Final Report to the National Energy Technology Laboratory on FY09-FY13 Cooperative Research with the Consortium for Electric Reliability Technology Solutions

Power Systems Engineering Research Center

Empowering Minds to Engineer
the Future Electric Energy System

Report from the Power Systems Engineering Research Center to the National Energy Technology Laboratory for Work Performed in Cooperation with the Consortium for Electric Reliability Technology Solutions Under FY 2009-2013 Funding from the U.S. DOE

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For information about PSERC, contact:

Vijay Vittal
PSERC Director
Ira A. Fulton Chair Professor in Electrical Engineering
School of Electrical Computer & Energy Engineering
Arizona State University
Email: Vijay.Vittal@asu.edu
Phone: (480) 965-1879

For information about CERTS, contact:

Joe Eto
CERTS Project Coordinator
Lawrence Berkeley National Laboratory
Email: JHEto@lbl.gov
Phone: (510) 486-7284

Power Systems Engineering Research Center

The Power Systems Engineering Research Center (PSERC) is a multi-university Center conducting research on challenges facing the electric power industry and educating the next generation of power engineers. More information about PSERC can be found at the Center's website: http://www.pserc.org.

For additional information, contact:

Power Systems Engineering Research Center
Arizona State University
527 Engineering Research Center
Tempe, Arizona 85287-5706
Phone: 480-965-1643
Fax: 480-965-0745

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Executive Summary

The Consortium for Electric Reliability Technology Solutions (CERTS) was formed in 1999 in response to a call from U.S. Congress to restart a federal transmission reliability R&D program to address concerns about the reliability of the U.S. electric power grid. CERTS is a partnership between industry, universities, national laboratories, and government agencies. It researches, develops, and disseminates new methods, tools, and technologies to protect and enhance the reliability of the U.S. electric power system and the efficiency of competitive electricity markets. It is funded by the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability (OE).

Since 1999, one of the CERTS research performers has been the Power Systems Engineering Research Center (PSERC). Since 1996, PSERC, a thirteen-university consortium with almost 40 industry members, is engaged in collaborative research and education with the mission of "empowering minds to engineer the future electric energy system." Its researchers are multi-disciplinary, conducting research in three principal areas: power systems, power markets and policy, and transmission and distribution technologies. PSERC works to achieve:

- An efficient, secure, resilient, adaptable, and economic electric power infrastructure serving society
- A new generation of educated technical professionals in electric power
- Knowledgeable decision-makers on critical energy policy issues
- Sustained, quality university programs in electric power engineering.

Beginning in January 2009, PSERC's research in collaboration with CERTS was administered through cooperative agreement DE-FC26-09NT43321 between the National Energy Technology Laboratory and Arizona State University, PSERC's lead university. This report describes the research performed under that agreement through March 2015 with funding from FY2009 to FY2013. Research under FY 2014 and 2015 OE funding is being administered under a separate cooperative agreement, DE-OE0000670, which ends in September 2017, so the results of that research are not included in this report.

The research can be categorized in two major areas: Reliability and Markets, and Real Time Grid Reliability Management (which includes the Advanced Applications Research and Development sub-area).

- The Reliability and Markets researchers worked to develop and demonstrate a broad set of integrated engineering and market-based approaches, tools, and technologies focused on improving the reliability and efficiency of the electric sector—both in planning and in operations. The emphasis of this research was on the linkage between the physics of the electric power grid and the economics of electricity markets.

- Real Time Grid Reliability Management research focused on developing and prototyping software tools that will ultimately enable the electricity grid to function as a smart, automatic, switchable network. In this area, PSERC has focused on Advanced Applications Research and Development (AARD), a subgroup of activities that works to develop advanced applications and tools to more effectively operate the electricity delivery system, by enabling advanced analysis, visualization, monitoring and alarming, and decision support capabilities for grid operators.

This report provides an overview of PSERC and CERTS, of the overall objectives and scope of the research, a summary of the major research accomplishments, highlights of the work done under the various elements of the NETL cooperative agreement, and brief reports written by the PSERC researchers on their accomplishments, including research results, publications, and software tools.

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1. Introduction

The Power System Engineering Research Center (PSERC) engages in technological, market, and policy research for an efficient, secure, resilient, adaptable, and economic U.S. electric power system. PSERC, as a founding partner of the Consortium for Electric Reliability Technology Solutions (CERTS), has conducted a multi-year program of research for U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE) to develop new methods, tools, and technologies to protect and enhance the reliability and efficiency of the U.S. electric power system as competitive electricity market structures evolve, and as the grid moves toward wide-scale use of decentralized generation (such as renewable energy sources) and demand-response programs.

PSERC activities were led by university members with substantial input from CERTS whose membership and advisors include the utility industry, national laboratories, universities, and government agencies. The scope, development, and review of PSERC research related to this effort were managed through CERTS under guidance and direction provided by OE. OE's funding for PSERC, starting in fiscal year (FY) 2009 and ending in FY2013, was administered by DOE's National Energy Technology Laboratory (NETL) through a cooperative agreement with Arizona State University (ASU). ASU provided sub-awards to the participating PSERC universities.

This document is PSERC's final report to NETL on the activities conducted for OE through CERTS from January 2009 through March 2015 using FY 2009 to FY 2013 funding under cooperative agreement DE-FC26-09NT43321. A no-cost extension was granted which resulted in the project ending date of March 31, 2015. Research under FY 2014 and 2015 OE funding is being administered under a separate cooperative agreement, DE-OE0000670, which ends in September 2017, so the results of that research are not included in this report.

2. Background

2.1. Power Systems Engineering Research Center (PSERC)

PSERC is a thirteen-university consortium with almost 40 industry members. Since 1996, PSERC has been engaged in research and education efforts with the mission of "empowering minds to engineer the future electric energy system." Its work is focused on achieving:

- An efficient, secure, resilient, adaptable, and economic electric power infrastructure serving society
- A new generation of educated technical professionals in electric power
- Knowledgeable decision-makers on critical energy policy issues
- Sustained, quality university programs in electric power engineering.

PSERC core research is funded by industry, with a budget supporting approximately 30 principal investigators and some 70 graduate students and other researchers. Its researchers are multi-disciplinary, conducting research in three principal areas: power systems, power markets and policy, and transmission and distribution technologies. The research is collaborative; each project involves researchers typically at two universities working with industry advisors who have expressed interest in the project. Examples of topics for recent PSERC research projects include grid integration of renewables and energy storage, new tools for taking advantage of increased penetration of real-time system measurements, advanced system protection methods to maintain grid reliability, and risk and reliability assessment of increasingly complex cyber-enabled power systems.

