PSERC

Consortium for Electric Reliability Technology Solutions

Grid of the Future White Paper on

Real Time Security Monitoring and Control of Power Systems

Prepared for the
Transmission Reliability Program
Office of Power Technologies
Assistant Secretary for Energy Efficiency and Renewable Energy
U.S. Department of Energy

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December, 1999

The work described in this paper was funded by the Assistant Secretary of Energy Efficiency and Renewable Energy, Office of Power Technologies of the U.S. Department of Energy under Interagency Agreement No.DE-AI-99EE35075 with the National Science Foundation.

Preface

In 1999, the Department of Energy (DOE) tasked the Consortium for Electric Reliability Technology Solutions (CERTS) to prepare a series of white papers on federal RD&D needs to maintain or enhance the reliability of the U.S. electric power system under the emerging competitive electricity market structure.[1] In so doing, the white papers build upon earlier DOE-sponsored technical reviews that had been prepared prior to the Federal Energy Regulatory Commission (FERC) orders 888 and 889.[2]

The six white papers represent the final step prior to the preparation of a multi-year research plan for DOE's Transmission Reliability program. The preparation of the white papers has benefited from substantial electricity industry review and input, culminating with a DOE/CERTS workshop in the fall of 1999 where drafts of the white papers were presented by the CERTS authors, and discussed with industry stakeholders.[3] Taken together, the white papers are intended to lay a broad foundation for an inclusive program of federal RD&D that extends – appropriately so -- beyond the scope of the Transmission Reliability program.

With these completed white papers, DOE working in close conjunction with industry stakeholders will begin preparation a multi-year research plan for the Transmission Reliability program that is both supportive of and consistent with the needs of this critical industry in transition.

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[1] The CERTS DOE research performers are Edison Technology Solutions (ETS), Lawrence Berkeley National Laboratory (LBNL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), Power Systems Engineering Research Center (PSERC) and Sandia National Laboratories (SNL). PSERC is an National Science Foundation Industry/University Collaborative Research Center that currently includes Cornell University, University of California at Berkeley, University of Illinois at Urbana-Champaign, University of Wisconsin-Madison, and Washington State University.
[2] See, for example, "Workshop on Real-Time Control and Operation of Electric Power Systems," edited by D. Rizy, W. Myers, L. Eilts, and C. Clemans. CONF-9111173. Oak Ridge National Laboratory. July, 1992.
[3] "Workshop on Electric Transmission Reliability," prepared by Sentech, Inc. U.S. Department of Energy. December, 1999.

U.S. Department of Energy

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List of Acronyms

AGC	automatic generation control
ATC	available transfer capability
BPA	Bonneville Power Administration
DSA	dynamic security assessment
EMS	energy management system
EPACT	National Energy Policy Act
FACTS	flexible AC transmission systems
FERC	Federal Energy Regulatory Commission
GPS	global positioning system
HDS	hybrid dynamical systems
IED	intelligent electronic device
IGO	independent grid operator
I / O	input / output
ISO	independent system operator
LAN	local area network
LTC	load tap changing
MWh	mega watt hour
NAERO	North American Electric Reliability Organization
NERC	North American Electric Reliability Council
OASIS	open access same-time information system
PJM	Pennsylvania – New Jersey – Maryland Interconnection
PMU	phasor measurement unit
PNNL	Pacific Northwest National Laboratory
PSS	power system stabilizer
PURPA	Public Utility Regulatory Policy Act
PX	power exchange
RTSMC	real-time security monitoring and control
SCADA	supervisory control and data acquisition
SVC	static VAr compensator
TLR	transmission line loading relief
UCA	utility communication architecture
UPFC	universal power flow controller
VAr	volt ampere reactive
VE	virtual environment
VIU	vertically integrated utility
WAMS	wide area measurement system
WAN	wide area network
WSCC	Western System Coordinating Council

Executive Summary

This white paper outlines the scope of issues, challenges and opportunities in the area of real-time security monitoring and control (RTSMC) of power systems in the restructured electricity industry. The counterpart of power system reliability in real-time operations is *security* – the ability of the power system to withstand contingencies. This White Paper is part of a set of six papers on reliability aspects of the electric power system prepared for the U.S. Department of Energy by the Consortium of Electric Reliability Technology Solutions (CERTS).

The principal role of power system control is to maintain a secure system state, i.e., one that can withstand each one of the specified contingencies. The RTSMC system is a collection of processes, computing equipment, measurement devices and communications that have been assembled to provide the means of accomplishing this role. The RTSMC system uses real-time measurements to identify whether or not the power system state is *normal*; this function is called *security monitoring*. If the state is normal, the RTSMC system determines whether or not it is secure; this task is termed *security assessment*. A broad range of control actions is deployed to ensure reliable around-the-clock tracking of the load by the generation. These actions cover a wide time spectrum resulting in a continuum of control actions from the very fast controls in the protection system to the slower controls of generators to provide the automatic generator control function.

As the power industry undergoes major transformations that are replacing the entrenched vertically integrated utility structure by new organizations offering unbundled services, the impacts on the RTSMC area are wide ranging. The objectives of this White Paper are to:

- identify key challenges and issues of concern in real-time secure operations of the restructured power industry
- define the scope of research required to meet the needs of real-time operations in the restructured environment
- analyze, assess and evaluate possible strategies for effectively meeting the challenges in RTSMC

The White Paper starts out with an introductory section to explain the framework for RTSMC; Appendix B reviews the major thrusts of the restructuring in electricity. An entire section is devoted to the multitude of challenges and opportunities in RTSMC under the unbundled regime. An overriding issue is the data problem in the restructured environment. There are two main aspects to this problem. On the one hand, the problem manifests itself in terms of making available all the data required for effectively discharging the RTSMC functions. This is rather sensitive due to the conflicts between physical system data and market data. The task of maintaining a reasonable balance between security maintenance and market integrity is a daunting challenge. The other aspect of the issue is the *data overwhelm* problem due to the vast amounts of data that need to be

managed in RTSMC. The volumes of data will increase, notwithstanding the difficulties of data acquisition due to the market-physical conflict issue. The section explores the challenges and opportunities in incorporating the advances in computer, communications and measurement/instrumentation technology and the state of the art in control theory. Critical attention is paid to the impacts of the interactions of the physical delivery layer of the power system, the market layer being established by the new organizations in the restructured environment and the communication, monitoring and control layer in which the RTSMC mechanisms and processes are housed. The impacts of the increased volatility on the system are given special attention.

As the industry restructures and new paradigms for its operation are established, the need to ensure the security of the power system will continue to require improved controls. An entire section is devoted to the reexamination of control laws in light of the changing environment and to take advantage of the opportunities from incorporating new technology advances. In particular, the impacts of developments in three important areas – substation automation, FACTS devices and dispersed resources – on control schemes are discussed in detail. The applications of advances in control theory in the area of robust control are explored with a view of formulation of effective control mechanisms for the restructured power system. The impacts of advances in communications technology on the deployment of faster controls are examined.

The last section of the White Paper focuses on possible strategies in the area of analytical and software tools to deal with the many aspects of RTSMC in the restructured environment. The *data overwhelm* problem is examined in terms of visualization tools. On the analytical side, the tools for information management, state estimation, voltage security analysis and available transfer capability are examined in detail. The software engineering aspects of RTSMC tools are given special consideration because the successful and reliable operation of the power grid will be increasingly dependent on effective software engineering of the data acquisition, communications, computation, control and market operation systems. Additional aspects of the discussion include model development and validation, the needs in the training simulator tools arena and some potentially useful approaches from complex system theory.

The concluding section focuses on a summary of the major thrusts of the research needs and strategies for RTSMC in the restructured environment.

1. Introduction

Reliability in real-time operations is referred to as *security.* Power system security is the ability of the system to withstand contingencies. This White Paper is part of a set of six papers on reliability aspects of the electric power system prepared for the U.S. Department of Energy by the Consortium of Electric Reliability Technology Solutions. The papers have been developed to aid in the planning of R&D activities on the reliability of the electric power system. This paper focuses on the real-time security monitoring and control (RTSMC) aspects of power system operations.

Power systems are continuously subject to disturbances covering a wide range of conditions. Typical examples of disturbance conditions are sudden changes in load demand, customer load changes, losses of one or more transmission lines, modifications in the system configuration, equipment outages and generator failures. System security is an instantaneous condition. It is a function of time and of the robustness of the system with respect to imminent disturbances. The notion of security is the basis of all real-time monitoring and control in today's power systems. The working definition of security is in terms of the system state.

The system state is a compact description used to summarize key information about the system; once the system state is known, it can be used to express any variables of interest. A state is classified as being one of three possible types – emergency, restorative or normal A *normal* state is classified by having all constraints and loads satisfied. An *emergency* state is one in which one or more of the physical operating limits are violated (e.g., line overloads, over/under voltages, over/under frequency). A *restorative* state is one where one or more of the loads are not met -- partial or total blackout, but the *partial* system is operating in a normal state. The notion of security is defined with respect to a set of *credible* contingencies. A normal state is *secure* if all postulated contingencies result in secure *normal* operations; if a disturbance transitions the state into emergency, the state is *insecure* with respect to that contingency. This definition is well aligned with the intuitive notion that a secure power system is one that has low probability of blackout or equipment damage.

