Costs and Consequences of Terrorist Attack*, Edgar Elgar, Cheltenham, U.K. (forthcoming 2007). (PSERC 05-50)

Toomey, David, Schulze, William, Schuler, Richard, Thomas, Robert, and Thorp, James. “Reliability, Electric Power, and Public versus Private Goods: A New Look at the Role of Markets”, *Proceedings of the 38th Hawaii International Conference on System Sciences*, January 2005. (PSERC 05-72)

Yang, Fang, Meliopoulos, A.P., Cokkinides, George J. and Stefopoulos, George K. “Contingency Simulation Using Single Phase Quadratized Power Flow”, *Proceedings of the IX Probabilistic Methods Applied to Power Systems (PMAPS) Conference*, Stockholm, June 11 -15, 2006. (PSERC 06-50)

Yang, Fang, Meliopoulos, A.P., Cokkinides, George J. and Stefopoulos, George K. “Security-Constrained Adequacy Evaluation of Bulk Power System Reliability”, *Proceedings of the IX Probabilistic Methods Applied to Power Systems (PMAPS) Conference*, Stockholm, June 11 -15, 2006. (PSERC 06-49)