PSERC's director, Vijay Vittal, is a professor at Arizona State University (ASU), PSERC's lead university. Professor Vittal was the project principal investigator for the work under the NETL cooperative agreement.

2.2. Consortium for Electric Reliability Technology Solutions (CERTS)

CERTS was formed in 1999 to research, develop, and disseminate new methods, tools, and technologies to protect and enhance the reliability of the U.S. electric power system and the efficiency of competitive electricity markets. The founding members of CERTS include Lawrence Berkeley National Laboratory; Oak Ridge National Laboratory; Pacific Northwest National Laboratory; Sandia National Laboratories; PSERC; and the Electric Power Group (EPG).

CERTS research is organized around the followed topical areas:

- ***Real Time Grid Reliability Management (Area 1)***
  Research in this area is focused on developing and prototyping software tools that will ultimately enable the electricity grid to function as a smart, automatic, switchable network. Research in this area is further divided between Synchrophasor Technology Initiatives, which involve support to the North American Synchrophasor Initiative and Advanced Applications R&D, which involve development and prototyping for software tools.
- ***Reliability and Markets (Area 2)***
  These activities work to develop and demonstrate a broad set of integrated engineering and market-based approaches, tools, and technologies focused on improving the reliability and efficiency of the electric sector—both in planning and in operations. The emphasis of this research is on the linkage between the physics of the electric power grid and the economics of electricity markets.
- ***Distributed Energy Resources Integration (Area 3)***
  CERTS is evaluating how distributed energy resources, when deployed in large numbers, affect—and could be modified to enhance—electricity grid reliability. These resources include microturbines, fuel cells, photovoltaic systems, and traditional internal combustion engines.
- ***Load as a Resource (Area 4)***
  The focus of this set of activities is to determine the effect of customer participation (demand response) on market efficiency, and to demonstrate advanced demand-response technologies and strategies that will improve the reliability of the grid—with the goal of accelerating meaningful opportunities for customers to participate voluntarily in competitive electricity markets.
- ***Reliability Technology Issues and Needs Assessment (Area 5)***
  Research in this area works to monitor and identify technology trends and emerging gaps in electricity system reliability research and development (R&D) to anticipate and scope new R&D efforts needed to enable the grid of the future.

The PSERC activities that were coordinated through CERTS for OE under the NETL cooperative agreement involved only the first two of the five CERTS research areas: Real Time Grid Reliability Management (which includes the Advanced Applications Research and Development sub-area), and Reliability and Markets.

CERTS' director is Joe Eto, a staff scientist at the Lawrence Berkeley National Laboratory. CERTS is funded by OE and meets regularly with an Industry Leaders Council (ILC), comprised of CEOs and senior VP-level representatives from CERTS industry partners, to review critical reliability-related R&D issues facing the electricity sector.

3. Overall Objectives and Research Scope

PSERC's objective is to proactively address the technical and policy challenges of U.S. electric power systems. To achieve this objective, PSERC works with CERTS to conduct technical research on advanced applications and investigate the design of fair and transparent electricity markets; these research topics align with CERTS research areas 1 and 2: Real-time Grid Reliability Management (Area 1), and Reliability and Markets (Area 2). The CERTS research areas overlap with the PSERC research stems: Power Systems, Power Markets, and Transmission and Distribution Technologies, as described on the PSERC website (see http://www.pserc.org/research/research_program.aspx).

Table 1 lists the PSERC principal investigators and projects conducted by PSERC through CERTS over the performance period of the NETL contract (including funding by project from FY 2009 through FY 2013). The performers were with Arizona State University (ASU), Cornell University (CU), Iowa State University (ISU), Texas A&M University (TAMU), University of California at Berkeley (UCB), University of Illinois at Urbana-Champaign (UIUC), University of Wisconsin-Madison (UW), and Washington State University (WSU).

3.1. Reliability and Markets (R&M)

PSERC research activities in the area of reliability and markets (CERTS Research Area 2) focused on electric market and power policy analyses. The resulting studies suggest ways to frame best practices using organized markets for managing U.S. grid assets reliably and to identify highest priority areas for improvement.

3.2. Advanced Applications Research and Development (AARD)

PSERC research activities in the area of advanced applications focused on mid- to long-term software research and development, with anticipated outcomes that move innovative ideas toward real-world application. Under CERTS Research Area 1 (Real-time Grid Reliability Management), PSERC has been focused on Advanced Applications Research and Development (AARD), a subgroup of activities that works to develop advanced applications and tools to more effectively operate the electricity delivery system, by enabling advanced analysis, visualization, monitoring and alarming, and decision support capabilities for grid operators.

Table 1: PSERC Research Projects, FY09 to FY13 Funding (project budgets shown in thousand dollars)

Lead	Project	FY09	FY10	FY11	FY12	FY13
Area: Advanced Applications R&D						
Kezunovic (TAMU)	Synchronized Sampling Uses for Real-Time Monitoring and Control	80				
McCalley (ISU)	New Security Tools for Real-Time Operations	120	120	120	90	
Vittal (ASU)	Adaptive Islanding Demonstration in the Western Electricity Coordinating Council	125	165	165		
Bose (WSU)	Real-time Wide-Area Control	25				
Sauer (UIUC)	Automatic Reliability Reports Research and Implementation, and Transmission Adequacy Performance Metrics		75	165	86	60
Area: Reliability and Markets						
Zimmerman (CU)	Development and Testing of New Tools	290	260	146	255	195
Schulze (CU)	Impact of New Energy and Environmental Regulations on the Future Reliability and Costs of Electric Power	260	240	113		
Schulze (CU)	Mapping Energy Futures: the SuperOPF Planning Tool				115	75
Mount (CU)	Evaluating System and Financial Adequacy Portfolios of Renewables, Storage, and Controllable Loads	260	340	113	190	155
Oren (UCB)	Transmission Unit Commitment in Economic Dispatch	50				
Oren (UCB)	Interactions of Environmental Policies in a Transmission-constrained Competitive Electric Market		60	80		
Oren (UCB)	Business Model for Retail Aggregation of Responsive Load				90	100
Chiang (CU)	SuperOPF Optimization Solver Enhancement and Commercialization of the SuperOPF Framework	70		31		60
Lesieutre (UW)	Proxy Limits	80				
Lesieutre (UW)	Market Power Monitoring Metrics	90	135			
Tylavsky (ASU)	ESP Network Reductions for Engineering and Economic Analysis of High Penetration Renewables			175	121	90
Schuler (CU)	Transmission Investment Assessment under Uncertainty			10	10	
Varaiya (UCB)	Renewable Integration of Risk-Limiting Dispatch			120	125	175
Tong (CU)	Effects of Data Quality on Market Functions			95	90	90
Overbye (UIUC)	Development of Attribute Preserving Network Equivalents				75	75
Zhang (CU)	Dynamic Energy and Environmental Dispatch of Power Systems			90	90	90
Anderson (CU)	Advanced Stochastic Unit Commitment Solution for Optimal Management of Uncertainty					75
	Total	1,450	1,395	1,423	1,337	1,240

4. Summary of Major Accomplishments

4.1. Reliability and Markets (R&M)

PSERC led seventeen research projects listed in Table 1 under the CERTS R&M research area under FY2009 through FY2013 funding. The major accomplishments are summarized in this section for each year of funding. Research under FY 2014 and 2015 OE funding is being administered under a separate cooperative agreement, DE-OE0000670, which ends in September 2017, so the results of that research are not included in this report.