The principal role of power system control is to maintain a secure system state, i.e., to prevent the system state from transitioning from secure to emergency over the widest range of operating conditions. The RTSMC system is a collection of processes, computing equipment, measurement devices and communications that have been assembled to provide the means of accomplishing this role. The RTSMC system uses real-time measurements to identify whether or not the power system state is *normal*; this function is called *security monitoring*. If the state is normal, the RTSMC system determines whether or not it is secure; this task is termed *security assessment.*

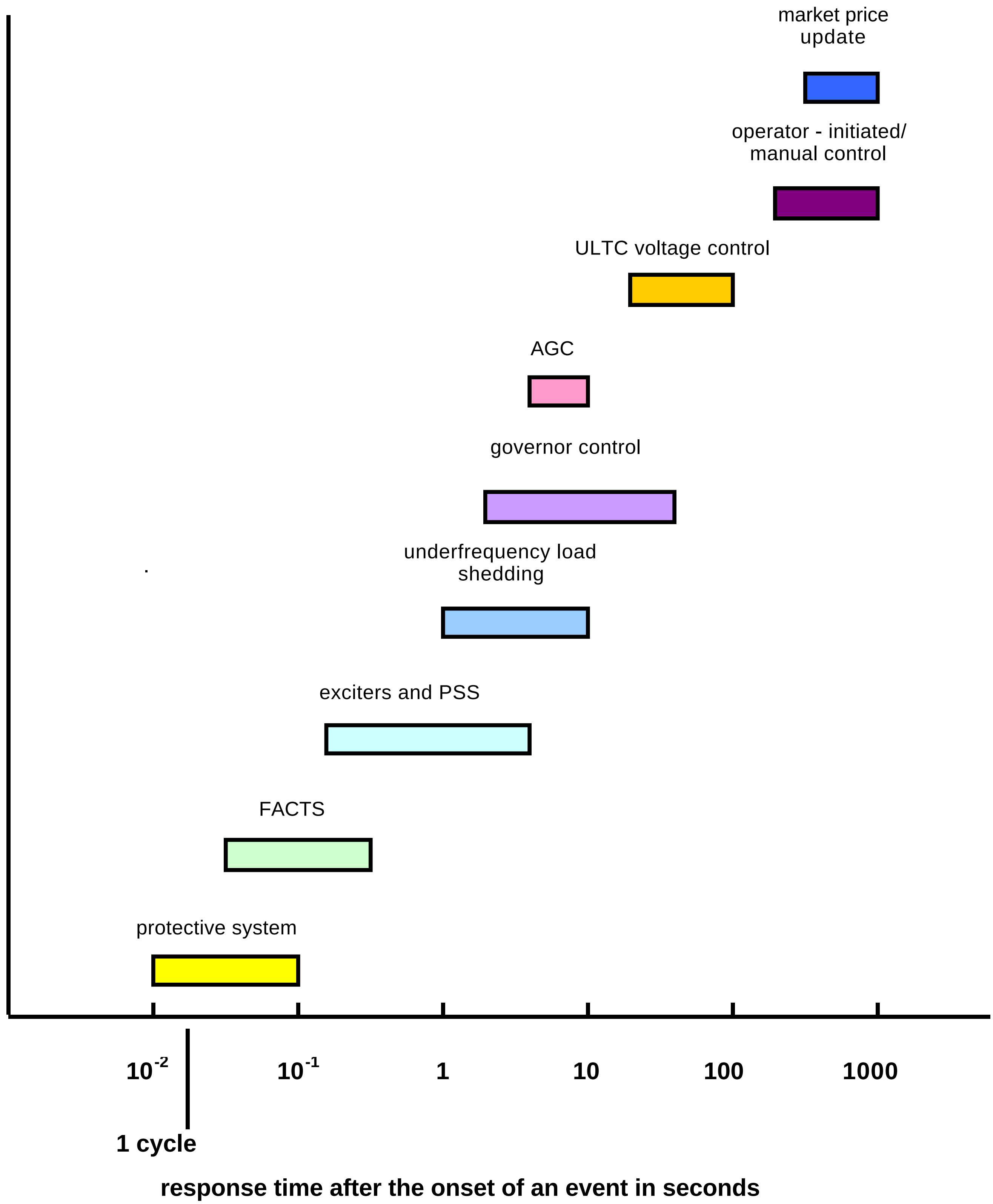

Figure 1: The real-time control action time scale

Basically, the principal task of operations is to ensure that the generation tracks load around the clock. There is a broad range of control actions that are deployed to ensure that this supply-demand balance is met reliably, i.e., with the security of the power system at a designated level, and cost effectively. The control actions in RTSMC may be classified according to their response times to the onset of a disturbance, as illustrated in Figure 1. Conceptually, we may partition this spectrum of control into two broad categories – fast-acting local controls and slower regional controls; however, the partitioning boundary is not sharply delineated.

The protection system is usually fast, acting on the monitored data available within a substation. So are the generator exciters, some governors and power electronic converters associated with FACTS devices, dispersed generation and controllable loads. Transformers and some governors are usually slower acting even though they often control only local variables. AGC, on the other hand, is a slow control mechanism using data gathered from remote sites in the interconnection. Any control, be it automatic or operator initiated, that needs monitored data from several substations scattered around the power system cannot be faster than the data acquisition allows. The data acquisition in today's control centers is slow with cycle times in the seconds and this necessarily results in a slow response for any global RTSMC action to be slow. *For the purposes of this White Paper, the basic time frame of interest is in the range of a hundredth of a second to minutes with an upper bound of one hour.*[1]

The integration of this continuum of control actions into a single framework in which both the security and economics functions are explicitly considered is a daunting challenge. When combined with the large-scale, nonlinear and "just-in-time" manufacturing nature of the power system and the absence of effective, large-scale energy storage mechanisms, a set of highly complex problems in analysis, computing and communications results. The power industry response was the development of the energy management system (EMS). The EMS is a large and complex hardware-software-communications system. It became the *central nervous system* of the power network of the traditional utility and is the principal tool to aid the operators in the real-time operations and control of the power system. As the power industry undergoes major transformations due to its restructuring, there are major impacts on all its sectors including the RTSMC area. The major thrusts of the restructuring in electricity are summarized in Appendix B.

The objectives of this White Paper are to:

- identify key challenges and issues of concern in real-time secure operations of the restructured power industry

[1] For the selected time frame, the areas of *emergency control* and *restorative control* are largely outside the scope of this paper. Currently, these controls are operator initiated and are on time scales typically longer than one hour. *Emergency control* is the set of corrective actions deployed to make the system normal. *Restorative control* is the set of processes invoked to restore service to all loads throughout the system.

- define the scope of research required to meet the needs of real-time operations in the restructured environment
- analyze, assess and evaluate possible strategies for effectively meeting the challenges in RTSMC

The remainder of the White Paper lays out the scope of the problems that need to be explored in the RTSMC area. The next section discusses the range of challenges and opportunities in RTSMC under the unbundled regime that is replacing the entrenched vertically integrated utility (VIU) structure of the past. The advances in technology and developments in control theory provide additional challenges. A section is devoted to the reexamination of control laws under the new industry paradigms that are implemented across the nation. In this section, means of exploiting the new developments in technology and theory are explored with the objective of formulating robust control strategies for the restructured power system. The section on analytical and software tools presents some possible strategies to deal with the myriad issues arising from the new environment and associated challenges. A final section summarizes the key R&D needs in the RTSMC area.

2. Challenges and Opportunities In RTSMC Under Unbundling

The vast amounts of data in large-scale power system RTSMC presents a major challenge even before the restructuring of the industry. For example, power system operations data of interest could include a large list of variables, such as bus voltage magnitudes, transmission line loadings, generator real and reactive reserves, transformer tap and phase positions, scheduled and actual flows between areas, interface loadings, and alarm locations. In advanced security analysis applications and available transfer capability (ATC) evaluation, this list of variables is even longer. As a result of the huge data involved in various RTSMC computations, operators, engineers and market participants are increasingly subject to *data overwhelm* problems.

The power grid is not unique in either its creation of large amounts of data, or in its large expanse since many infrastructural systems, such as gas, telecommunications, airlines as well as other transportation systems may be even more expansive. However, power systems have salient characteristics that make more pronounced the *data overwhelm* problem. For example, the limited capability in today's systems to directly control the flow of electricity on the grid and the lack of electrical analogues to a control valve in the gas industry, a busy signal in the telecommunications industry, or a holding pattern in the airline industry, have major impacts. Because electricity travels through the grid at nearly the speed of light, the actions of any grid participant affect every other grid participant virtually instantaneously. And these effects must be known in RTSMC with as little delay as physically possible. Due to the impacts that the weather may have on system load and facilities, the tracking of weather information is key in the definition of current as well as future contingencies. The amount of data for each postulated contingency (a possible operating condition) and the potentially large number of contingencies are resulting in vast amounts of data that need to be processed and managed.

Restructuring is substantially increasing the data requirements for RTSMC. The greater region covered by an independent grid operator or IGO (see Appendix B) is one major reason for this increase. The advent of the new players, the attendant increase in the total number of players, the increasing role of markets in the new environment and the proliferation in the number of transactions are resulting in major changes in power systems operations. One of the most visible impacts is the increased volatility in the system. The volatility effects entail the need for measurements for both monitoring and billing purposes, which, in turn, result in increased volumes of data to manage. The increasingly severe *data overwhelm* problem results in many challenges in terms of development of effective analytical and software tools. Certainly, the rapid advances in the fields of computing and communications may offer some help; however, they bring about their own set of challenges in RTSMC.

This section explores some of the challenges and opportunities arising from the restructured environment as well as the advances in computer, communications and measurement/instrumentation technology and the state of the art in control theory. For example, the breakthroughs in communications will enable much faster data acquisition. The data can be moved very fast with the greater bandwidth of the fiber optic cables. Also, the data can be synchronized by GPS satellites. Thus, communications is becoming less of a bottleneck for controls. Faster computers are also enabling the rapid processing of the vast amount of data and each substation is being monitored more comprehensively. However, the new control schemes that fully utilize the communication and computation capabilities have not yet been developed but the technology today does allow for a continuum of control schemes in which the distinction between local and global control is becoming blurred. There are also a number of major challenges associated with the restructuring of the industry. These stem from the way control services can be acquired and provided in the new regime as well as the level of authority of the IGO. These issues are also discussed below.

In discussing the various challenges and research needs, it may help to view the RTSMC within a multi-layer framework for the restructured environment. The three interconnected layers are:

- the *generation and physical delivery* layer
- the *market* layer
- the *communication, monitoring and control* layer

This construct[2] incorporates all the essential elements of the restructured electricity system. The generation and physical delivery layer consists of all the generation, transmission/distribution facilities and their associated embedded control/protective equipment, and the loads. In addition, organizational structures such as the IGO are included. The market layer represents the spot markets and commodity markets in electricity and produces the price signals from inputs from the participants in the bulk electricity markets. It includes the representation of both physical entities such as generators and financial entities such as brokers/marketeters. In addition, organizational structures such as the regional power exchange and scheduling coordinators are included. The third layer represents the sensor/measurement equipment throughout the physical network, the data communication network and the RTSMC commands and signals. This layer serves as a link between the other layers and provides the interface to operators.

