Consequence and Impact of Electric Utility Industry Restructuring on Transient Stability and Small-Signal Stability Analysis

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Invited Paper

The electric utility industry is undergoing unprecedented changes in its structure worldwide. With the advent of an open market environment and competition in the industry, and restructuring of the industry into separate generation, transmission, and distribution entities, new issues in power system operation and planning are inevitable. One of the major consequences of this new electric utility environment is the greater emphasis on reliability and secure operation of the power system. This paper examines the impact of restructuring on power system dynamic analysis. It specifically addresses issues related to transient stability analysis and small-signal stability analysis. Four major topics to examine the effect on the nature of studies conducted are considered. These topics are 1) system adequacy and security, 2) system modeling data requirements, 3) system protection and control, and 4) system restoration. The consequences and impact of each of these topics on the nature of the studies conducted are examined and discussed. The emphasis on greater reliability has led to a clearer enunciation of standards, measurements, and guides in some countries. These requirements will result in: 1) more measurements on existing systems, 2) rigorous analysis of transient stability and small-signal stability to determine operating limits and plan systems, 3) greater emphasis on studies to verify coordination and proper performance of protection and controls, and 4) development of a detailed plan for system restoration in the case of wide-spread outages.

Keywords**—***Deregulated environment, dynamic performance, power system dynamics, restructuring, stability criteria, steady-state stability, transient stability.*

I. INTRODUCTION

The electric utility industry in several countries has undergone a major change in their vertically integrated structure. In other countries, the industry is in the process of restructuring. The major consequence of restructuring is the emergence of separate entities for generation, transmission, and distribution. This has resulted in greater competition, emphasis on efficiency and reliability, and the development of a market structure for trading and supplying electrical energy. In many countries, the generation market has been deregulated however, there is some level of regulation in the transmission and distribution sectors. The primary goal of this restructuring is to increase competition, and provide the customer a quality product at a competitive price. The quality of the product is measured by several characteristics. Reliable and uninterrupted service to the loads constitutes one of the important characteristics. Reliability is composed of two aspects: 1) adequacy and 2) security. *Adequacy* is the ability of the electric systems to supply the aggregate electrical demand and energy requirements of their customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements. *Security* is the ability of the electric systems to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements. Security analysis is an important ingredient of power system operation and planning. It is composed of both steady-state and dynamic security analysis. Transient stability analysis and small-signal stability analysis are essential components of security analysis. A great deal of effort is put into these analyses to ensure reliable and secure planning and operation of electric power systems. In this paper, the consequences and impact of restructuring on the aspects of security analysis specifically relating to transient stability analysis and small-signal stability analysis will be examined. Restructuring and the renewed emphasis on reliability have resulted in governing bodies dealing with establishing power system operation and planning criteria in various countries reexamining existing criteria and setting more stringent criteria in terms of compliance standards. In North America, the North American Reliability Council (NERC) has approved a document called the NERC Planning Standards [1]. The British Grid system is managed by the National Grid Company

Manuscript received April 29, 1999; revised August 15, 1999.

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Publisher Item Identifier S 0018-9219(00)00836-7.

(NGC) as the grid operator. Under its transmission license, NGC must establish, implement, comply and ensure compliance with the Grid Code [2] which covers all material technical aspects relating to the connections, operation, and use of the transmission system. In [3] (pp. 24–28), a description of the international criteria and practices for system reliability in various European countries is given. These criteria and standards will be used as a guide to examine the impact and consequences of restructuring on the nature and requirements for transient stability and small-signal stability studies.

A brief overview of how stability studies evolved and became an important aspect of power system analysis is provided below. Problems associated with dynamic performance were noticed in power systems when synchronous machines were first operated in parallel. Hunting was a serious problem. The pulsating torque delivered by direct connected steam engines gave rise to hunting. The seriousness of this problem was alleviated by the use of damper windings. The problem disappeared with the advent of steam turbines, which have no torque pulsations. An excellent review of the history and the development of the stability problem can be found in [4]–[6]. The problem of power system stability became important when long-distance transmission from remote hydroelectric stations started supplying metropolitan load centers. Since about 1920, the problem of power system stability was the object of thorough investigation. Some of the important steps in the analytical development in the early years included, circle diagrams, improved synchronous machine modeling, point-by-point solution of differential equations, equal area criterion, and the ac network analyzer. The advent of the commercial and scientific use of the digital computer in the 1960's also resulted in the computer-based analysis of stability problems. The November 1965 blackout in the Northeastern part of the U.S., followed by another extensive blackout in another area in 1967, had a profound effect on the electric utility industry all around the world. Many questions were raised such as: Are planning criteria valid? Are design concepts adequate? Should interconnections between power systems be increased or should they be eliminated? These blackouts also led to an era in which great emphasis was placed on modeling of power system components and detailed simulation studies. Several excellent textbooks and references that provide a detailed description of the modeling and simulation efforts are available [3], [7]–[9].

Following the restructuring of the electric utility industry in North America, NERC has developed a new set of Planning Standards. These were approved in September 1997. These standards address four main topics.

1) System Adequacy and Security.
2) System Modeling Data Requirements.
3) System Protection and Control.
4) System Restoration.

Each main topic contains several subtopics. Unlike previous NERC reliability criteria [8], (Section 1.4), the new NERC planning standards consist of three items for each subtopic.

1) Standards—which state the fundamental requirements for planning reliable interconnected bulk electric systems.
2) Measurements—which define the required actions or system performance necessary to comply with the standards.
3) Guides—which describe good planning practices and considerations.