4.1.1. FY2009 Reliability and Markets Program Accomplishments

- **Development of a market simulation tool that co-optimizes dispatch of energy and ancillary services by taking proper account of reliability requirements (e.g., contingencies).** This was the kernel for what came to be known as the "Super Optimal Power Flow (SuperOPF)" tool. The vision underlying the tool is one that is grid-wide in scope, and where all limits and "products" are properly priced. The focus in FY 2009 was on examination of methods to incorporate unit commitment within the basic simulation framework. Other projects conducted in FY 2009 began to utilize earlier versions of the SuperOPF tool (without unit commitment) to examine a variety of operating and planning questions, including:
    - *Application of the SuperOPF framework to examine the impact of environmental regulations and approaches for implementing these regulations on planning for future generation and transmission additions*
    - *Application of the SuperOPF framework to examine the economic value of controllable loads and customer-owned energy storage in power system operations*. The researchers conducted a series of case studies to evaluate the potential benefits from an electric grid with installed wind generation from adding (1) plug-in hybrid electric vehicles with intelligent charging/discharging capabilities (as an example of a controllable load), and (2) intelligent loads representing the types of capabilities that could be provided by a microgrid.
- **Examination of the economic dispatch savings that might be achievable by dispatching generation resources in conjunction with a new, counter-intuitive procedure that involves switching off transmission line segments.** The analysis showed that switching off selected transmission lines can lower total generation dispatch costs when doing so reduced the congestion that was created with those lines energized.

4.1.2. FY2010 Reliability and Markets Program Accomplishments

- **The SuperOPF development work focused on implementing, testing, and validating the formulations designed and prototyped in FY2009.** Specifically, work focused on two new elements to incorporate unit commitment into the basic formulation of the tool. The first element addressed the multi-period nature of the unit commitment and power system operations problem by modeling inter-temporal restrictions, such as generator ramping limits and conservation of energy constraints needed for correctly modeling energy storage. The second element addressed the introduction of integer unit commitment variables, along with generator startup and shutdown costs, minimum generator up and down times, among other unit commitment considerations. After a successful proof-of-concept test of the basic price coordination scheme for separation of inter-temporal constraints, work focused on developing software for the horizon planning, unit commitment, and expansion-planning frameworks, including the software that provided sufficiently general optimization problem solvers.

- **The SuperOPF tool was used to examine optimal investment in different new generation types for the Eastern Interconnection given the existing network and generation characteristics as well as various legislative initiatives.** Emissions of CO_2, NO_x, and SO_2 as well as ambient levels of ozone and fine particulates were explicitly modeled. Interactions with the permit markets were considered in the analysis.
- **The SuperOPF tool was also used to analyze the effects of adding wind capacity to a network.** The optimization was based on a full AC representation of a network and the effects of equipment failures (i.e., contingencies) were considered explicitly. Given these two features, the amounts and locations of the reserve capacity needed to maintain operating reliability were determined endogenously, and changed in response to changes in operating conditions. From a planning perspective, the optimal amounts of reserve capacity calculated by the SuperOPF increased, as expected, when intermittent sources of generation (such as wind generation with unmitigated variable production) were added to the network. From an economic perspective, the research team was able to evaluate the combined benefits of lower operating costs and lower capital costs in order to make an accurate assessment of the economic value of adding new capabilities, such as controllable load and energy storage, to a network.
- **Finally, a sensitivity-based market-monitoring tool was successfully demonstrated on data provided by the PJM Interconnection.** PJM was able to confirm the research team's independent findings as well as confirm and explain anomalies uncovered by the researchers. The research team began discussions on incorporating its algorithms into commercial software tools.

4.1.3. FY2011 Reliability and Markets Program Accomplishments

The research plan for FY2011 represented a significant evolution from FY2010 primarily because many of the projects from FY2010 had either substantially matured or had been completed. In FY2011, the program seeded several new projects, initiated commercialization of a successful mature project, and entered the final completion stages of previously funded projects.

- **The structure of the multi-period SuperOPF was redesigned from its initial prototype to use a new decomposition involving linking (via price-coordinated constraints) many single-period optimal power flow problems to a single, large quadratic program comprised of all of the inter-temporal and reserve-related costs and constraints.** Various techniques and strategies were employed to improve the convergence of the price coordination scheme, but none resulted in sufficient performance and robustness to allow for integration with the unit commitment portion. Several contributing factors were identified, including scaling issues and non-convexities due to negative prices.
- **Research using the SuperOPF to study generation planning completed comparisons between a 300 node reduced network and a 4,400 node simplified network that retained all high voltage lines, to the full 60,000 node Eastern Interconnection network.** Being able to use simplified network models with acceptable accuracy greatly improves the usability of the tool. The comparisons showed that the 4,400 bus network was substantially more accurate (about 3% average line flow error) than a 300 bus network (about 20% average line flow error) compared to the full system for a 5% reduction in use of coal-fired power plants. This is

especially important since the location of new generation will be determined in great part by the capacity of existing transmission since it is extraordinarily difficult to build new lines. Thus, use of a reduced network that retains all high voltage lines is essential for realistic planning purposes of industry and policymakers.