2.1 Volatility of the System

The multiplicity of players in electricity markets results in a proliferation of transactions of, typically, considerably shorter duration and larger variety than those in the VIU environment. Not only does this lead to more frequent changes in system conditions and flows, but, due to the nature of the interaction of the increasingly competitive markets

[2] This is a slight modification of the functional model proposed by PSERC in the EPRI/ARO-DOD Project on Complex Systems currently under investigation.

with the physical considerations in transmission, there results considerable price volatility. There are implications in terms of the nature and direction of the physical flows as well as in the more volatile patterns of generator commitment, i.e., individual units may be connected and disconnected from the grid in rather unpredictable and more frequently varying patterns. Such variability in generation results in wide variability in the structure/configuration of the system; each resulting configuration has a different set of controllers. To make a rough analogy, the challenge to the IGO or the NERC security coordinator is that of a coach trying to effectively manage a large number of player substitutions through the course of a game. The IGO must ensure that overall system-wide control objectives are met, while the individual control hardware on specific generator sets may be coming in and out of play frequently but randomly. The research needs that this challenge creates constitute a class of problems, which are similar to ones solved using robust control techniques. As a minimum, controllers must be developed that guarantee that new units added to the system “do no evil,” i.e., volatile dispatch and commitment must not be allowed to degrade system security.

An additional challenge to control design arising from market-driven volatility is due to the introduction of an entirely new class of dynamic phenomena into the power grid. Generating units and, eventually under retail access, customer load respond to market signals that are impacted by grid conditions, such as congestion, which are, in turn, influenced by the generator and load response. In this way, a closed-loop system results in which, the generator and load responses to market prices form a feedback path. In real-time operations, these market responses inevitably have a stochastic behavior. Therefore, the realistic analysis of power system control performance will require explicit modeling of the stochastic, price-driven feedback loops, which couple market phenomena with physical response of generators and loads. This is a good example of the coupling between the generation / physical delivery layer and the market layer in the multi-layer framework described above. Preliminary work has indicated that in a deterministic framework subtle mechanisms of instability may be introduced when market responses form a feedback loop with physical generator control response. Such phenomena point to the need to redesign the monitoring and control layer to mitigate these problems and ensure system stability. In particular, research needs to focus on the development of analysis tools capable of assessing the impacts of stochastic phenomena in market feedback, as well as, delays and communication failures in the pricing/bidding mechanism. The ultimate goal is a redesign of generation control systems to account for these market-driven responses and to provide robustness that ensures both physical system stability and market stability over a wide range of generator and load responses.

2.2 Providing Control Under Unbundling

With the unbundling of the electricity services and the introduction of an IGO, the providers of control actions and the controlling authority will be under different ownership. As such, there arises a need to specify procedures – *rules of the road* – for the

IGO to acquire and deploy control services in the new environment. While there is general agreement among industry practitioners that the power system requires coordination to maintain its integrity and security, there is considerable controversy on the best ways to implement such coordination under competitive conditions. The development of workable coordination paradigms is a very challenging task.

At the same time that the technology is available for some major leaps in RTSMC, the restructuring of the power industry will inevitably require some restructuring of the control schemes. With the separation of generation and transmission services, their integrated control is a challenge. Just as the technology is on the threshold of allowing massive data transfers, the competitive nature of the business is encouraging the players to limit the data to be shared. It is becoming clear that in the transition from the VIU to the restructured regimes, *information availability* is a major issue. Secure operations under open access require widespread availability of real-time information about physical, as distinct from financial, variables. Unfortunately, the competitive environment is not conducive to information sharing. For example, data for state estimation algorithms is becoming increasingly difficult to obtain because of the ability of that data to reveal sensitive financial information. If the state of the power grid, i.e., the vector of complex voltages at each node of the network, is known, then the generation patterns become known and can easily be analyzed for cost/price information. Consequently, conflicts may arise between the interest in maintaining the reliability of the system and, at the same time, fostering a competitive market place. Care must be taken to maintain the required level of security without jeopardizing the smooth functioning of the market. At the same time, a policy on data sharing needs to be formulated to enable the IGO to effectively carry out its RTSMC role.

Maintaining the security of the grid without unduly affecting the market is especially difficult when the power system encounters operational constraints. Once some operational limit is reached, some real-time control may have to move variables away from the values in the agreements made in the market. The challenge is to design real-time controls that minimize the deviation from the market agreements. For example, if a thermal limit is reached on a line, the congestion management should determine the *minimum impact* procedure to allow the proposed transactions to be undertaken. Unfortunately, it is difficult to agree on what constitutes the *minimum impact* and, consequently, cumbersome procedures are being constructed that are consensually acceptable. These procedures and, in certain cases, specific associated performance standards are being developed by industry committees under the aegis of NERC. Unfortunately, these procedures can become very complicated. While the management of congestion caused by a thermal limit may be tractable in a straightforward way, the relief of congestion caused by an oscillatory stability limit may be far more difficult and complex to achieve.

The issue of the future nature of the AGC system provides an important example of the real-time control challenges that will be recurring themes as the competitive generation market evolves. The existing control structure was largely predicated upon centralized ownership and integrated management of generation and transmission control equipment; the new structure seeks to provide ancillary services and control on an unbundled basis. A major research challenge is associated with mapping out the trajectory of migration from the old control structure to the new. This trajectory will need to make wide use of the generators, which are among the most effective elements for achieving system-wide control objectives of frequency regulation, stable dynamic response, and to a lesser degree, voltage control. However, these “control resources” are owned and operated by independent, profit-maximizing entities. Moreover, the IGO has the responsibility for providing transmission and operating the interconnected grid. The key research issue is that of determining new structures for control and the associated control performance-based economic incentives under which the system-wide security control objectives of the IGO can be attained without unduly constraining the ability of the individual generation owners to maximize their profits.

The unbundling of electricity services brings about a set of new measurement and metering needs. A major challenge is the appropriate quantification of each control service to be provided to the IGO. Once a service is quantified, measurement is required. Due to unbundling, there will be a large volume of measurements which will produce additional volumes of data. Specific issues in measurement of each service will need to be determined. The specification must encompass attributes such as frequency and accuracy of the measurements[3]. The additional data will further exacerbate the *data overwhelm* problem and effective schemes for storage, management and extraction of the metered data will be required. A particularly important area will be the development of data compression techniques for the new metered data.

In addition, there is the related challenge of control performance assessment. This assessment will require the formulation of standards by which all the players will abide. Such standard specification is a necessary first step before one can even begin to address the policy question of how such control performance should be rewarded and/or regulated by the IGO. The challenge is to develop schemes which can provide appropriate incentives for effective performance of control actions.

The restructuring in the industry has led to paradigms with varying levels of centralized control and operations. At one end of the spectrum is the integrated IGO-PX structure in the PJM and the England and Wales Power Pool. At the other end is the distinct separation of the PX and IGO functions in the California restructuring. There is a major controversy over the IGO’s need to know information of a financial nature. These issues clearly impact the control and decision making authority of the IGO as well as the availability of the relevant information. Due to the fact that the separation of information into financial and physical data is not clearly defined, this relevant information need will

[3] The quantification/evaluation of relay and high speed control performance is a major problem because of the difficulty of making the measurements.

continue to be a challenge that must be effectively handled. The implementation of control actions must be aligned with the level of centralization/decentralization of decision making vested in the IGO.

2.3 Advances in Measurement Instrumentation and Communications Technology

Another advance in measurement and communications technology impacting the power system is the capability to make phasor measurements effectively. A phasor is a complex number, used to represent a pure sinusoidal function of time (steady state AC voltages and currents). The single frequency limitation may be removed by stipulating that the phasor represent the fundamental frequency component of a wave form observed over a finite window. The phasor may be computed from equidistant samples of the wave form under appropriate limitations on filtering and sampling rate.

The instant at which the first data sample is obtained defines the orientation of the phasor in the complex plane. The reference axis for the phasor is specified by the first sample in the data window. If the power system frequency is precisely the nominal 60 Hz, then the computed phasor is stationary. Else, the computed phasor rotates at the difference between the off-nominal frequency and 60 Hz.

Phasors, representing voltages and currents at various buses in a power system, define the *state* of the power system. If several phasors are to be measured, it is essential that they be measured using a common reference. The reference is determined by the instant at which the samples are taken. In order to achieve a common reference for the phasors, it is essential to achieve synchronization of the sampling pulses. The precision requirements for the time synchronization depend upon the uses of the phasor measurements. The Global Positioning System (GPS) provides a 1 pulse per second (1 pps) at any location in the world with an accuracy of about 1 *μsec*. In addition to the 1 pps signal, the GPS provides along with other information, the unique time-stamp to the pulse.

The capability of making phasor measurements using GPS are incorporated in the phasor measurement unit (PMU). A multiplexed analog-to-digital converter samples the power system voltages and currents. The time stamp, provided by the GPS receiver clock on the serial line, constitutes a part of the time tag of the phasors. By matching the complete time-tag of a phasor measurement, simultaneous measurements can be assured to within 1 sec. The time-tagged phasors are communicated to remote locations on a serial line. The channel speed available for this line determines the rate at which the phasors can be communicated to a central site. As the number of phasor measurement units installed on a system increases, a possible data bottleneck may develop at the central receiving site.

