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

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

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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 *RTOs*/*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