- **Research using the SuperOPF to examine controllable demand and distributed energy resources showed that using only 10% of the potential thermal storage in New York City would make it possible to flatten the amount of generation needed from conventional sources and also to mitigate the variability of generation from renewable sources.** As a result, the typical price arbitrage between on-peak and off-peak demand would disappear. Hence, if customers pay rates based on the amount of energy purchased, as most still do, all customers would benefit equally from the flattened daily profile of prices regardless of whether or not they had adopted some form of controllable demand service. The analysis showed that the correct economic incentives imply that 1) customers should pay a demand charge for their demand at the system peak load, 2) customers should pay for ramping if they exacerbate system ramping requirements, and 3) customers should be paid if they offset system ramping requirements. With these incentives, the customers with controllable demand pay a lower demand charge than other customers and are paid for providing ramping services.
- **Two new research projects were initiated to examine systematic methods for recreating reduced order networks that accurately capture relevant features of the full network.** Reduced order networks are required when simulation of a full network is too computationally intensive.
    - The first project utilized data mining (with clustering), coherency, and equivalencing to investigate different properties of a full network that are important to preserve in a reduced order network, such as for determining locational marginal prices (that is, energy prices at network nodes). The project determined which buses were in the same congestion zones, and then created an equivalent with representative buses for each of these groups.
    - The second project advanced a previously developed three-staged approach to the calculation of an attribute-preserving equivalent. The first stage of the algorithm "probed" the system to determine the appropriate system features that retained the attributes of interest. The second stage of the algorithm grouped the buses based upon the features from the first stage. Each feature, applied to all the buses in the system, was defined as a feature vector. Clustering algorithms were then used on the feature vectors to develop a much smaller number of bus groupings in which all the buses in the group had very similar features. The last stage of the algorithm was to use more traditional network reduction techniques to greatly reduce the number of buses in each group.
- **New research was also initiated on "risk-limiting dispatch" (RLD) to optimize the purchase of forward energy and reserve capacity in an arbitrary sequence of markets.** The dispatch decision in each market depends on the information about net load (that is, load minus variable generation) available at the time. Algorithms were developed to calculate RLD very efficiently. Case studies showed that RLD requires much lower levels of reserve than the current "decoupled" dispatch process in which a decision taken in one market (say 24 hours ahead) does not take into account the fact that future decisions can compensate for the "errors" made in current decisions.

- **Finally, new research was initiated to develop an analytical model for bad and malicious data, and establish a measure of data quality that connects directly to the real-time market price.** A major theoretical result was the development of a geometric approach to characterizing the sensitivity of real-time prices with respect to the location of the bad data. The research demonstrated the effects of worst case data on real-time prices for a number of test networks, including the PJM 5-bus system, the IEEE 14-bus system, and the IEEE 118-bus system.

4.1.4. FY2012 Reliability and Markets Program Accomplishments

- **Analyses using the multi-period SuperOPF and a test network showed that the optimum composition of hourly dispatch is very sensitive to how the stochastic properties of wind generation are represented in the model.** For example, treating potential wind generation as deterministic but still allowing for variability from period to period, makes system costs much lower because less wind is spilled. This demonstrated that it is important to use a realistic representation of the stochastic characteristics of wind generation to determine the true optimum pattern of dispatch. The results showed that it is also important to mitigate the inherent variability of wind generation effectively. Without some form of inexpensive mitigation, the ramping costs of using conventional generators to offset changes in wind speeds result in more wind being spilled. In other words, the least-cost dispatch uses less wind generation even though this source is offered at zero cost into the market. For the specific network topology, adding energy storage capacity leads to more wind being dispatched than upgrading transmission even though all congestion on the network is eliminated. The results also show that operating costs are reduced substantially whenever wind generation is available.
- **The framework to study data quality and its impact on real-time locational marginal prices was extended to include topology errors.** Real-time locational marginal prices are electric energy prices at given grid locations. A major finding was that network topology errors have very different ways of affecting locational marginal prices and the impact of topology errors on locational marginal prices seems to be more significant than measurement data errors. A second finding was that nonlinear state estimation to determine the state of the power system at a point in time has a mitigating effect on data errors. On the other hand, a nonlinear state estimator does not address topology errors and is insufficient to provide the necessary quality assurance in the presence of topology errors. Finally, necessary and sufficient conditions were identified for undetectable topology errors arising from events that change network topology.
- **Researchers analyzed the potential for use of ice storage in buildings in New York State.** A detailed engineering model was developed for ice storage for individual building simulations. The research team used the model to study how building managers could optimally operate an ice storage system under high peak-pricing scenarios, such as during heat waves. They quantified the system benefits if all large commercial buildings in New York State were equipped with ice storage systems and were managed through a super-aggregator. In the process of conducting the system analysis, they greatly improved the quality of power plant emissions analysis using several advanced numerical techniques, such as clustering analysis and density mapping.

4.1.5. FY2013 Reliability and Markets Program Accomplishments

- **The 3rd generation SuperOPF tool based on a receding-horizon framework was developed and tested**. The 3rd generation SuperOPF required creating a new simulation framework in which the temporal structure of the various energy, reserves, and load following markets were explicitly defined and simulated. The SuperOPF also incorporated binary unit commitment decisions. The development required new tools necessary for generating input data with the appropriate uncertainty statistics consistent with a receding horizon simulation. Analyses using the SuperOPF demonstrated the value of moving to a receding horizon planning approach from the once-a-day, day-ahead type of market structures in wide use today. As forecasting uncertainty increases, the receding horizon approach is expected to show clear advantages in both cost and reliability.
- **A computationally tractable price forecasting technique for independent service operators was developed.** The technique offers a framework for incorporating data from emerging applications including (1) synchrophasor data that provide high fidelity monitoring of the grid condition, (2) weather forecasts that have a strong correlation with variable generation, and (3) aggregated smart meter data that provide real-time estimates of the state of demand (and which potentially measures closed-loop demand side management and demand response).
- **Researchers investigated the engineering and economic feasibility of using demand-side resources to provide power system services currently offered by peaking generation units at load pockets in New York City.** The investigation applied a building energy modeling software package (TRNSYS) to simulate how demand-side assets (including, but not limited to, building thermal mass, thermal storage, and electro-chemical storage) in individual buildings or a cluster of buildings could be managed to provide power system services including emergency load curtailment, spinning reserve, and voltage support. The potential role of dedicated utility-scale energy storage in the load pockets was also investigated.
- **Research was initiated to update the efficient rationing theory and adapt developments in financial theory of risk pooling for the purpose of designing service contracts and load control operation strategies based on such contracts.** The research evaluated the designs of portfolio strategies for aggregation of load control contracts with intermittent supply resources, including development of scheduling strategies for these resources at the retail level to maximize their combined value at the wholesale level and develop compensation schemes that incentivize participation by such resources.

4.2. Advanced Applications Research and Development (AARD)

PSERC led five research projects under the CERTS AARD research area from FY2009 through FY2013 as listed Table 1. The major accomplishments for each project are summarized below.

4.2.1. Synchronized Sampling Uses for Real-Time Monitoring and Control

This one-year project (FY 2009) developed techniques for presenting information extracted from synchronized samples and synchronized phasor measurements obtained from emerging, new substation intelligent electronic devices to help improve system awareness of the operators and other utility staff. The tools enable the real-time control improvements associated with clearing faults and managing transmission line restoration, including fault location and alarm processing. The usefulness of these tools will only increase as substations continue to incorporate greater levels of intelligence into their designs.