2.4 Hybrid Controls

The coexistence of hybrid -- continuous and discrete -- controls adds a major level of complexity in the power system. There is a branch of control devoted to "hybrid control" which focuses on control systems that mix continuously acting regulation with discrete actions. Discrete events[4] correspond to the actions of equipment such as load tap changing (LTC) transformers, switched compensation elements, excitation control limits and protective relays. This is another instance of the coupling between the generation / physical delivery layer and the market layer. The interaction of such discontinuous "events" with continuously acting feedback loops makes the analysis of grid control performance a huge computational challenge. The emerging research tools from the field of hybrid dynamical systems (HDS) are critical to improve the state of the art in performance prediction and design for the next generation of real-time controls. The HDS mathematical framework consists of:

- differential equations
- algebraic equations (power flow relations)
- discrete time controls (LTC transformers, FACTS devices)
- discrete-event-driven actions (relay operations)

The implementation of the HDS framework in power systems requires the solution of very large-scale algebraic systems with the associated computational tractability problems. While the time-domain simulation under a single disturbance is feasible, the variable structure of disturbed power systems is a key challenge. For effective real-time control design, additional factors such as the influence of the misoperation of relays and the associated tripping of critical facilities, and the influence of parameters of control subsystems (e.g., gains of exciters, PSS) need to be considered. These complexities are further compounded when the system is subjected to the increased volatility under market conditions. Currently there exist *no* tools to capture the hybrid characteristics of the power system adequately for real-time control design. Clearly, there are major challenges in developing appropriate models to effectively represent the interaction in the multi-layer structure and to construct implementable control schemes.

2.5 Determination of Static and Dynamic Limits

In considering new roles for control systems in the restructured power system, it should be clear that the nature and performance of controllers impact the transfer capability and

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[4]Autonomously acting discrete switching events (as opposed to those commanded by human intervention from a control center operator) are largely associated with protective devices. These act when system states deviate widely from accepted operating range. therefore, it is reasonable to suppose that interaction between these effects and normal feedback controls should occur only under fault or disturbance conditions. However, among the common contributing disturbances may be an inappropriate triggering of one of the protective devices themselves.

other operating limits within the grid. For example, the tuning of the power system stabilizer of a generator may be a key factor in determining if the system is first contingency stable at high transfer levels. Moreover, such impacts may be manifested in transactions in which a controlled device is not a party, e.g., a cogenerator providing VAr support in the middle of a long radial transmission path, where the parties to the transaction are located at either end of the path. This complex interaction of real-time control performance with system limits creates a significant research challenge.

A related research question is that of the accurate assessment of system transfer limits; evaluation of these limits is particularly challenging when the limits are dictated by system stability considerations. For example, monitoring of system limits dictated by the onset of oscillatory behavior, the so-called Hopf bifurcation point, represents a key research need in the area of real-time control. The broader issue of accurately characterizing transient stability limits has generally come under the heading of dynamic security assessment (DSA).

The literature is replete with a number of methods for DSA using variants of transient energy function techniques and equal area criterion extensions. These schemes use very simplified models of the system and of the controller dynamics and are applied primarily to filtering contingencies. Hence, their usefulness in judging the impact on security of real-time control strategies is limited. Trajectory sensitivity based methods show promise in providing DSA tools that are model independent, and hence can be used to examine real-time control impact in system models of arbitrary structure. The deployment of distributed computing for DSA needs to be explored. The application of parallel processing of the DSA task at geographically dispersed centers may help in making the DSA computation tractable.

Recent progress has been made in moving DSA tools toward on-line application; for example, DSA software recently installed at Northern States Power Co. provides the first working tool for near real-time dynamic limit determination. Despite this first step, DSA remains a challenging topic, and the volatility and changing nature of the generation/load mix in a competitive environment make this challenge considerably harder. Research into the interaction of real-time control and system security limits is critical as competitive pressures demand less conservative operating margins in power networks. A source of more accurate information for this purpose will be provided by the dynamic monitoring of transmission lines.

2.6 Protection System Reliability

Security and dependability are terms protection engineers use to describe the reliability of the protection system. The special terms are necessary since the protection system can fail in two distinct ways, i.e., tripping incorrectly or failing to trip. Security and dependability are conflicting requirements for a protection system. In modern systems, existing protection systems have a bias in favor of dependability, i.e., a virtual guarantee that faults will be tripped with an attendant reduction in level of security. Such a bias is desirable when the system is in a healthy state, i.e., an accidental loss of some equipment through incorrect relay operation may be tolerated without stressing the remaining power system. However, such a bias is highly undesirable when the power system is in a stressed state. In such a case, it would be desirable to avoid incorrect tripping of unfaulted equipment, even though one may increase the probability of not clearing a fault if it should occur. It should be recognized that the probability of not clearing a fault in existing protection systems is incredibly small. Increasing such probabilities by a small amount in order to deter major system disturbances is an option that must be examined. This behavior of the protection system should be explicitly considered in the reformulation of control laws. For example, some double contingencies are much more likely than others when the behavior of the protection system is considered.

With redundant primary protection systems it is possible to alter the security/dependability of protection by combining the outputs of the primary relays. In conventional schemes the outputs are logically in parallel in that any relay can trip the breaker. The extreme in security would be achieved by requiring all of the primary relays to indicate fault before the relay was tripped (a series connection). With three primary systems a two out of three voting scheme may be implemented. More subtle trade-offs between security and dependability can be achieved in the relay algorithm design. It is then possible to imagine a relaying system that had a continuously adjustable security/dependability index. It has been observed that security/dependability might be altered when the system is in a stressed state. During a cascading outage it would be desirable that a rapid change in security/dependability could be achieved to stop relay involvement in the disturbance propagation. Such techniques are unorthodox but may form effective control actions.

2.7 The Changing Nature of EMS

The EMS of the VIU integrated the security and economic functions. With the functional unbundling of generation and transmission, the two functions have effectively become separated. Moreover, the original applications of economic dispatch and unit commitment have been transformed with the consideration of prices rather than costs. In addition, many of the merchant functions have set up trading floors, which subsume some of the functions previously embedded in EMS. Thus, the EMS as we knew it is disappearing. The security applications still remain but are fast becoming the purview of the IGO and the network controlled by an IGO is often considerably larger than a single VIU. The restructuring of the industry and the unbundling of services are rapidly transforming the products of the EMS vendor industry. It is likely that the VIU EMS will be replaced by several specialized systems in the new organizational structures with specialized dedicated systems for the power exchanges, IGOs, resource portfolio managers, transmission owning entities and scheduling coordinators.

3. Reexamination of Control Laws

As the industry restructures and new paradigms for its operation are established, the need to ensure the security of the power system will continue to require improved controls. Such controls will make detailed use of the new advances in electrical technology. The impacts of developments in three important areas – substation automation, FACTS devices and dispersed resources – on control schemes are discussed in the next subsection. Then, the applications of advances in control theory in the area of robust control are explored with a view of formulation of effective control mechanisms for the restructured power system. The last topic of this section treats the impacts of advances in communications technology on the deployment of faster controls.

The reexamination of control laws coupled with the enhancement of analytical tools and software are key to enabling the migration of today's manual operator-initiated controls to automatic controls. There are still many barriers that need to be removed to reach this stage. Some of these are of a policy or institutional structure nature and some pertain to the reliable execution of the sophisticated programs that embody these controls. However, the technology is making this possible and it will be highly beneficial to move away from the slow response in human control to automatic execution.

3.1 Impacts of New Developments in Technology

We consider in this subsection, the impacts of advances in three key areas -- substation automation, FACTS devices and dispersed generation. The effects of these impacts on RTSMC are discussed separately for each of these areas.

3.1.1 Substation automation

A major trend in substation automation is the closer integration of control and protection functions. The development of digital relays over the past 25 years has been paralleled by the installation of other IED's in the substation. Such IEDs include microprocessor-based systems for monitoring, control, metering, oscillography, sequence-of-events recording, and the computation of phasors with synchronous sampling. Traditionally, these IEDs have been stand-alone equipment even though the obvious advantages of integration into the substation equipment are widely recognized. That is, digital relays produced by different manufacturers are unable to communicate with each other, cannot share data, and cannot provide backup of functions. Moreover, digital relays are not communicating with digital fault recorders or SCADA equipment. These are the so-called *islands of automation* in the industry. More recently, however, the area of substation automation or integration has created the possibility of retrofitting old substations or building new substations with comprehensive automated power management, control, protection, and monitoring. The different communication protocols from the various IEDs are integrated using the new Utility Communication Architecture (UCA) to make possible a substation LAN. A substation host computer that can be addressed by a dial-up telephone line or locally by a serial port or Ethernet connection is generally imagined. Communication from the host computer and the IED's can be direct connections to serial I/O ports or through Ethernet.

We believe that the use of automation will increase reliability and provide an environment in which data will be available for inter-substation networking through a “utility Internet”. It can also be argued that restructuring will require access to more data in the substation in order to verify that benchmarks such as service interruption times can be effectively monitored. Remote monitoring and diagnostics, predictive maintenance, faster restoration, and energy monitoring along with self monitoring and reporting by the IED's are all mechanisms that improve reliability of an integrated substation. In addition, control and supervisory operation may provide control of switches and circuit breakers to coordinate supervisory control of breaker trip and close, LTC transformer control, capacitor bank switching, and downstream reclosers, line switches, and capacitor banks. The information that would be communicated beyond the substation on a WAN through a router would range in time scale from SCADA data to phasor measurements to relay data.

It is also clear that substation integration provides the necessary platform for RTSMC. Integration of IED's into the substation, synchronized sampling by some (if not all) IED's, self monitoring and checking of IED's, and the creation of a utility Internet with the appropriate bandwidth are primary prerequisites for implementation of new monitoring and control schemes.

3.1.2 FACTS devices

Among the technologies with the potential for significant control impact is that of new applications of high power electronics, which are often grouped under the heading of flexible AC transmissions systems or FACTS. In the eyes of many observers, FACTS technologies have been a potential revolution that has continued to wait in the wings for a number of years. A small number of innovative FACTS demonstration projects have been completed or are currently underway. However, deep, large-scale penetration of this technology into the North American transmission grid has yet to occur. Notwithstanding current status, it would be a mistake to assume that the FACTS implementation will not occur, and with it, a range of interesting and highly challenging control applications and problems. Power electronics controllers can present difficult nonlinear controller design problems, because fundamentally, these devices are synthesized from circuits in which binary switches are the primary controllable element. In many transmission applications, the objective is typically to control the 60 Hz component of a current or voltage waveform, or of an impedance, by switching within an appropriate circuit topology. When the switching frequency is significantly above that of the fundamental, as is the case in low power applications, averaging techniques provide a tractable model for control design. However, present solid state technologies for high power often are limited in their switching frequency due to loss effects. The limitations on switching frequency create much more complex dynamic behavior and the need for new methods of control design.