This paper will not attempt to focus on the NERC planning standards, but will use their approach and philosophy to emphasize the new issues which arise due to restructuring, and the implications in terms of engineering manpower, expertise, data needed, and types of analyses that will need to be conducted. In addition, there are several countries which have criteria similar to that of NERC. One aspect of the NERC planning standards that is directly impacted by deregulation is that the standards have now become more specific than in the past, and the differences between the different NERC reliability areas are considered in some depth. This clearly illustrates the fact that reliability criteria to some extent are system dependent and should be tailored to fit the needs and requirements of each system. The development of these standards or criteria will necessarily have to be an evolutionary process with continual additions, changes, and deletions. One important impact of the restructured environment with regard to reliability criteria deals with the recognition that the new competitive electricity environment is fostering an increasing demand for transmission services. With this focus on transmission and its ability to support competitive electric power transfers, all users of the interconnected transmission system must understand the electrical limitations of the transmission systems and their capability to support a wide variety of transfers. The studies conducted in the future would support planning and operating functions to provide requested electric power transfers while maintaining overall system reliability.

The paper has the following structure. A brief introduction to stability analysis is provided in Section II; objectives of the analysis are presented in Section III; Section IV describes implications with regard to system adequacy and security; system modeling and data requirements are presented in Section V; the important aspect of coordinated protection and control is discussed in Section VI; Section VII presents issues related to system restoration; and finally, conclusions are presented in Section VIII.

II. OVERVIEW OF POWER SYSTEM STABILITY ANALYSIS

The following definitions from [11] provide the foundation for transient stability and small-signal stability analysis.

1) *Disturbance in a Power System.* A disturbance in a power system is a sudden change or a sequence of changes in one or more of the operating parameters of the system, or in one or more of the operating quantities.
2) *Small Disturbance in a Power System.* A small disturbance is disturbance for which the equations that de-

Fig. 1. Transient and steady-state stability.

scribe the dynamics of the power system may be linearized for the purpose of analysis.

3) *Large Disturbance in a Power System.* A large disturbance is a disturbance for which the equations that describe the dynamics of the power system cannot be linearized for the purpose of analysis.
4) *Steady-State Stability of a Power System.* A power system is steady-state stable for a particular steady-state operating condition if, following any small disturbance, it reaches a steady-state operating condition which is identical or close to the pre-disturbance operating condition. This is also known as small disturbance stability of a power system.
5) *Transient Stability of a Power System.* A power system is transiently stable for a particular steady-state operating condition and for a particular disturbance if, following that disturbance, it reaches an acceptable steady-state operating condition.

From the above definitions, one observes, as shown in Fig. 1, that the transient stability problem encompasses the small-disturbance stability problem. The transient stability analysis involves more detailed nonlinear models, solution techniques, and includes steady-state stability analysis of the operating condition that will be reached following the transient.

A. Rotor Angle Stability

Based on the above definitions, one observes that instability in a power system can occur in a variety of ways depending on the system configuration and operating conditions. Traditionally, the stability problem has been associated with maintaining synchronous operation. In the evaluation of stability, the concern is the behavior of the power system when subjected to a disturbance. The disturbance may be small or large. This aspect of stability is influenced by the dynamics of the generator rotor angles and the power-angle relationships and is referred to as rotor angle stability. Further details of rotor angle stability analysis can be found in [7]–[9]. This stability problem deals with the study of the electromechanical oscillations inherent in power systems. The fundamental factor in this analysis is the characterization of the variation of the power or torque outputs of synchronous machines as their rotors oscillate.

In a large power system with numerous synchronous machines, transmission lines, and loads, and the complexity of the consequences of any disturbance, one may tend to think that it is hopeless to attempt analysis. However, the time scales of various phenomena allow a decomposition of the problem on the key elements affecting dynamic behavior. The first step in a stability study consists of obtaining a suitable mathematical model of the system during the transient. The elements included in the model should provide a characterization of the acceleration (or deceleration) of the synchronous machine rotors. The complexity of the model is a function of the phenomena being investigated. In general, the components of the power system that influence the electrical and mechanical torques of the synchronous machines are included in the model. These components are listed below.

1) The transmission network before, during, and after the disturbance.
2) The loads and their characteristics.
3) The parameters of the synchronous machines.
4) The control components of the synchronous machines (excitation systems, power system stabilizers).
5) The mechanical turbine and the speed governor.
6) Other power plant components that influence the mechanical torque.
7) Other control devices, such as supplementary controls, special protection schemes, and FACTS (Flexible AC Transmission System) devices that are deemed necessary in the mathematical description of the system.

The number of power system components included in the analysis and the complexity of their mathematical models is dependent on several factors. References [7]–[9] provide detailed descriptions of these factors. In general, however, a coupled system of differential-algebraic equations are used to represent the system with it components. Study of the dynamic behavior of the system depends on the nature of these differential equations.

1) *Small-signal (small-disturbance) stability* is the ability of the power system to maintain synchronism under small disturbances. Instability can result in the form of 1) steady increase in rotor angle due to lack of sufficient synchronizing forces, or 2) rotor oscillations due to lack of sufficient damping forces. In today's power systems, small-signal stability is largely a problem of insufficient damping of oscillations. The analysis is conducted by considering a suitable model and linearizing the governing equations at the steady-state operating point to obtain a system of equations given by

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \tag{1}$$

where $\mathbf{x}$ is an n-dimensional vector denoting the states of the system and $\mathbf{A}$ is a coefficient matrix. The system inputs are represented by the m-dimensional vector $\mathbf{u}$, and the effect of these inputs on the differential equations is represented by an $n \times m$ matrix $\mathbf{B}$. Several conventional linear analysis techniques are used to analyze the above system of equations. Several different types of oscillations are of concern. They include the following:

a) local modes or machine-system modes;
b) interarea modes;
c) control modes;
d) torsional modes.