4.2.2. New Security Tools for Real-Time Operations

This four-year project (FY 2009 through FY 2012) involved the development and demonstration of two distinct software security tools for real-time operations. The first tool, Risk-Based Security Assessment, involved an enhancement to traditional security analysis that takes the likelihood of contingencies into consideration in the analysis. Traditional security analysis treats each contingency separately and as equally likely. By taking the likelihood of each contingency into consideration and considering all contingencies together, the tool can optimize jointly both reliability and the costs of dispatch. This enables lower cost dispatch at equal levels of reliability to traditional approaches. The tool was demonstrated using information provided by ISO New England.

The second tool, high-speed extended-term time-domain simulation, involved the introduction of parallel computing techniques to accelerate and increase the fidelity of power system simulation approaches. One set of improvements considered varying the time-step of simulations to increase or decrease the time-step interval depending on the power system phenomena under study. Another set of improvements considered breaking up a time sequence of simulations into discrete blocks of time, solving each in parallel, and then reintegrating the results to ensure consistency across the entire time interval. These approaches were demonstrated using information provided by PJM Interconnection.

Both tools were implemented on a commercial grade operator training simulator provided to the project by AREVA, an industrial partner.

4.2.3. Adaptive Islanding Demonstration in the Western Electricity Coordinating Council

This three-year project (FY 2009 through FY 2011) demonstrated use of analytical methods to establish electrical islands within an interconnection. Currently, electrical islands are pre-established within the Western Interconnection based on a variety of ad hoc study methods. The islands are formed through a pre-determined sequence of automatic actions following extremely severe disturbances as a final strategy to maintain power delivery to portions of the interconnection for which a load and generation balance can be sustained. Use of such analytic methods, rather than the current ad hoc approaches, for establishing these islands would enhance the reliability of an interconnection. The project demonstrated an analytical approach for establishing islands by first working directly with Pacific Gas and Electric (PG&E) and then, with PG&E's endorsement of the approach, by demonstrating the approach to relevant Western Electric Coordinating Council (WECC) planning committees.

4.2.4. Real-Time Wide-Area Control

This one year project (FY 2009) involved a series of discussions with the Bonneville Power Administration and other power companies in WECC about possible real-time control applications that could help the Northwest grid.

4.2.5. Automatic Reliability Reports Research and Implementation and Transmission Adequacy Performance Metrics

This four year project (FY 2010 through FY 2013) involved the development of a method for assessing and supporting new metrics for presenting information on transmission grid adequacy following a contingency, including reporting of this information in an automated fashion to grid operators. A demonstration of the method and approach was conducted with the Midwest Independent System

Operator (now named the Midcontinent Independent System Operator). The project was led by one of the CERTS industrial partners; the university's role was to develop the method for assessing transmission adequacy post-contingency using synchrophasor measurements.

5. Elements of the Statement of Project Objectives

This section highlights the work done on the project objectives given in the Statement of Project Objectives (SOPO), dated January 2009, under the cooperative agreement between the National Energy Technology Laboratory and Arizona State University as the lead PSERC university.

5.1. Research Acquisition

Based upon a defined process managed by CERTS, PSERC-participating universities were selected to execute specific research tasks. Selected universities were funded in accordance with ASU's contract selection methodologies as approved by the DOE Project Officer. With guidance from CERTS management, PSERC participated in program management and facilitation, providing support as necessary to ensure funded university research was executed according to appropriate project management principles.

With guidance from CERTS management, PSERC supported the yearly development of an Annual Operating Plan that defined the major processes in the program, summarized accomplishments in the previous year, and clearly described the work plan for the fiscal year covered under the Annual Operating Plan.

5.2. Research Identification

PSERC researchers and management supported CERTS management in identifying and prioritizing research needs, ensuring that the areas of highest technical importance were investigated. At the time of the award, the topic areas determined to be of highest technical important were identified as:

- Real Time Grid Reliability Management (CERTS Research Area 1)
- Reliability and Markets (CERTS Research Area 2)

In addition, PSERC management and researchers worked to identify synergies between study areas.

The CERTS projects were synergistic with PSERC's core research activities. Consequently, NETL allowed the industry-supported PSERC projects to be eligible for meeting cost sharing requirements. In addition, a number of PSERC projects either expanded upon or contributed to CERTS projects. For example, the PSERC project "Facilitating Environmental Initiatives while Maintaining Efficient Markets and Electric System Reliability" contributed both to PSERC's work (with industry support) and its work under CERTS funding.

PSERC's core research projects are identified through a collaborative solicitation process that starts with discussions among PSERC's industry members and university researchers on research needs and ideas. A solicitation is then created that reflects those discussions. Project teams with industry advisors submit proposals that undergo subsequent industry and academic reviews. Projects of strong academic quality must also have high industry support to be ultimately selected for funding. Synergistic work with CERTS was also a plus for selection because of the contribution in expanding or advancing the scope of work.

5.3. Research Awards

In cooperation with CERTS management, PSERC supported the solicitation process of research from PSERC researchers in a manner that encouraged university applications of high quality. PSERC also supported the process for recommending research applications for award, awarded and monitored research projects, and encouraged technology transfer by distributing relevant reports, papers, and other deliverables. PSERC also participated in periodic project reviews initiated by the DOE OE. A list of PSERC projects for FY09-FY13 funding was given above in Table 1.

5.4. Education and Outreach

In keeping with its mission of "empowering minds to engineer the future electric energy system," PSERC management worked closely with PSERC researchers, DOE, and CERTS management to educate students, industry, and government on power system principles, practices and policies, and challenges to providing electric energy economically and reliably in ways that address major public policy initiatives.

Throughout the project, consistent with PSERC's mission, research performers educated students, industry and government on power system principles, practices and policies; and challenges to providing electric energy economically and reliably in ways that address major public policy initiatives. Over the course of this project, a major change occurred in university student interest in power engineering as a career. The number of students at the undergraduate and graduate levels almost doubled over the last ten years in part because of their interest in many of the same topics covered in the CERTS work, such as ways to make a difference in addressing global environmental challenges. The research served to inform curriculum development in ways that helped students see possible solutions to those challenges. At the same time, through outreach activities of PSERC and CERTS, the research results were shared with the broader energy community. In general, PSERC worked to advance power engineering education both in PSERC classrooms and in classrooms throughout the university education system. PSERC helped quantify changes in power engineering curricula, faculty, and students by helping in the design, implementation, and analysis of the IEEE Power and Energy Society's Power and Energy Education Committee's Survey of U.S. and Canadian universities. The results are available at: http://ieee-pes.org/professional-development/education/university-power-programs.