The possibility for undesirable interactions between controllers on individual FACTS device, and with other system control elements (such as supplemental excitation control signals at generators or torsional oscillations) is known. Moreover, combinations of new circuit topologies and devices in the UPFC create an opportunity for significantly enhancing steady state power flow. In addition, once such devices gain penetration in the industry, the economics of FACTS could change dramatically. Formulation of optimal control policies for the integration of large-scale power electronics in new transmission network facilities, such as FACTS, will need to be addressed and effective solution methodologies will be to be developed. Control design for dynamic performance enhancement presents a set of many challenging and important problems.

3.1.3 Dispersed resources

One of the growing challenges for control in the restructured environment in electricity is the potentially explosive growth of distributed or dispersed resources, both on the supply- and the demand-side. The anticipated increase in penetration of non-standard generating technologies, often being attached to the system at the lower voltage distribution level, will have major ramifications on the control of the grid. In the past, such units constituted a tiny percentage of overall generation, and their impact on system control could be ignored. These systems typically are not standard synchronous generating units. Some are induction units operating asynchronously, coupled to the grid via AC-AC power electronic converters. Others are non-rotating, "inertia-less" sources, such as photovoltaic units or fuel cells. Absent the stored kinetic energy of the rotating inertia in a synchronous generator, such sources present very different characteristics to the grid, and their ability to contribute to frequency regulation and voltage control will likewise be very different than that of traditional units. Virtually no effort has been directed to preparing such units to contribute to system wide control objectives. Indeed, even the mathematical models to characterize their impacts on system-wide dynamic response are severely lacking at this stage. This is a key area for research, which must be coordinated closely with research efforts described in the white paper on distributed generation resources.

3.2 Impacts of New Developments in Control Theory

A potentially fruitful research direction relates to agent-based concepts of control. The agent approach provides an appropriate model for many examples in nature in which simple local control laws succeed in generating complex global behavior in the aggregate. Examples include flocking behavior in birds and the operation of bee and ant colonies. Clearly, this is a broadly appealing notion, but rigorous research must follow to explore its applicability to obtaining desirable global dynamic performance from relatively simple local control actions in the restructured power system.

Agent-based control approaches may provide a source of new control methods appropriate to a more decentralized environment. Very challenging computational complexity problems abound in power system control and optimization. The required computation time of these problems grows at least exponentially with problem size. Such problems are formally classified as “NP-complete” or “NP-hard.” Agent-based approaches have enjoyed success in improving solution algorithms for several classical NP-complete problems, suggesting promise for more specific power system control computations. In another indication of their promise, agent-based approaches are seeing power system applications not directly in control design, but in closely related problems of design of bidding/offering strategies for competitive generating units.

The advances in control theory, particularly in the area of robust control, are particularly promising for investigation to various control schemes in RTSMC. In the context of development of localized generator controls, the nature of the power grid suggests research should be directed to design methodologies that marry developments in adaptive agents with more classical robust control concepts, such as dissipativity/passivity-based design of controllers, "H-infinity" and "l-1" notions[5]. Future grid control must allow simultaneous pursuit of the goals of improved performance, as might be obtained through the use of intelligent local agents for real-time control, while protecting against the unforeseen emergence of destabilizing phenomena that might result from complex interaction of such agents through the grid[6]. In a broad sense, the practical implication of such a design goal may be a tradeoff of some set point regulation performance for improved guarantees of overall grid stability[7]. There appears to be considerable value in real-time control designs

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[5] "Robust" control is used in applications that seek to achieve the control objective under a set of conditions with very wide variations. In applications of classical control techniques, in contrast, the controller performance is optimized under the (unrealistic) assumption that a single, fixed mathematical model fully describes the physical system that is being controlled. Control techniques based on "dissipativity/passivity" seek to modify the dynamics of a system in such a way that energy in any motion that deviates from the desired operating point is damped out by forces analogous to "viscous" friction. The approach guarantees that when multiple controllers provide such damping, their actions are mutually re-enforcing, without any possibility of undesirable interactions between controllers. The "H-infinity" and "l-1" schools of control design came to the forefront in the 1980's. They seek to extend the benefits of classical control methods applicable only to systems with a single input and a single output to systems having multiple, interacting inputs and outputs. These methods allow the multivariable controller design goals to be specified in the frequency domain. Proponents of these schools of thought point out that frequency domain descriptions, as opposed to time domain descriptions in state space form, allow a more appropriate match to the physical engineering considerations in controller design. In a rough sense, the terms "H-infinity" and "l-1" are shorthand for different *metrics* that may be used to measure effective gain in a multivariable input-output system. In particular, such contoller design can result in stable operation of the controlled system over a wider range of operating conditions.

[6] In "intelligent local agent," the term intelligent refers the high degree of cost-effective processing power which may now be deployed in the increasing number of embedded systems throughout the power grid. Such great processing power allows very sophisticated algorithms to be executed in real time, giving a controller a semblance of intelligence. The terminology "local agent" is used to suggest that such devices would operate using locally measured information, and make local decisions, with little or no centralized coordination.

[7] Classical control theory and its multivariable generalizations through such methods as H-infinity establish a fundamental tradeoff in feedback design that exists in a wide class of

that more explicitly consider this tradeoff in the light of the needs in the restructured North American power grid. Studies of the application to RTSMC of robust control advances should be fruitful in the development of new robust control schemes. Such schemes will be designed to effectively utilize continuously acting controls, for example in the feedback loops of generators, FACTS devices and loads, together with discrete controls such as grid switching, dynamic braking, fast valving, LTC transformer and protective breaker actions.

3.3 Impacts of New Developments in Communications

In the power system, GPS created the opportunity to precisely and directly measure relative phase angles of geographically dispersed sinusoidal voltages in the grid; the term wide area measurement system or WAMS has been coined to describe this development, which makes effective use of GPS technology. The *EPRI Roadmap*[8] envisions the rapid deployment of WAMS based on the GPS technology. Such a system is in the early stages of development in the WSCC by EPRI, BPA, and PNNL. Various versions of the PMU's are interconnected by data concentrators and communicated to a few central locations. The implementation of such a system is planned to cover the entire western interconnection. The total distance for communication of the measurements could reach 1200 miles. The total time delay for reasonable direct transmission over an extensive fiber optic network could be as short as 10 milliseconds (1200 miles at 2/3 the speed of light in a vacuum). The additional delays caused by non-direct transmission paths, data concentrators and other digital processing, multiplexing and transitions to and from fiber can increase the total delay by as much as a factor of 10 to 100 milliseconds. Transient swings with periods of around a second can be effectively controlled based on measurements with a latency of 0.1 sec if the measurements are taken sufficiently frequently. Due to the uncertainty in the delay it is important that the measurements be time tagged. The data rate and volume for the thousands of measurements proposed in the *EPRI Roadmap* present formidable challenges. Even rates of measurements every few cycles can require immense processing power. The *EPRI Roadmap* couples the WAMS with the development of massively parallel processing computers and new on-line analysis software. Current WAMS with far fewer measurements still opt for local storage and selective messaging to deal with the data volume. The challenges of developing practical and workable schemes to deal with this specific *data overwhelm* issues will need to be met over the next few years to effectively harness the capability provided by the new advances in measurement technology.

WAMS is making possible the effective implementation of faster controls for security enhancement. Special protection schemes such as remedial action schemes are not actual

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systems. High loop gain yields a system with good performance, as measured by such criteria as its ability to regulate to set point. However, high gain lessens the stabilty margin, and in the extreme, can destabilize a system. This tradeoff becomes more pronounced when the characteristics of the system being controlled are imprecisely known.

[8] EPRI, *Electricity Technology Roadmap: Power Delivery Module*, draft, October 15, 1998

protection schemes but rather directed control schemes that are intimately tied to protective relays and operate in the same time scale as the protection. These are much faster acting controls than those involved in transient stability. Remedial action schemes are designed to react to prevailing system conditions and are usually programmed to respond to a particular set of system conditions. For example, a remedial action scheme could be designed to increase the maximum power transfer through a given transmission corridor. The scheme would involve the shedding of the generation at one end and/or load at the other upon the opening of the breakers at one end of the lines in case where the amount of power transferred before the trip was too large for the remaining lines.

Existing schemes have been criticized for exacerbating cascading outages. It is also not clear that the action of such schemes are being considered adequately in ATC calculations. Nevertheless, future schemes involving improved communication systems, FACTS devices, and new control algorithms can be designed to overcome some of these limitations and offer exciting new possibilities in real-time operations. The possibility of bypassing the control center and providing immediate local remedial strategies to correct flow and voltage violations in response to relay and breaker action is not hard to envision. Out-of-step relaying can become considerably more sophisticated in the near future. As adaptive relays become more popular it is also possible to complement the "control in response to protection schemes" with "changes in protection in response to control schemes". That is, a given control action might only be acceptable if a corresponding change in protection accompanied it. For example, a substantial change in a FACTS device might require a change in settings of the line relays protecting the line on which the FACTS device is connected as well as in the other relays that coordinate with those relays. In this way, tight coordination of protection and control could make the system more robust to disturbances.

There is still considerable work to be done in the integration of faster controls into the real-time control scheme of the power system. The developments underway, such as the remedial action schemes, are laying the groundwork towards the development of effective automatic schemes utilizing fast controls. Future research will lead to more extensive implementation of even faster mechanisms for security enhancement.

4. Enhancement of Analytical Tools and Software

The unbundling of electricity services coupled with the major breakthroughs in information technology is making available massive amounts of data – a considerable increase over the information used in the VIU environment. Additional huge volumes of measurement data are clearly exacerbating the *data overwhelm* problem in RTSMC. The challenge of effectively managing the problem calls for the development of approaches and tools for data storage, handling, extraction and compression which exploit the structural features of RTSMC data. Applications of data warehousing and data mining techniques to the massive volumes of data will be required to utilize the data for various purposes in RTSMC, as well as, other areas from planning to billing.