For further details, the reader is referred to [7]–[9].

2) *Transient stability* is the ability of the power system to maintain synchronism when subjected to large disturbances. The system equations for a transient stability study are usually nonlinear. Here, the system is described by a large set of couples nonlinear algebraic differential equations of the form

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{f}(\mathbf{x}, \mathbf{y}, \mathbf{u}, t) \\ \mathbf{0} &= \mathbf{g}(\mathbf{x}, \mathbf{y}, \mathbf{u}, t). \end{aligned} \tag{2}$$

Determining the dynamic behavior of the system described by (2) is a more difficult task than that of the linearized system of (1). Usually, numerical solutions of the system of nonlinear algebraic differential equations are obtained. Stability of synchronous machines is usually decided by the behavior of the rotor angles. Fig. 2 shows the rotor angle plot of a synchronous machine in the 50-Generator IEEE Test System [10] obtained from transient stability analysis. Case 1 corresponds to a disturbance following which the generator is transiently stable. Case 2 corresponds to a transiently unstable disturbance.

B. Voltage Stability

Instability may also be encountered without loss of synchronism. A system could become unstable because of the collapse of voltages at certain buses in the system. In this instance, the concern is stability and control of voltage. The analysis in this case deals with the ability of the power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to disturbances. The main factor causing instability is the inability of the power system to meet the demand for reactive power. Further details of this analysis can be found in [8], [12], and [13]. A paper [14] in this Special Issue also discusses the impact of restructuring on voltage stability.

C. Mid-Term and Long-Term Stability

The concepts of mid-term stability and long-term stability are relatively new to the literature on power system stability. They were introduced as a result of the need to deal with problems associated with the dynamic response of power systems to severe upsets [8], [15]–[20]. These upsets result in large excursions of voltage, frequency, and power flows. Hence, their analysis must include the actions of slow processes, controls, and protection schemes not modeled in conventional transient stability studies.

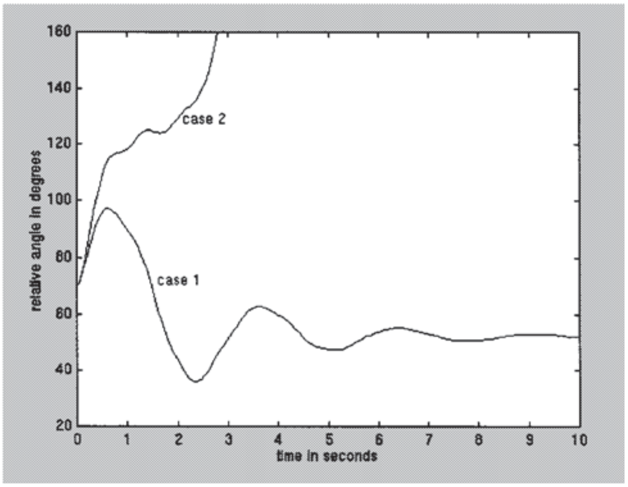


Fig. 2. Rotor angle stability.

1) *Long-Term Stability* analysis assumes that inter-machine synchronizing power oscillations have damped out, the result being uniform system frequency. The analysis focuses on the slower and longer-duration phenomena accompanying large system upsets and on the resulting large, sustained mismatches between generation and load. The modeling requirements for this analysis include boiler dynamics of thermal units, penstock and conduit dynamics of hydro units, automatic generation control, power plant and transmission system protection and controls, transformer saturation, and off-nominal frequency effects on load and the transmission network.
2) *Mid-Term Stability* analysis includes the transition between transient and long-term responses. The focus is on synchronizing power oscillations between the synchronous machines, including the effects of some of the slower phenomena, and possibly large voltage or frequency excursions.

Fig. 3 presents a classification of the typical ranges of time periods for the different types of stability analysis.

There is limited experience related to the analysis of long-term and mid-term stability. In the restructured environment the need to perform such analysis will increase since there will be greater emphasis on providing limits and answers to all parties involved in the various transactions. This issue will also be discussed in other sections.

III. OBJECTIVES OF RELIABILITY CRITERIA AND STABILITY ANALYSIS

Typically, reliability criteria and the analysis described in Sections II and III are intended to apply primarily to the bulk electric systems. Because of the individual character of the electric system in different parts of the world, in different regions within a country, in different subregions with a region, in different power pools within a subregion, and in dif-

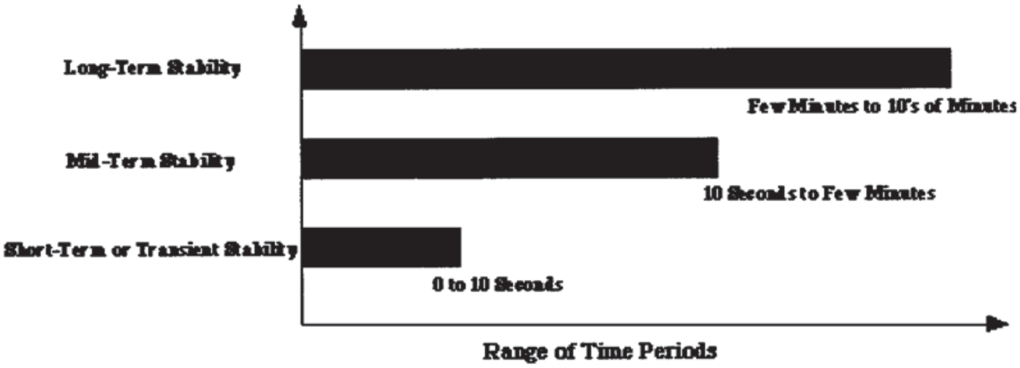


Fig. 3. Classification of types of stability.