5.5. Human Resources Development

With the goal of empowering the next generation of researchers, PSERC management encouraged its researchers to engage in education and outreach activities, including ongoing student development, internship programs, assistance in obtaining post-graduation employment, and educational outreach. Much of the research funding for CERTS and PSERC projects supported graduate students. PSERC researchers helped student researchers to better understand industry challenges and how research can address those challenges. To help students understand the context of their research within the overall CERTS and PSERC research efforts, PSERC researchers involved students in project and industry meetings to the extent possible. PSERC graduate students presented project posters at its industry meetings and engaged in conversations with industry about their research.

PSERC estimates that it graduates about 450 undergraduates, 270 Masters, and 100 PhD students in power engineering and related disciplines every year. Many of these students, perhaps around 50, go to work for PSERC's industry members. To help connect students at PSERC universities and universities throughout the U.S. and Canada (and beyond), with potential employers, over the project period PSERC:

- Sponsored mini-job fairs at its semi-annual industry meetings
- Provided student resumes and profiles to its industry members
- Maintained an on-line career service (PES Careers US & Canada) sponsored by the IEEE Power & Energy Society, with subscriptions by some 1,800 undergraduate and graduate students, and 300 employers in the US and Canada. Supported the creation of PES Careers Europe & Middle East and PES Careers Australia
- Organized job fairs at the IEEE Power & Energy Society's General Meetings
- University researchers provided student recommendations and advice to industry
- Emailed position openings to students on its listserv
- Facilitated a better of understanding of industry challenged by supporting graduate students in its projects, enabling industry-university meeting attendance, and involving students in project poster presentations
- Advertised industry member career web pages on the PSERC website
- Advanced university education in power and energy engineering in general through collaborating U.S. Power and Energy Engineering Workforce Collaborative in the creating the report *Preparing the U.S. Foundation for Future Electric Energy Systems: A Strong Power and Energy Engineering Workforce* (IEEE Power & Energy Society. 2009.) influential in bring attention to the need to increase student interest in power and energy engineering careers and in getting government support of enhancing university education.

Students were given insights into industry issues that provided a context for their research and education, and into current research topics and methods in a number of ways.

- PSERC offered twice monthly research webinars during the academic year that were shown in graduate seminars/classes at a number of universities.
- Students attended PSERC's semi-annual industry meetings at no cost, hearing not only presentations by researchers, but also discussions with and presentations by industry.
- Students presented posters at PSERC meetings, interacting with industry in discussions on research projects.
- Students also attended CERTS project review meetings.

5.6. Communications about PSERC CERTS Projects

PSERC's involvement in CERTS research was regularly reported to its industry members and other researchers. CERTS researchers gave posters at PSERC industry meetings. In the spring of 2014, CERTS researchers gave PSERC webinars that were attended via internet by an estimated 300-400 people each time, including industry, government, faculty and students. The webinars were archived and continue to be available globally via the PSERC website. The presentation slides from the webinars can also be found on the PSERC website (http://www.pserc.org).

CERTS researchers have made presentations about their work to DOE, FERC, state public utility commissions, and other government entities. Of course, besides academic publications, the researchers made presentations on their CERTS work in conferences worldwide that were attended by industry and academics.

CERTS managed public communications about PSERC's portion of the overall CERTS research program, such as in its reporting to the U.S. DOE, and through its website at http://certs.lbl.gov.

5.7. Internal Review and Bi-Annual Formal Peer Review Meetings

PSERC management encouraged PSERC researcher participation in annual internal project review meetings to present information in a format requested by the U.S. DOE. CERTS peer-review meetings were held annually. The peer-review meetings for the Reliability and Markets area were held at Cornell University in August each year. The other CERTS research projects held a project meeting in Washington DC. Presentations at the meetings were posted on the DOE website.

5.8. Benchmarking for Improvement

On an on-going basis, PSERC management identifies other university collaborations of similar nature and interact with leaders of those collaborations for purpose of discovering ideas for improved operation and for sharing ideas.

By virtue of its size, as a matter of due course, PSERC maintains professional collaborations with a large number of universities and centers. Its researchers are engaged with other centers both at their own universities as well as at other universities. PSERC has benefited greatly by these collaborations. For instance, the collaboration with the Trustworthy Cyber Infrastructure for the Power Grid, with the lead university at the University of Illinois at Urbana-Champaign, has contributed to PSERC's greater awareness of and research on cyber-security issues.

5.9. Critical Path Project Milestones (Milestone Plan/Status)

As part of the Annual Operating Plan process, CERTS developed annual Milestone Plans for use as a planning tool to establish the time schedule for accomplishing planned work. The Milestone Plan served as the baseline for tracking project performance and identified critical path project milestones for each awarded project. CERTS provided Milestone Status as part of its required quarterly reporting.

6. Individual Project Reports

This section provides reports provided by project researchers on their accomplishments in their CERTS research.

6.1. Reliability and Markets

In the Reliability and Markets area, researchers worked to develop and demonstrate a broad set of integrated engineering and market-based approaches, tools, and technologies focused on improving the reliability and efficiency of the electric sector—both in planning and in operations. The emphasis of this research was on the linkage between the physics of the electric power grid and the economics of electricity markets.

PI (Lead)	**Ray Zimmerman**		**Institution**	**Cornell**
Project Title	**Development and Testing of New Tools**			
Funding	**FY**	09	**$**	290,000
	FY	10	**$**	260,000
	FY	11	**$**	146,000
	FY	12	**$**	255,000
	FY	13	**$**	195,000

Summary of project intent/scope

A smarter electricity grid with increased uncertainty from intermittent renewable sources, more demand-side involvement, with new storage technologies requires new tools for planning on all time scales, from investment to real-time operations. This effort involves development of problem formulations, research grade software, and case studies to demonstrate the added value of the methods and algorithms. It uses a "SuperOPF" approach with the following unifying themes (1) simultaneous, explicit modeling of multiple states, each with full set of OPF variables, constraints, costs, (2) stochastic or weighted costs, and (3) additional variables, constraints and costs that tie these states together.

Summary of project activities for the entire period of funding stated above

The project activities can be divided into three main categories: (1) problem formulation design and refinement, (2) software development, testing and documentation, (3) case studies and support for others using the tools.