The *data overwhelm* problem is common to both automatic and manual control. A particularly challenging problem is the man-machine interface in RTSMC, especially, in light of increasing volumes of data. The issue becomes critical in the area of alarms in response to power system disturbance conditions. The area of data visualization may be able to aid in the development of effective tools for interfacing the operators with the massive data volumes. This topic is discussed below in this section.

The additional data gathered and stored should be able to provide major benefits in allowing the development of enhanced tools for security assessment and control. The utilization of the data is discussed for enhancing tools in information management, state estimation, voltage security analysis, ATC evaluation, model development for both RTSMC and study applications, and training simulators. An important part of improving the RTSMC is the software engineering. The key issues of interest related to this aspect are delineated. The final topic considered is the possible application of complex systems to power system disruptions.

4.1 Data Visualization

The data visualization advances in computing have yet to be put to use on any widespread basis in power systems. In fact, because visualization tools have evolved little beyond the traditional one-line diagram and tabular displays, it is more and more difficult for operators and others to gain an intuitive understanding of the actual real-time operations and control of the grid.

Recent advances in computer hardware and software technology have made it possible to move beyond simple tabular displays and one-line diagrams. The ability to redraw even relatively complex displays at frame rates close to, or even at, full-motion video speeds opens up substantial new possibilities for dynamic one-line displays. Use of animation can produce visually appealing displays of flows, both real and reactive, and line loadings to point out overloads. An additional visualization tool to effectively compact the large data set is the use of contours to show spatial data, such as bus voltage magnitudes/angles, line flows, or even derived values such as line power transfer distribution values. Contours provide a natural encoding for showing large amounts of spatial data. The advantage of the contour is it allows the user to rapidly process large amounts of data and to quickly spot developing trends. Through the combined use of contour and animation, the operator could quickly assess how the system state has been changing over a specified time period. Such a display could also be particularly helpful for engineers in the study of system disturbances and in the design of new control strategies.

One promising new tool for power system visualization is the use of virtual environments (VE's), or virtual reality systems. These are simulation frameworks that present information using interactive three-dimensional (3-D) graphics. VE's differ from standard desktop computing environments by the extent to which the user is immersed in the comprehension of a complex environment with which he or she can directly interact to observe immediate results. Additional enhancement is possible through the use of specialized equipment, such as wrap-around viewing to fill both foveal and peripheral views, stereoscopic displays to invoke the perception of a true three-dimensional sense in the brain, direct-manipulation of the environment via space sensors, and an array of speakers to reproduce a data-driven auditory field.

The key research challenges associated with VE applications are the construction of appropriate paradigms for the interactive display of the large amounts of power system data and the development of effective human factors for such applications. A key difficulty to overcome is the lack of "physical" representation for power systems variables such as the reactive power output of a generator the voltage at a bus, or the percentage loading of a transmission line as a function of power transfer levels. These variables are typically presented as numerical values on either a one-line diagram or in a tabular display. Research is needed to develop effective schemes to aggregate power system application data for presentation in the VE.

The VE application in operations in the alarming area is logical. The management of alarms has become a major issue in system operations. Without effective alarm management, the system operator is easily overwhelmed by alarms during the system response to a disturbance. The challenge to the operator is to ascertain the initiating event from the onslaught of alarms, most of which are due to a single initiating event. For example, the opening of a heavily loaded transmission line could create numerous low bus voltage, line overload on other transmission lines, and even generator VAr loading, alarms. The visual power of VE can be effectively exploited to indicate to the operator the key initiating event. Also, the VE can help to alert the operator of the extent of the system problems. This could be a major development in improving alarm management.

4.2 Analytical Tools

The restructured industry environment will require new and/or improved tools for RTSMC applications. Some important areas for which such tools are required include data management, state estimation, voltage security analysis and ATC evaluation. These are discussed below.

4.2.1 Information management

A key research area in a restructured, competitive power network is the role of grid information. The FERC Orders require that information regarding the power transfer capability of the grid be auditable and made widely available to allow evaluation of the grid's capability to undertake desired or potential transactions. In contrast to this, in the new electricity markets, the players, in general, and individual generator owners, in particular, want to guard their data as proprietary information due to their potentially significant competitive impacts. However, typical studies of power system dynamic performance and associated real-time control system design require both physical and what may be viewed by some as market data: the transmission system parameters and configuration, and detailed dynamic characteristics of generating units. Who will get access to both types of data in the future is an open issue. The responsibilities and authority of the IGO may vary from region to region. Consequently, so will its ability to *collect* both types of data. It would be natural for the IGO to assume responsibility for analyses to ensure desirable dynamic performance. But even if the IGO has the authority to collect proprietary dynamic data from individual plant owners, one must consider the engineering resources and computational tools necessary to validate this huge data set. For example consider the studies carried out to investigate the reliability events in the West in 1996. The models in use in the Western US, arguably among the most advanced in the world, had sufficient inaccuracies that even if the exact scenarios of the 1996 Western US outages been studied in advance, the simulation tools would have produced results that diverged from reality. Such studies would consequently have failed to predict the scope of the major blackouts that actually occurred. An in-depth "post-mortem" engineering study later corrected model parameters to a degree that the simulation tools *did* match actual occurrences with some fidelity. The question naturally arises of how much more severe the mismatch between actual system performance and simulation predictions could become in the future, if one relies on traditional methods to gather data and assemble dynamic models.

The Secretary of Energy Advisory Board, Task Force on Electric System Reliability recognized the need for improved communications and increased information sharing between control centers. It recommends developing interoperability standards to this end. In addition, it recommends study of information assurance issues to counter the growing vulnerability to cyber threats.

4.2.2 State estimation

If an IGO is to carry out time domain simulations of network dynamics, and perform control design based upon these studies, supplemental means of collecting and analyzing data related to the dynamic performance of the system will become increasingly critical. Strong motivation will exist for improved tools for estimating steady state operating points and validating dynamic parameters using physical measurements of the system; the Western US example discussed above provides a good example for this motivation. The former task, that of estimating current system operating point and grid configuration from on-line measurements, has an established basis in power systems and is termed state estimation. State estimation is a vital component of the RTSMC applications tool box. The state estimator provides the most up-to-date snapshot of the system and is the basis for all security assessment computations.

With growth in the number of entities whose competitive position is impacted by system operating condition and grid configuration, it is easy to predict that research needs even in this traditional form of power system state estimation will increase markedly. A desirable extension of the current state of the art in state estimation is to dynamic state estimation. Operators would like to be able to track the dynamical state of the system to help in actual operations. Among new technologies impacting these developments, most notable is the growing availability of high sampling rate PMU's. Such PMU's provide a highly useful tool for adding measurements to the set available for state estimation. It also opens possibilities for pushing the envelope for improved system protection and dynamic control.

Opportunities created by WAMS applications provide a counter trend to the forces of structural and organization change in the power system that would seem to dictate more decentralized, autonomous measurement and control approaches. Future work in real-time control must seek a symbiotic fusion of these trends. In particular, we see the structural changes in the system suggesting most strongly that generation control be decentralized and autonomous. However, the emergence of the IGO will put greater centralized authority into the hands of a single entity with regard to control of the transmission facilities. Therefore, we envision a need for use of WAMS to create a hierarchical system of estimation that would compress the high volume of measured data at distributed measurement points, passing key real time dynamic information to the IGO. This trend may be driven in part by the fact that the IGO will have less direct information from the generator operator regarding its dynamic characteristics and control action, which may be deemed to be proprietary data. Instead, the IGO must cull the dynamic data it needs to predict system-wide dynamic performance and coordinate its grid control actions, using WAMS measurements. Key to this effort will be design of appropriate data compression algorithms, as well as determining the dynamic modeling, estimation and control needs of the IGO.

As an example, one might consider the control algorithms for a critical transmission system control element, such as a DC transmission link, or future FACTS technologies such as thyristor-controlled series capacitors or UPFC's. The conventional approach to design such control elements in a vertically integrated utility would involve construction of complete dynamic models for the interconnected grid, generator units, and their controls. These models would be used to tune control parameters to avoid potentially destabilizing interactions of generator controls (e.g., PSS) and FACTS controls. Even if one assumes an IGO has broad authority, it is still likely that generator dynamic data may be more difficult to obtain and less reliable in a competitive environment, and this creates challenges for the traditional control design approach. Deployment by the IGO of advanced estimation techniques based on WAMS data could prevent associated degradation of reliability and real-time control performance. However, the various sources of uncertainty in measurements and models will lead to a greater reliance on methods for quantifying the error bounds associated with studies of dynamic behavior.

4.2.3 Voltage security analysis

Considerable work has been done on characterizing steady state system limits with respect to the voltage collapse phenomena. However, tools for characterizing dynamic voltage collapse and the ability of real-time controls to mitigate this collapse, are much less mature. The dynamic elements of voltage collapse are often determined by the rate of recovery and, most importantly, the rate of reactive recovery in the load and by intentional control delay response characteristics in LTC transformers. Such phenomena act on a time scale of several minutes, during which anticipated market mechanisms for procuring reactive ancillary services could be exercised. This situation presents an opportunity for reducing system vulnerability to voltage collapse by constructively exploiting the interplay in the previously described three layers structure. The coupling of reactive load recovery in the physical delivery layer and the reactive/voltage ancillary services in the market layer can be effectively utilized in the communication/control layer for greater intelligence and operating condition "awareness" in such devices as LTC transformers.

4.2.4 ATC evaluation

A critical area for new and improved tool development is ATC evaluation. The two major aspects requiring attention are the computation and the actual implementation of ATC software for interconnected systems. As the primary and most visible mechanism for tracking the margin of a power system to its operating limits, ATC evaluation must be based on good and up-to-date state estimation results and must correctly reflect the impacts of all possible anticipated security enhancement and control actions. Enhanced real-time monitoring with measurements such as those from WAMS will greatly improve the reliability of data describing existing conditions, particularly in describing the external equivalents, i.e., the systems of the neighboring entities. The associated high-performance real-time control will provide the flexibility to actually ensure operation within computed operating limits and thereby improve the reliability of ATC posted data. One of the key issues in ATC computation is the need to rapidly update posted data to reflect changing conditions as well as scheduled and reserved transactions. Research is needed to properly utilize the capabilities of RTSMC to realize improvements in this ATC data.