ferent members within a power pool, each entity typically defines those facilities that are to be included as its bulk electric system for which application of the stability analysis will be required. The general definition of the bulk electric system is as follows: the bulk electric system is a term commonly applied to that portion of an electric utility system, which encompasses the electrical generation resources, transmission lines, interconnections with neighboring systems, and associated equipment generally operated at voltage of 100 kV or higher.

The bulk power systems are the principal media for achieving reliable electric supply. They interconnect the major electric system facilities, generation resources, and customer demand centers. These systems must be planned, designed, and constructed to operate reliably within thermal, voltage, and stability limits (the overview of the stability analysis conducted was given in Section II) while achieving their major objectives. These objectives are listed below.

1) *Delivery of electric power to areas of customer demand*—Transmission system provide for the integration of electric generation resources and electric system facilities to ensure reliable delivery of electric power to continuously changing customer demands under variety of system operating conditions. With restructuring, there will be increase customer demand from areas of the interconnected system where prices are high. These customers will seek low cost energy suppliers.
2) *Provide flexibility for changing system conditions*—Transmission capacity must be available on the interconnected transmission systems to provide flexibility to handle the shift in facility loading caused by maintenance of equipment, forced outages of equipment, and a variety of system variable conditions, such as construction delays, higher than expected customer demands, and generating unit fuel shortages. With competition and trading of electricity on the open market, the change in system conditions will have a greater range of uncertainty. In a typical scenario, when buy and sell bids are matched between a consumer and a supplier, there will be need to guarantee that there is sufficient transmission capability to conduct this transaction without jeopardizing the reliability of the entire system. This aspect takes on even more significance when the electricity is wheeled across states or provinces and over independently operated transmission systems. The entity responsible for maintaining the reliability of the transmission system will have to predict such scenarios and conduct analyses to evaluate limiting conditions in the system. The limits would typically have to be posted twenty four hours before the bids are confirmed. This will result in a need for conducting studies to provide reliable operating limits in a shorter period of time.
3) *Reduced installed generating capacity*—Transmission interconnections with neighboring systems allow for sharing of generation resources through diversity in customer demands and generator availability, thereby reducing investment in generation facilities. This is one of the primary objectives of electric utility restructuring. In countries where the electric utility industry was privatized, customers in different states were paying vastly different prices for the same commodity. Since the industry was regulated, these customers were constrained to buy electricity from the regulated supplier in their geographical region. With the growing disparity between rates and with the hope that a less regulated environment will spur competition, restructuring was introduced. It was envisioned that a flexible market place with open transmission access would provide better opportunities for both consumer and providers. Suppliers who can provide lower cost generation will seek customers currently paying higher costs. This would hopefully bring down costs. However, it would impose new challenges with regard to providing sufficient capability to transport electricity from the provider to the customer. This would relax the burden of high cost on the customer, it would spur competition among the providers, but would result in new constraints dealing with possible transmission bottlenecks.
4) *Allow economic exchange of electric power among systems*—Transmission interconnections between systems allow for economic exchange of electric power among all systems and participants. Such transfers are critical in reducing cost of electric supply to customers. This objective is the driving force behind competition. There will be increased transfers, and the

transmission system has to provide the pathways to allow the exchange while maintaining expected levels of reliability.

The new environment of competition will place an increasing demand on transmission services. With this focus on transmission and its critical role in supporting competitive electric power transfers, it will be imperative that all users of the interconnected transmission system must understand the electrical limitations of the transmission systems in supporting a wide variety of transfers. The challenge will be to plan and operate transmission systems to provide the requested electric power transfers while maintaining overall system reliability. In the following sections the impact of restructuring on various aspects of power system planning and operation dealing with stability analysis will be examined in greater detail.

IV. SYSTEM ADEQUACY AND SECURITY

The impact of restructuring on stability analysis related to the determination of system adequacy and security will be reflected in the following subtopics.

1) Transmission Systems.
2) Reliability Assessment.
3) Facility Connection Requirements.
4) Voltage Support and Reactive Power.
5) Transfer Capability.
6) Disturbance Monitoring.

Each one of these subtopics will be examined in greater detail to study the consequences and impact of restructuring on stability studies related to these subtopics.