The work on problem formulations began by building upon Matpower's extensible OPF architecture [37] using the SuperOPF framework of co-optimization across multiple states, with stochastic costs and additional variables, costs and constraints that link the states together into a single mathematical programming problem. The initial single-period formulation was focused on a secure, stochastic version of the optimal power flow problem, where reserves are price-responsive and optimally located to cover an explicit set of contingencies. This resulted in the first generation SuperOPF. From here the problem formulations extended two directions. The first involved re-purposing the reserve variables to represent installed capacities in a generator investment planning problem framework with cost-to-keep for existing generation units and cost-to-build for new investments. Over time additional features were added to this planning formulation to address maximum build limits, minimum generation limits, operating reserves, hour-specific unit availability factors (to better model intermittent renewables) and aggregate output constraints (for emission caps, annual hydro energy limits, etc.). The second direction was the extension of the operations (e.g. day-ahead market) formulation to include many new features: multiperiod look ahead, multiple base cases per period to model renewable uncertainty, ramping wear and tear costs, ramping reserves, storage and unit commitment, complete with startup/shutdown costs and minimum up/down times. These formulations went through multiple iterations of prototyping, testing and re-designing over this funding period.

As the foundation for all of the new tool development, the open-source Matpower package saw many substantial improvements and additions, going through several major public releases [6]-[15], and including an entirely re-written and expanded User's Manual [38]-[41], along with two technical notes [42], [42]. New features include extensive OPF enhancements, high-performance solvers for AC and DC OPF problems, GNU Octave compatibility, reserve co-optimization, interface limits, dispatchable HVDC transmission lines and much more, along with performance enhancements, bug fixes and new large-scale test systems. In addition to a new User's Manual for the single-period SuperOPF, the software also saw ongoing development to add new features, such as quadratic redispatch and reserve costs, fix bugs and refine the code. A new tool, E4ST (Engineering, Economic, and Environmental Electricity Simulation Tool, formerly SuperOPF Planning Tool), for generation investment planning was developed using the first generation SuperOPF as the starting codebase. After initial development, the E4ST software continued to see updated features added as the problem formulation was refined as described above. Finally, the multi-period and unit commitment formulations were implemented in what is now called MOPS (Matpower Optimal Power Scheduler). As the most complex of the problem formulations, the corresponding software prototypes for this tool went through many iterations as the formulation was refined in response to testing and case studies. Case studies performed as part of this project [24] and by others with our support demonstrated the value of the SuperOPF framework across planning and operations environments.

What was accomplished by this research? What were the contributions to the field?

The direct contributions of this research include the software tools, the manuals and technical notes and published papers on the tools and case studies. The software tools consist of four main tools. (1) The publicly available Matpower is a collection of widely-used open-source tools for steady-state analysis of power systems, including AC and DC power flow, continuation power flow, and AC and DC optimal power flow, with an extensible formulation and included extensions for handling DC transmission lines, interface limits and co-optimized zonal reserves. (2) The first generation, single-period SuperOPF, still available to collaborating researchers by request, is a secure, stochastic version of the OPF with locationally optimal, price-responsive reserves and explicit contingencies. (3) E4ST is a generation investment planning tool designed to be used with a detailed transmission network model. (4) MOPS is the multi-period SuperOPF with unit commitment, currently based on a DC network model. With a problem formulation that is a super-set of many classes of scheduling problems, it can span the range from simple economic dispatch through optimal power flow with co-optimized reserves, from single period through multi-period look-ahead with storage and ramping, from a single deterministic state to stochastic representations of intermittent renewables and contingencies. MOPS is currently being integrated into Matpower for public release in the next version.

These direct contributions of the software, manuals, technical notes and papers are only the tip of the iceberg, as their effect is multiplied by the many other researchers who are enabled to conduct their own research using the tools developed under this project. Under the CERTS Reliability and Markets program itself, the projects directed by Tim Mount and William Schulze are examples of types of studies and analyses made possible by the SuperOPF based tools developed here.

Even more significant, perhaps, is the impact of the underlying Matpower software. Without it, we could not have built the SuperOPF, E4ST or MOPS and it has enabled many other researchers to build simulations and perform analyses that would not otherwise have been possible. The magnitude of the impact can be gauged in part by the increasing rate of Matpower downloads, which currently stand at about 2000 per month, and the growing number of citations for the canonical Matpower paper from 2011 [36], which according to Google Scholar, is currently over 850.

What are the current and/or future applications of this research?

The development of these tools is on-going. The current focus is to complete the incorporation of MOPS into the next version of the Matpower distribution, along with a complete User's Manual and tutorial examples of the wide array of problems it can address. The SuperOPF framework approach is also being applied to new formulations of the generation investment planning problem that include integer investment variables and a structure amenable to embedding a multi-period operational model to capture ramping and commitment restrictions more accurately. While there is a prototype version of MOPS that incorporates the full non-linear AC

network model, it is still considered experimental since the convergence properties are not yet adequate for general use. Improvements to the decomposition schemes used to address this large-scale, mixed-integer, non-linear programming problem need to be further explored. Other enhancements are planned for Matpower to expand the user extensible optimal power flow capabilities to include non-linear constraints and costs, opening up the door to many new user-contributed enhancements and additions.

Identify any products developed and any technology transfer activities

Website(s)	1. Matpower – A MATLAB® Power system Simulation Package (http://www.pserc.cornell.edu/matpower/) 2. TSPOPF – High performance AC optimal power flow solvers for Matpower (http://www.pserc.cornell.edu/tspopf/) 3. BPMPD_MEX – A MATLAB® MEX interface for the BPMPD Interior Point Solver (http://www.pserc.cornell.edu/bpmpd/) 4. E4ST – Engineering, Economic, and Environmental Electricity Simulation Tool (http://e4st.com/)

Networks/collaborations	Collaborations with researches at ASU, RPI, Lehigh, Johns-Hopkins, LBNL, Wichita State.

Other products	1. Matpower 2. SuperOPF 3. E4ST (SuperOPF Planning Tool) 4. Multi-period SuperOPF with UC (to be released soon as MOPS, Matpower Optimal Power Scheduler)

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I (Lead)	Bill Schulze			Institution	Cornell
Project Title	Impact of New Energy and Environmental Regulations on the Future Reliability and Costs of Electric Power				
Funding	FY	09	$	260,000	
	FY	10	$	240,000	
	FY	11	$	113,000	

Summary of project intent/scope

The purpose of the research was to develop a planning model that can examine the feasibility of providing reliable electricity by efficiently managing load with a smart grid, switching to renewable and other new sources of energy, reducing emissions, while obeying the laws of physics and economics. To do this, the SuperOPF Planning Tool was developed and used to examine optimal investment in different new generation types first for Northeast as a test bed, then for the Eastern Interconnection, and finally for the nation as a whole given the existing network and generation as a starting point.

Summary of project activities for the entire period of funding stated above

This project provided core funding for the development of the SuperOPF planning Tool. Application of the tool was funded collaboratively by two PSERC projects, M-21 and M-24, that applied the model first to the Northeastern US (M-21) and then to the continental US and parts of Canada (M-24) to examine the impact of environmental policies on investment in different generation types, electricity prices and environmental impacts.