With advances in RTSMC, the interconnected grid will be able to accommodate a wider range of transactions and should make transfer capabilities more predictable and controllable. In both steady state operation and dynamic response, these advances will allow operations closer to thermal limits[9]. With limited resources, there will be a challenging problem to determine the optimal RTSMC siting and control strategy to maximize system performance including ATC. An additional challenge in this area will be to extend the capability of linear distribution factor methods to include the impacts of flow controllers. Significant advances in the appropriate representation of the nonlinear nature of these controllers is required to obtain required simulation efficiency to meet the needs of real-time ATC analysis.

A closely related topic to ATC is the transmission loading relief (TLR) procedure developed by NERC. Since summer 1997, TLR is the predominant line loading relief procedure used in the Eastern Interconnection. TLR is a regional procedure relying on multi-control-area regional security coordinators' curtailment of transmission. TLR is a flow-based approach, with the curtailment evaluation based on impacts of overloaded facilities. This method for ordering the curtailment of transactions to address congestion problems does not take costs into consideration. When invoked, one or more transactions on the system is ordered to be curtailed. The curtailed power is, typically, made up from local sources such as reserves. The invocation of a TLR procedure leads to a new operating state with the congestion eliminated.

The implementation of TLR is hampered by a number of policy and technical complications. The policy complications include the realities of conflicting commercial interests and issues of fairness and equity, as well as, information availability. The technical problems are associated with the need to accurately predict the impact of each and every transaction on the system limiting capabilities or flow gates. For accuracy and effectiveness, this requires not only a good estimate of the system state, but also a good estimate of each and every curtailable transaction. Once the state of the system is known, an additional challenge is to compute and disseminate the results to all parties involved in the congestion relief. In all these calculations, it will be necessary to take into consideration time response capabilities associated with the various options possible for congestion relief.

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9 Moreover, through the dynamic monitoring of transmission lines, the limits of transformers and generator rotors/stators, for example, will more accurately reflect the actual system constraints.

Since TLR is a procedure that has been institutionalized, at least for the time being, it is clear that the analysis of TLR actions requires a comprehensive set of tools. A key need is a tool that permits the accurate evaluation of the impact of trades and actions on system limits and capabilities, including response time capabilities. It should also permit coordinated or packaged trades as single entities. Another tool that appears quite important is the development of schemes for compliance monitoring – after invocation of a TLR order, there is the need to be able to effectively monitor the actual execution and its impacts. Moreover, an economic assessment capability will become necessary to provide appropriate incentives for parties to cooperate with the TLR order.

4.3 Software Engineering

In addition to research efforts concerned with the reliable operation of the electric power grid focused on power systems engineering, control systems engineering and institutional design issues, there is a need to emphasize the software engineering aspects. We believe that successful and reliable operation and control of the power grid will be increasingly dependent on good software engineering of the data acquisition, communications, computation, control, and market operation systems. The software engineering issues confronted in the development of these systems are not unique to the electric power sector. Similar issues arise in software design in all other sectors of the economy including avionics, process plant control systems, military command and control and large financial trading systems. However, the enormous scale, geographic dispersion, real-time requirements, continuous operation, and long service life of electric power systems make many of the issues more severe in the power systems environment. In recent years large-scale failures of major web sites, some telephone systems and other computer-communications systems have demonstrated the vulnerability of these systems to software failures. Prolonged power and transportation system outages (e.g., the BART system in the San Francisco Bay Area) have arisen because of inadequate failure recovery software. A number of major control systems projects, e.g., the Federal Aviation Authority's Air Traffic Control system , have suffered very large, expensive failures of software involving huge costs in dollars.

An important and substantial part of the R&D program in real-time monitoring and control of electric power grids is the software engineering component. The major thrusts of this component are the design, implementation, testing, maintenance, and evolution of large-scale real-time reliable distributed systems with focus on both computing and communications aspects. The effort addresses issues such as networking and time coordination protocols, distributed system frameworks, security, fault tolerant computing and communications, real-time databases, time series databases, event notification services, directory and namespace management, large-scale system administration, (geographic) partitioning of control operations, data exchange protocol design, standardization and translation of diverse database schemas, model-based diagnostic software, recovery planning software architecture, etc.

Historically, we have seen an evolution in the power industry from vendor specific (or more recently industry specific) software technology toward the use of more standardized software and communications components. The motivation is simply to take advantage of the economies of scale in software development. However, many of the commercial software components have not been constructed specifically to meet the critical performance, reliability, scalability, or the security requirements of electric power grid control. The information security aspects require careful attention since the consequences of a cyber attack would have drastic impacts.

Many of these software engineering issues are not entirely independent of other aspects of the design of the electric power grid. For example, the software architecture, institutional design and the control system design are deeply intertwined in the distributed aspects of the control system. Also, of concern, are the difficulties of building and testing control systems against failure scenarios, especially large-scale systemic failures under conditions of natural disasters or attack. The ability of software to handle various faults or operational errors are among the most difficult to implement. The task is tedious and often accounts for major portions of the code.

An additional need in control system software is genetic diversity. The replication of software is very tempting and the use of identical software throughout the control system produces major savings in software development costs. However, this exposes the aggregate control systems to considerable risks due to possible common programming error causing system failure and the common vulnerability to cyber attack. The cultivation of genetic diversity (alternative software implementations) throughout the control system is desirable to avert such events.

4.4 Model Development

Lessons learned from recent reliability events indicate that the controls performed as designed. A major deficiency was, however, in the models used for the design of control laws and the tuning of controllers. An important overriding consideration is that it is very difficult to control systems if the system dynamics and control policy impacts are not well understood. Properly calibrated models of system dynamics and the appropriate application of control systems theory are a prerequisite for effective control system design and implementation. This is a particularly critical concern in operations in regimes well outside of normal conditions brought on by a major natural or man-made disaster.

The new metering technology and broader measurement actions can provide data for improved modeling of equipment. Efforts to construct more detailed representation of equipment and loads, and higher fidelity models, to develop better parameter estimates and to undertake improved model validation will have measurable benefit in RTSMC. In addition, deployment of improved models in planning will add to system robustness and retuning of controllers. An accompanying benefit of improved models is the reduction of uncertainty in operations. Another application of improved models is in the area of training simulators.

4.5 Training Simulators

As the structure of the power system changes, parallel modifications must be implemented in the simulators used for training of power system operators. The unbundling in the industry has resulted in the creation of new operator functions in the disintegrated environment. There are operators of generation entities, transmission entities, brokers, IGO's, PX's and scheduling coordinators with widely different scope of activities and responsibilities. Clearly, the training required for each of these operators will be different. The common ground can still be the real-time simulation of the power grid but the training subsystem will have to be customized for the type of operator. The use of VE's for training will be beneficial since it has excellent ability to mimic, as closely as possible, an existing physical environment.

4.6 Complex Systems Applications to Power Systems

The multi-layer construct, discussed in a previous section, lends itself naturally to exploring the application of complex systems. In analyzing the cascading failures leading to blackouts, such as the 1996 West Coast in reliability events, it is valuable to study the particular rare events and chains of causes leading to the system failure. Defensible and reasonable explanations for the particular events can be found and can form a useful basis for action to help prevent recurrence of the particular events. Complex systems analysis offers a different, more global perspective on understanding and avoiding system failure. The application of complex systems perspective to power systems may offer good additional insights. The idea of self-organized criticality has been applied to a wide range of cascading events in complex interconnected systems: for example, avalanches in rice piles, models of forest fires, models of traffic jams, turbulent transport in plasmas, earthquakes, and spin glass systems. We illustrate the potential of complex system approaches to understand, predict and control the response of stressed power systems to cascading events using this idea of self-organized criticality.

Self-organized criticality is the tendency of complex systems to organize themselves to a subcritical state in which the system responds to stresses by exhibiting events at a wide range of scope and frequency. In the power system context this would imply overloads and blackouts of widely varying spatial extent and frequency. The idea is that maximizing power transfers while subject to overloads inherently and at a global system level leads to a self- organized critical state. A key feature contributing to the self-organized critical state is the tendency of overload conditions to propagate in the network in a cascading manner. Some events would be localized, whereas, others would cascade into widespread blackouts. In the various applications to the models cited, there has been progress in predicting and controlling the complex system responses to the stresses causing the cascading events.

The potential for power systems is that cascading overload and blackout phenomena could similarly be understood and mitigated from a complex systems perspective.

The research needs to focus first to the study of the extent to which power systems display self-organized criticality by analyzing power system data and constructing and simulating suitable power system models. A blend of traditional and novel approaches will be needed to devise and test power system models capturing the essence of self-organized criticality. Then, once the complex system aspects of power systems are better characterized, the mitigation or control of cascading events can be addressed from a global systems perspective. The interdisciplinary nature of this approach suggests that for increased effectiveness the work should be performed together with researchers involved in the rapidly developing complex systems efforts in physics, mathematics and other areas.

5. Conclusions

The restructuring underway in the electricity business is impacting RTSMC at all levels and in all aspects as the industry moves away from its well entrenched VIU structure. This section presents a brief summary of the critical research needs to meet the vast scope of challenges in RTSMC to ensure reliable and cost effective electricity in the future. Given the dependence of RTSMC on technology advances in the areas of computers, communications, control and power electronics, the effective integration of these advances is a major challenge that needs to be addressed in the RTSMC research agenda. In addition, there are myriad problems ranging from the very basic research needed in formulation of the problems emerging from the restructuring to the *data overwhelm* issues to the needs for new control laws and analytical tools. All these are summarized below under three separate rubrics – automatic controls, security monitoring and security enhancement.

Given that the restructuring of the industry is evolving in fits and starts, and that the RTSMC procedures put some constraints on the market and vice versa, the research discussed in this document has to respect the evolving policy decisions. Fortunately, restructuring is taking different shapes in different countries, which in turn is allowing some examination of best practices both for market design as well as the control system. The working definition of ancillary services is probably a good example of this evolution.