A. Transmission Systems

The transmission systems are the critical pathways in delivering electric power from the generators to the loads. As pointed out in the previous section, the demand on these systems will increase. They will also be subjected to a wide variety of expected system conditions. As a result, the transmission system will have to be planned and operated to withstand the more probable forced and maintenance outages at projected customer demand and anticipated electricity transfer levels. Since there is greater uncertainty in terms of customer demand and transfer levels due to the competitive environment, there will be a need to perform a wider range of stability studies. In addition, a need arises to develop better techniques to account for the uncertainty in operating conditions. Extreme but less probable contingencies measure the robustness of electric systems and should be evaluated for risks and consequences. The stability techniques currently in use are deterministic in nature and do not provide a convenient measure of risk. They also do not account for the probability of occurrence of an extreme contingency. The current analysis tools also do not provide any index to measure the consequence or impact of these less probable events. Hence, there is a definite need to incorporate risk analysis and account for the impact of the event in stability analysis. Preliminary research [21], [22] related to these aspects have shown encouraging results. There will be a greater need to analyze the system more thoroughly and verify the ability of the transmission system to withstand probable and extreme contingencies by simulated testing of the systems. An added complexity in the analysis is that the time window to perform the analysis in the restructured environment will be quite small compared to the current environment where the transactions were largely firm transactions. With open access the entities in charge of maintaining transmission system reliability will have to provide answers regarding allowable transfers in a shorter time frame. This may require different analytical approaches to stability analysis that could analyze or screen contingencies faster than conventional techniques. Direct methods [23], [24] of transient stability analysis fall under this category. Recent efforts [25], [26] have been successful in implementing these approaches in an online environment.

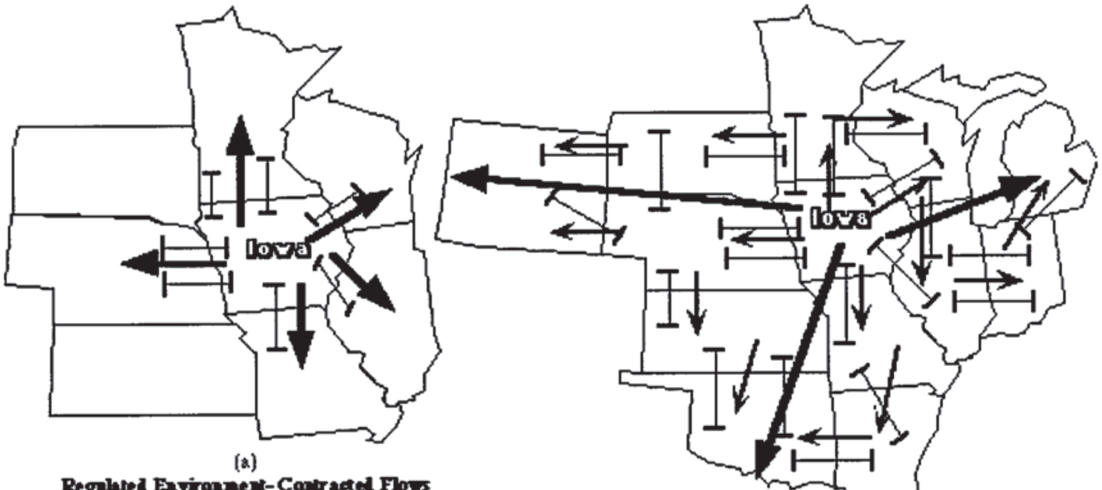
The restructured environment and the associated increase in uncertainty of operating conditions will result in a more comprehensive assessment of normal and contingency conditions. This would require more detailed analysis including a larger number of scenarios and variables to be conducted putting a greater burden on trained manpower and computational requirements. Since transfers could be taking place over larger geographical areas, the size of the system being analyzed will increase. With the increase in system size, transfers, and loading on the system, dynamic phenomena could increase in complexity, e.g., incidence of large interarea oscillations could increase. Adequate analytical techniques to detect such phenomena and analyze them in detail will need to be developed. Fig. 4 provides a schematic description of this need. With the increased transfers across the system, as shown in Fig. 4(b), the loop flows increase, and a large geographical area would need to be studied to accurately determine transmission limits.

B. Reliability Assessment

Entities responsible for regional bulk system reliability will have to assess reliability within the context of interconnected networks. With open access, there will be a greater need for individual members within a region to coordinate assessment efforts not only within their region, but also with neighboring systems and regions. This will put greater emphasis on cooperation between neighboring regions to maintain reliability. The trade off between this requirement and the need to compete will be complex.

C. Facility Connection Requirements

All facilities involved in the generation, transmission, and use of electricity must be properly connected to ensure reliability of the interconnected system. There will be a greater responsibility for entities that specify reliability to develop standards and guides, and also compliance requirements for generation and transmission owners and electricity end-users with regard to facility connection and performance. This will result in a greater need for inspection and documentation of facility connection requirements.



(a)
Regulated Environment- Contracted Flows

(b)
Restructured Environment - Contracted Bids
& Loop Flows

Fig. 4. Restructured environment and transmission limits.

D. Voltage Support and Reactive Power

Reactive power sources must be distributed throughout the electric system among the generation, transmission, and distribution facilities, as well as at some customer locations. Because of the greater uncertainty in reactive power demands and facility loading there will be a need to develop more efficient techniques to analyze reactive power problems. There will also be a greater need to coordinate reactive power demand. This topic is addressed in greater detail in [14]. For the generation owner, there will be a greater need to 1) coordinate generator step-up transformer impedance and tap specification and settings, 2) calculate underexcited limits based on stability considerations, and 3) ensure the availability of the full range of reactive power capability for normal and emergency network voltage ranges. Transmission owners will have to design and plan adequate reactive power reserves in anticipation of system disturbances. This will result in a need for more detailed analysis and studies.

E. Transfer Capability

The success of the competitive market environment hinges on the availability of adequate transmission services. The availability of these services must be based strictly on the physical and electrical characteristics and capabilities of the interconnected transmission networks and should be planned and operated reliably using appropriate system criteria and guides. In order for the electricity market to be commercially viable, the constraints on the transmission system should be available to the market participants. These constraints would also need to be posted in advance so that the market players can utilize them to make their bids. In the US these will be posted on the Open Access Same Time Information System (OASIS). These constraints are calculated through computer simulations of the interconnected transmission systems under a specific set of system conditions. These simulations will need to be conducted off line for both the operating horizon and the planning horizon periods. This type of analysis combines several aspects of stability studies. The transmission constraints will need to include thermal, voltage, and stability limits. The constraint is based on the most constraining limit. This type of calculation imposes several new issues that did not exist in the deregulated environment. The calculations will have to satisfy certain principles that balance both technical and commercial issues. New requirements will be imposed on the analysis. The best available information on anticipated system configuration and conditions for the time of the study will need to be developed and used. Base system conditions including customer demands, generation dispatch, system configuration, and firm transmission services will need to identified and modeled. In determining transfer capabilities contingencies throughout the interconnected system will have to be evaluated. There will be a greater emphasis on documenting the guideline and procedures for calculating and updating the transmission constraints. Known conditions in other systems that affect transmission constraints should be taken into account. This type of analysis will greatly increase the analysis done by entities that ensure transmission system reliability. It will also greatly increase the trained manpower requirement.

F. Disturbance Monitoring

Recorded information about transmission system faults or disturbances is essential to determine the performance of system components and to analyze the nature and cause of a disturbance. In the past, some utilities had developed concrete plans to acquire and install disturbance monitoring equipment [27], [28]. In the restructured environment, requirements will be established to install disturbance monitoring equipment to determine performance and causes of system disturbances on a regional basis. Requirements will also be placed on providing disturbance monitoring data for the purpose of developing, maintaining, and updating transmission system models on a regional basis. This requirement will definitely result in greater capital investment in disturbance monitoring equipment. There will also be a need to develop a consistent format to exchange data. The requirement for monitoring is an evolutionary process and locations for additional data monitoring will be identified. A procedure to validate and update models using the monitored data will have to be developed. The results obtained from stability studies using the updated models will also have to be compared to the monitoring data. This again reflects on the trained manpower requirement to continually update models.

V. SYSTEM MODELING DATA REQUIREMENTS

A critical ingredient in performing any stability analysis is the system data. The accuracy of the analysis is dependent on the quality of the data available. In the previous section, some of the major reliability and security analysis issues have been identified. Since model data plays such a crucial role in the accuracy of the analysis, and with the increase in the players in the competitive market environment, new data requirements will be placed on simulation models for system components, system configuration, customer demands, and electric power transactions. These requirements can be broadly classified according to the following subtopics.

1) System Data.
2) Generation Equipment.
3) Facility Ratings.
4) Actual and Forecast Demands.
5) Demand Characteristics (Dynamic).

We will now examine the issues associated with each one of these subtopics.

A. System Data

Complete, accurate, and timely data is needed for system stability analyses to ensure reliability and security of the interconnected transmission systems. Requirements will be placed on identifying the scope and specificity of the steady-state and dynamics data required for reliability analyses. A procedure for reporting data will also have to be developed [29]. All users of the interconnected transmission system will have to provide appropriate equipment characteristics. The data requirement to conduct studies on a regional basis would be huge. The development of a database will be critical. Dynamics data will also have to include appropriate control system data and will have to be consistent with reported steady-state data. The requirements for data will continually change. The requirements and procedures will need to be revisited on a regular basis, reviewed, and documented for all users of the interconnected transmission systems.

B. Generation Equipment

Accurate, validated generator models and data are essential for planning and operating studies to ensure electric system reliability [30]. Generating capability to meet projected demands and to provide the required amount of capacity margins is essential to ensure reliability. This capability will have to be accounted for in an uniform manner that ensures the use of realistically attainable values when planning and operating the systems or scheduling equipment maintenance. Synchronous generators are the primary means of voltage and frequency control [31]–[42]. The correct operation of generator controls is crucial in preventing cascading outages. Hence, there is stringent requirement on the accuracy of the data. Similar requirements will also be placed on the generator reactive power capability for voltage limits [43]–[50]. This need to have accurate generator data will impose new requirements to test and verify data used for stability studies. Requirement will also be placed on measuring and validating data on a regular basis (e.g., once in five years). This testing will have to done by all generation owners. It increases the need for trained manpower to perform the testing and also verify the models.

C. Facility Ratings

Knowledge of facility ratings is essential for the reliable planning and operation of the interconnected transmission systems. These ratings provide acceptable electrical loading on equipment, before, during, and after system disturbances, and together with the constraints on stability and voltage determine the ability of the system to deliver electric power to meet customer demands. In the new environment facility owner will have to document the procedures for determining facility ratings. Facility owners will also have to provide facility ratings for all facilities required in system modeling. These ratings would have to be updated based on weather assumptions and seasonal conditions.

D. Actual and Forecast Demands

Actual customer demand data is needed for forecasting future system requirements, reliability assessments of past system events, and validation of databases. Forecast customer demand data is used for system modeling and the analysis of the security of the interconnected transmission systems. These data include hourly, monthly, and annual demands and monthly and annual net energy for load. This data will be required in a variety of forms aggregated regional, subregional, power pool, individual system, or on a dispersed transmission substation basis. In addition, the portion of the demand that is part of the controllable demand-side management and which may be interrupted by system operators will also be required in evaluating security of the interconnected systems. Information regarding the assumptions, methods, and accounting of uncertainty in developing the forecasts for aggregated peak demands and net energy for load will have to be provided to the regions.