A fixed structure of the marketplace alone is not enough for the development of RTSMC. The surveillance of the marketplace also must be in place. Performance standards for security and control are required and must be met. The research and development in RTSMC will use these standards as constraints in the formulation of the various problems. The development and refinement of these RTSMC performance standards must be part of this research agenda. A related issue is the availability of real-time data to all the market players; any restrictions on data because of market sensitivity may affect the feasibility of different RTSMC schemes.

All aspects of RTSMC are dependent on the extensive use of computation and communications in complex multi-layered structures. The security and reliability of these structures are also research issues. Although the general issue of computer security or communication reliability is outside the scope of this paper, the security and reliability of these computing/communication structures developed specifically for RTSMC of power systems must be investigated to accomplish the overall goals of the RTSMC.

5.1 Automatic Controls

We consider under this topic both the slower and faster controls. The slower controls are the ones exhibiting the strong coupling between the physical delivery and the marketing layers. Two striking needs in the slower controls area are the following:

- Automatic generation control to follow load while maintaining contractual power deliveries must be adapted to enable this control to be acquired effectively as an ancillary service without degrading system performance. Although the basic control scheme is not expected to change, the problems of handling many more loads and control variables and monitoring generation control performance must be investigated.
- Voltage control to keep voltage magnitudes within specified operational limits is largely a local substation level issue. As this control is acquired as an ancillary service, effective means to implement such control on a regional basis need to be explored.

In the realm of faster controls, the protection system is basically a local control, which will be strongly impacted by the advancements in communications which are making regional data available in a timely manner to perform fast stability controls. Of course, a number of key research problems need to be solved before such regional stabilization is feasible, including:

- the identification of the control problem objectives and constraints within the large mass of data is required before control action can be taken;
- the explicit recognition that different phenomena, such as voltage or angular stability require different control strategies and the formulation of the appropriate control strategy;
- the development and implementation of possibly new control laws may require the judicious application of advances in control theory.

5.2 Security Monitoring

An overriding problem is the *data overwhelm* issue that requires the development of innovative and creative tools for RTSMC. The purpose of automatic control is to automatically keep the power system within normal operating conditions. The purpose of security monitoring is to look ahead for possible contingencies that may transition the power system away from a normal operating state. Examining the effects of specified contingencies is a computationally intensive task and requires fast computation for monitoring the security of large interconnections.

For example, the state estimation area presents some critical needs. The state estimator is a basic tool in the tracking of the real-time model of the power system from the collected data. While present day state estimators can handle the slowly acquired static data, the expected imminent availability of larger sets of real-time measurements raises new challenges. The tracking the real-time model of the power system more closely becomes possible only when the more complex problem of state estimation from these larger and more frequent data sets can be solved. In performing security assessment, the increases in computing power have enabled the simulation of a vast number of contingencies, including in some cases the dynamic regime response, but the recognition of security problems within these large volumes of simulation outputs remain a daunting problem. Since the problems caused by a contingency can range from the simple overloading of a line to the various complicated instability phenomena, identifying, classifying and ranking the security problems on a continuing basis will require considerable research.

5.3 Security Enhancement

A logical step to follow security monitoring improvements is security enhancement, that is, once specific problems are detected under possible contingencies, the subsequent question is what should be done about it. Although the last two decades have seen a lot of research in security monitoring, very little has been done in security enhancement. Also, given that any enhancement of security will almost surely increase the cost of operations and disrupt the prevailing market agreements, some measures of security performance must be accepted as thresholds. The determination of these thresholds alone is a major research topic in itself.

Appendix A: Major Thrusts in Restructuring

The electric utility industry, the last major regulated monopoly to undergo restructuring, is in the midst of its most turbulent period since Edison started the Pearl Street Station in 1888. A number of driving forces including the environment, technology advances, legislative/regulatory initiatives and market pressures are bringing major changes to the industry. The Public Utility Regulatory Policy Act (PURPA) of 1978 ended the utility monopoly in generation. It unleashed competition through the introduction of non-utility generators, the so-called *qualifying facilities.* These once fledgling power enterprises constitute today a multibillion dollar industry and are the major source of new electric capacity in the nation.

The passage of the National Energy Policy Act (EPACT) of 1992 marked the end of a highly regulated and structured period for electric utilities. By broadening the powers of the Federal Energy Regulatory Commission (FERC) to mandate wheeling by transmission owning entities, EPACT made possible the start of the transmission open access regime in North America. FERC seized on its newly enlarged authority and issued a series of decisions which laid out the regulatory framework for the operation of the open access transmission system. The FERC Orders 888 and 889 constitute the most fundamental reexamination of wholesale electric power operations and regulation since the creation of federal oversight over electricity in 1935. The Orders serve to promote aggressively robust competition in wholesale electricity markets by mandating open access to all wholesale players, remedy undue discrimination in providing transmission service through a major overhaul of the industry's past practices and address transition costs associated with industry restructuring.

Major thrusts of the FERC Orders 888 and 889 changed fundamentally the functioning and operations of electric utilities. The following are among the most important ones:

- functional unbundling of transmission and generation services;
- establishment by each transmission provider of an electronic bulletin board known as OASIS (Open Access Same Time Information System);
- specification of the basic service requirements of transmission providers; and,
- unbundling of *ancillary services* from transmission services.

The functional unbundling serves as the basis for the implementation of non-discriminatory open access transmission by requiring the transmitting utility to

(i) separate pricing of wholesale generation, transmission, and ancillary services,
(ii) take transmission and ancillary services for all its future wholesale transactions under the same terms, conditions and rates as offered to its competitors, and
(iii) provide access to all transmission customers to the information on the same OASIS, at the same time and in the same manner.

The OASIS is the primary tool for implementation of functional unbundling. Each OASIS is required to display information on transmission services available, tariffs, schedules and ATC estimates. The set up of OASIS is accompanied by the establishment of *Standards of Conduct* which establish a clear separation between the merchant and transmission functions. This so-called “Chinese” wall is erected to prevent preferential access to transmission prices and availability.

The basic service requirement provisions obligate transmission entities to offer transmission and ancillary services which they are reasonably capable of providing. There are six mandated ancillary services which must be offered unbundled from basic transmission service[10]. These FERC Orders together with many associated decisions serve to make transmission a *common carrier* service[11]. The unbundling brought about by the FERC actions serves to spur competition, results in the entry of many new market players and changes the industry’s structure. Most prominent among these new players are the power marketers and brokers whose advent has established the MWh as a commodity not different than any others (e.g., hog bellies, aluminum, coffee, etc.)traded today. Today, utilities, financial services, marketers, brokers, generating entities and speculators are buying, selling and swapping power/energy on a scale unimaginable a few years ago.

The proliferation in financial and physical flow transactions is changing the face and organizational structure of the industry at a rapid pace. A major development is the establishment of an independent system operator (ISO) in various regions of the nation. The motivation for the ISO concept stems from the FERC policies that make it clear to transmission utilities that the “transmission and…” business would be difficult, problematic and possibly of limited strategic value. In light of the increasing volumes of transactions in each region, the need to solve transmission problems on a regional basis became critically important. Transmission owning entities realized that independent decision making on transmission service and pricing issues necessitates the removal of control of the transmission system from the owners who also control other sectors of the electricity business. In addition, the facilitation of the commercial market by an independent entity can remove impediments to grid access and can provide transmission service. In Order 888 FERC set out 11 principles with which a properly constituted ISO must comply. The basic requirement is compliance with FERC’s nondiscriminatory

[10] Ancillary services are system support services that are essential for physical delivery of energy from a source point to a load point. Such services are fundamental and indispensable system services required for the provision of transmission service and in their absence instantaneous system collapse would result. The FERC list of ancillary services consist of scheduling, system control and dispatch; reactive power and voltage control from generating sources; regulation and frequency response; energy imbalance; spinning reserves; and, supplemental reserves.

[11] A key impact of the *common carrier* transmission network is the utilization of the transmission grid in very different ways than those for which it was planned. For RTSMC, there are significant implications in terms of contingency definition and selection, the setting of limits and relays for operations and in the control issues.

transmission tariff requirement. The establishment and operation of an ISO, essentially a regulated monopoly, is under FERC jurisdiction, except in Texas, where it is under state regulation.

The advent of the new players was accompanied by the establishment of various market mechanisms for the trading of electricity. In addition to the conventional physical-flow-based transactions, a large amount of financial transactions have been taking place. The market mechanisms have introduced new structures such as the power exchange (PX) in California. In other venues such as PJM, the market mechanism has been integrated as part of the new independent system organization.

In the restructuring, the role of NERC, the industry self-regulating organization for ensuring reliability is also undergoing major transformation. NERC has played an active part in facilitating the markets to evolve through its involvement in the development of OASIS, the evaluation of ATC and the establishment of new security coordinators for the RTSMC function. There are many activities underway to replace the voluntary NERC organization by the mandatory NAERO structure which would have FERC as a regulatory backstop.

Different visions of the ISO concept are evident in the implementation in place or planned. The key dimensions along which they differ are:

- geographic extent
- level of authority vested in the organization and responsibilities
- amount and nature of information available to the organization
- level of centralization/decentralization in the control authority

There is considerable controversy among various industry participants and FERC has given notice of its proposal to extend the ISO concept into a regional transmission organization (RTO). An RTO would be a central authority covering a larger geographic territory with responsibilities encompassing both operation and planning. For the purposes of this White Paper, we adopt the notion of a *generic* independent grid operator (IGO) so as to remove any of the “baggage” associated with the ISO/RTO issue. The principal role for the IGO is to facilitate markets, i.e., to attempt to enable the undertaking of as many transactions as possible by the various market players. This role is discharged under the constraint of maintaining the reliability and security of the interconnected system. The IGO has the obligation to provide transmission service to all customers to have reliable supply so as “to keep the lights on”. The IGO has the responsibility to acquire all necessary services such as ancillary services to fulfill this obligation. We assume that the IGO is independent of all entities under its control and that it has no ownership/financial interests in any of these entities.