E. Demand Characteristics (Dynamic)

Various components of customer demand respond differently to changes in system voltage and frequency. This demand is also affected by seasonal and time-of-day characteristics. Accurate characterization of the customer demand is needed in system modeling for stability studies. The entities responsible for reliability of interconnected systems will have to develop plans to incorporate frequency and voltage characteristics of customer demand, and determine the procedure and schedules for data reporting. Load serving entities will provide customer demand characteristics to entities responsible for reliability. This requirement places new emphasis on load serving entities to provide a more accurate representation of the customer demand for stability analysis. In the current environment many utilities assumed a certain percentage of constant current, constant impedance, or constant MVA representation for the real power and reactive power portion of the demand at each node in the analysis. This requirement will require more tests to be conducted and procedures to be developed to obtain a more accurate characterization of the loads.

VI. PROTECTION AND CONTROL

Protection and control systems are critical components in ensuring reliable operation of the interconnected transmission networks. Protection systems include relays, fuses, circuit breakers, and switches. These systems are designed to automatically detect and isolate components from the transmission network following electrical faults or disturbances in order to protect equipment from damage due to voltage, current, or frequency excursions outside the designed limits. Control systems automatically adjust or maintain system parameters within pre-defined limits. Protection and control systems should have the following characteristics shown in Fig. 5.

Protection and control system reliability is greatly enhanced by incorporating redundancy. This is, however, a double-edged sword and should be carefully designed. Increased redundancy improves dependability but it can also decrease security through greater complexity and greater exposure to component failure. Protection and control system reliability is also a function of the testing and maintenance practices. A vital aspect of the protection and control system reliability is the proper coordination of protection and control systems. The transmission system reliability could be seriously affected by misoperation due to uncoordinated protection and control systems.

In the restructured environment, there will be a greater need to coordinate the design of protection and control systems with the overall design and operation of the generation and transmission systems. In the past, some of the severe upsets which have occurred in power systems have originated in protection and control systems. With greater emphasis being given to avoid these severe upsets in the restructured environment, there is a need to develop appropriate techniques to determine and prevent hidden faults in protection and control systems. In addition, in the recent past several utilities have successfully attacked reliability problems with the use of special protection schemes, these include generation rejection, load rejection, fast valving, breaking resistors, etc. In the competitive environment the renewed emphasis on reliability will increase reliance on such special protection schemes. Hence, there will be a greater need to coordinate and design their operation with protection and control components.

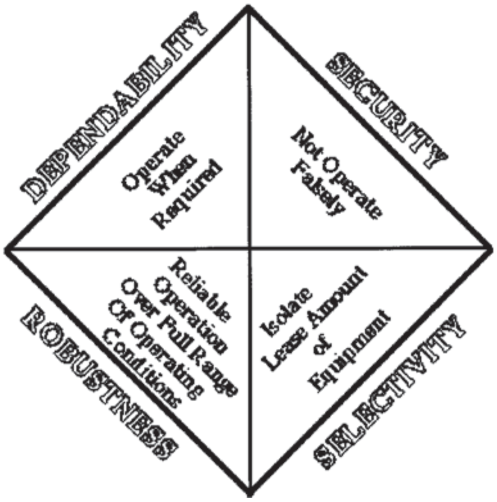


Fig. 5. Protection and control system characteristics.

Traditionally, many transient stability programs have provided for the representation of certain types of relays. These include load shedding relays, under frequency load shedding relays, voltage difference load dropping relays, under frequency generation rejection relays, under frequency line tripping relays, impedance distance relays, series gap capacitor relays, and rate of change of power relays. With regard to control systems, conventional transient stability programs offer a wide range of control models. They also provide the flexibility to develop user defined models for components for which models are not provided in the program. In conducting studies however, utility companies have largely modeled those protection systems that are relevant to a particular problem in the system. A comprehensive representation of the various protection systems and an analysis of the coordination between protection and control systems is rarely done. Entities involved in ensuring transmission system reliability will need to expand the scope and level of details of their analyses in order to design and operate reliable systems.

The requirement pertaining to protection and control systems will be further examined using the following subtopics.

1) Transmission Protection Systems.
2) Transmission Control Devices.
3) Generation Control and Protection.
4) Underfrequency Load Shedding.
5) Undervoltage Load Shedding.
6) Special Protection Systems.

A. Transmission Protection Systems

The protection systems will need to be provided to ensure the performance requirements set by entities responsible for ensuring reliability. There will be a greater need to provide redundancy, analyze misoperations, and develop maintenance and testing programs. In order to provide proper coordination more emphasis on representing relays in stability studies will have to be placed. In addition the analysis will also have to focus on coordination between protection and control systems.

B. *Transmission Control Devices*

These devices provide dynamic control of system quantities. They are typically devices involving feedback control mechanisms, and utilize modern power electronics to provide appropriate response. These devices fall under the category of FACTS [51]–[53]. They include, HVDC links, unified power flow controllers (UPFC), static var compensators (SVC), thyristor controlled series capacitors (TCSC), etc. These devices are very fast acting and have the capability to significantly affect power system dynamic performance. In order to design and operate the system including these components it is essential to accurately model the components in stability studies. The HVDC link representation has been studied in great detail, and excellent modeling capability exists in this area. In terms of the other devices, some models exist. This however, is an ongoing area of research and development. There is also a need to carefully analyze the impact of such devices on system dynamic behavior. Since these devices are capable of making dramatic changes in very short periods of time careful analysis should be done to verify that these devices initiate no complex dynamic phenomena. Currently, the design of these devices is largely done without taking into account the coordination with other control and protection systems. New approaches will need to be developed to coordinate the design procedure. The design will also need to include the effect of system uncertainty and guarantee robustness.

C. *Generation Control and Protection*

Excitation and prime mover control play a key role in maintaining power system reliability. The generator protection system must be coordinated with these controls to minimize generator tripping during disturbances. The excitation system provides voltage control, and the prime mover control primarily controls the system frequency. Excellent models to represent these controls exist. There however is a important need to coordinate these controls with the generator protection systems. In addition, effort will be needed to validate the parameters used for these models in stability studies. Several instances of major outages in the past few years have shown the importance of accurately representing the over excitation limits. Greater emphasis will be placed on analyzing generation protection [54], [55] and control system misoperations.

D. *Underfrequency Load Shedding*

Underfrequency load shedding is key element in preserving the security of the generation and interconnected transmission systems during major disturbances which involve declining system frequency [56]–[58]. In this situation, the load is typically greater than the generation available, and the frequency declines. Load shedding is essential to minimize the risk of a total system collapse, and to protect expensive generation and transmission equipment against damage. The coordination and control of load shedding is important. This is needed in order to balance available generation and customer demand. In the competitive environment there will be a need to plan and implement underfrequency load shedding on a regional basis. It would also have to be carefully coordinated with generation control and protection systems, undervoltage load shedding programs, transmission protection and control systems, and load restoration programs. This will significantly increase the complexity of the analysis.

E. *Undervoltage Load Shedding*

Heavily loaded transmission systems with limited reactive power supply experience low voltages and are susceptible to voltage instability. Such instability can result in tripping of generators and transmission facilities resulting in customer interruptions. Voltage collapse can also occur suddenly, and usually there is not sufficient time for operator actions. In such situations automatic load shedding schemes are activated [12, ch.7], [59]–[60]. In the competitive environment, the transfers across the system will increase. The vulnerability to voltage problems will be higher. Hence, similar to the underfrequency load shedding discussed above, a need exists to carefully coordinate and design an undervoltage load shedding program.

F. *Special Protection Schemes*

The importance and the relevance of such schemes were discussed at the beginning of this section. In the restructured environment there will be greater emphasis on designing and operating the special protection schemes [8, ch.17], [61]–[63] to ensure reliability and prevent cascading outages. It should be noted that special protection schemes are usually introduced in systems where stability or other problems are known to exist. Misoperation of such system will result in severe system conditions. The special protection schemes will also have to be carefully coordinate with other protection and control systems. This again involves the inclusion of the special protection schemes in stability studies along with the other protection and control systems increasing the complexity and scope of the analysis.

VII. SYSTEM RESTORATION

System restoration [64]–[66] will also be an important factor in the restructured environment. Since generators outside the load area could supply loads any major interruption of the transmission network connecting the load to the generators will require careful analysis in order to restore supply to the load. The major interruptions or blackouts could take place as a result of dynamic instability, steady-state overloads, or voltage collapse. Blackouts could also occur at a variety of operating conditions. Once a blackout occurs it is important to identify resources that would be needed to restore the load, determine the coordination required between these resources, and develop a plan to systematically restore the system. The system restoration function has the following two important aspects:

1) System Blackstart Capability.
2) Automatic Restoration of Load.

A. System Blackstart Capability

If a complete system blackout occurs, and all the generation is lost, it will be necessary to establish initial generation that can supply electric power to other system generation to handle the supply to the auxiliaries in the power plant, the coal handling equipment, etc. These generators are called blackstart generators and must have the capability to self-start without any source of off-site electric power. These generators should also have the capability to maintain adequate voltage and frequency while supplying isolated transmission facilities and auxiliary loads of other generators. In order to provide this capability a coordinated system blackstart capability plan will need to be estabilished, maintained, and verified through analysis. The analysis will check the ability of the blackstart units to perform the required function in system restoration plans. This type of analysis would again involve conducting more cases, examining a wide variety of scenarios, and developing a comprehensive blackstart capability.

B. Automatic Restoration of Load

With the increased emphasis on providing better service to the customer, it would be important to develop a properly coordinated and implemented, automatic load restoration plan. This would require careful analysis and should be coordinated with the recovery of voltage and frequency. This would also require careful analysis of the settings of relays used to restore load automatically, sequence in which tie lines are restored, and the impact of restoring large blocks of customer demand. This would again require careful stability analysis. It would also need longer terms studies and would include modeling of the frequency control equipment.

VIII. CONCLUSION

This paper has provided a fairly detailed description of the issues that will impact transient stability analysis and small-signal stability analysis in the restructured utility environment. Several important aspects related to maintaining the reliability and security of the bulk electric systems have been identified and analyzed. The consequences and impact of these issues on transient stability analysis and small-signal stability analysis have been discussed in detail. A summary of these impacts are provided below.

1) Analysis of systems of large size and complexity because of the economy transfers.
2) Incorporate risk and probability in the analysis for extreme events.
3) Use of faster techniques to analyze stability such as Direct methods.
4) Increased complexity of analysis in determining transfer limits.
5) Greater emphasis on monitoring and measurement to verify and validate simulation models.
6) Enormous burden of conceptualizing, building, and maintaining database.
7) Stringent requirement of validating model data with measured data.
8) More accurate forecast of customer demand.
9) Comprehensive incorporation of protective and control systems in stability studies.
10) FACTS elements could give rise to complex dynamic phenomena requiring development of new analytical methods of analysis.
11) Emphasis on coordinated protective and control system design leading to increase in scope and complexity of stability studies.
12) Development of coordinated system restoration plans.

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