What was accomplished by this research? What were the contributions to the field?

No planning tool existed that fully optimized long term investment incorporating environmental impacts with sufficient network detail to reliably model the electric power system. The SuperOPF planning Tool accomplishes that objective and was demonstrated to be feasible. One of the major hurdles discovered in the project was that the tightly messed Eastern Interconnection could not be modelled accurately with network reductions using fewer than 5000 nodes.

What are the current and/or future applications of this research?

The planning tool developed at Cornell was used by both Wichita State University and Arizona State University as part of the PSERC funded activities cited below, demonstrating the portability of the tool and its use to show the impact of environmental policies.

Identify any products developed and any technology transfer activities

Website(s)	The SuperOPF Planning Tool was developed by this project as well as tools for integrating environmental and electric power system datasets. The planning tool has been renamed the Engineering, Economic, Environmental and Electricity Simulation Tool (E4ST). The tools developed as part of the project are now available on the E4ST website.

Networks/collaborations	PSERC funded a two year project (June 2010-May 2012) entitled "Interactions of Multiple Market-based Energy and Environmental Policies in a Transmission-Constrained Competitive National Electricity Market" that had as industry team members: Michael Swider (NYISO), Jim Price (CAISO), Floyd Galvan (Entergy), Robert Ethier (ISO-NE), Mark Westendorf and Rao Konidena (Midwest ISO), Lisa Beard (TVA); Gary Stern (Southern California Edison), Ray Williams (PG&E), and Matt Barmack (Calpine). This project, led by William Schulze (Cornell), funded complementary work by Ward Jewell (Wichita State University, wardj@ieee.org), Daniel Tylavsky, (Arizona State University, Tylavsky@asu.edu), Shmuel Oren

	(Berkeley, oren@ieor. berkeley.edu), James Bushnell (ISU, Jimb@iastate.edu), Yihsu Chen (UC Merced, yihsu. chen@ucmerced.edu), and Siny Joseph (Wichita State, siny@resecon.umass.edu) to integrate the work Cornell did on the SuperOPF and modeling the Eastern Interconnect with an existing PSERC project headed by Ward Jewell that is modeling WECC using a similar network reduction of about 250 nodes. Daniel Tylavsky developed a network reduction for the Texas Interconnection so that a national network and environmental model using the SuperOPF as a planning tool could be used for analyzing policy options and impacts on reliability, costs and emissions for all of the United States and much of Canada. This PSERC project was funded at a level of 125K per year for two years. The final reported is cited below.

Other products	Environmental and generator data developed by the project are now available on the E4ST website.

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PI (Lead)	Bill Schulze				Institution	Cornell
Project Title	Mapping Energy Futures: The SuperOPF Planning Tool					
Funding	FY	12	$	115,000		
	FY	13	$	75,000		

Summary of project intent/scope

Energy futures for the United States depend critically on the electric power system. A planning tool that optimizes investment in generation, transmission, and demand-side management is needed because the electric power industry faces new environmental pressure associated with CO2 regulation and integration of a smart grid that allows for demand response. Both reliability and environmental regulation require planning. This project developed an integrated engineering, economic and environmental modeling framework for the electric power system, the Engineering, Economic, and Environmental Electricity Simulation Tool (E4ST).

Summary of project activities for the entire period of funding stated above

The Engineering, Economic, and Environmental Electricity Simulation Tool or E4ST was extended to the entire contiguous United States and parts of Canada. This involved three tasks. First, integrated data on transmission, generation, and emissions had to be obtained and matched. Second, network reductions had to be developed at a very high level of detail to accurately model transmission. Third, the E4ST required both new development and new optimization techniques to allow solution of the very large problems required to accurately model the grid for around forty hour types simultaneously. All of these tasks were successfully accomplished.

What was accomplished by this research? What were the contributions to the field?

No model of the North American electric power system exists that includes a sufficiently detailed specification of the electricity network, power generation, and air transport and environmental quality modules, to allow optimal investment and retirement in response to incentives or regulations while maintaining reliability. The E4ST was made operational for North America during this research period. New methods of network reduction had to be developed and new methods of solution were applied to solve the resulting optimization problem.

What are the current and/or future applications of this research?

As part of this project, it was shown in a paper published in Resource and Energy Economics (cited below) that leakage of CO2 emissions from the Regional Greenhouse Gas Initiative cannot be modelled accurately without use of at least 5000 node reduction for the Eastern Interconnect. Resources for the Future is now adopting the model for applied research with the Mexican Government and other projects. The simulation tool is also being used to estimate the benefits and costs of new transmission lines as well as implications of new CO2 regulations for DOE. The NYISO is interested in replicating some of the studies done for the Eastern Interconnection study funded by DOE using the current E4ST model.

Identify any products developed and any technology transfer activities

Website(s)	The E4ST website can found at: http://e4st.com
Networks/collaborations	We are collaborating with Resources for the Future to utilize the E4ST in there e extensive power systems research efforts funded by industry and governments.
Technologies/Techniques	Articles below on network reduction techniques and improved modeling of investment and environmental impacts of the electric power system can be found below.
Other products	The data sets, network reduction tools, and data matching tools along with the E4ST model itself can be found on the E4ST website.

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PI (Lead)	Tim Mount			Institution	Cornell
Project Title	**Evaluating System and Financial Adequacy Portfolios of Renewables, Storage, and Controllable Loads**				
Funding	FY	09	$	260,000	
	FY	10	$	340,000	
	FY	11	$	113,000	
	FY	12	$	190,000	
	FY	13	$	155,000	

Summary of project intent/scope

The primary objective is to test new capabilities of the SuperOPF and show how they improve our capabilities to analyze the effects of high penetrations of renewable generation on system requirements and costs. The second objective is to evaluate how storage can mitigate variable generation and lower system costs.

Summary of project activities for the entire period of funding stated above

For the first two years of the project, analyses were based on a single-period version of the SuperOPF. This made it necessary to treat the stochastic characteristics of wind generation in a simple way as a set of contingencies representing different possible levels of generation with specified probabilities of occurring. Storage was represented indirectly as a way to reduce the range of possible wind generation.

Within this limited framework, we were able to demonstrate 1) the value of reducing the uncertainty of wind generation and the associated system requirements for reserve capacity, and 2) the increase in the “missing” money needed by conventional generators to cover their capital costs with higher levels of wind generation.

As soon as the multi-period SuperOPF became available in 2011, it became feasible to model the stochastic characteristics of wind generation more realistically, address ramping needs explicitly and manage the charging and discharging of storage more effectively. Using a 36-bus reduction of the NPCC network, econometric models were estimated for wind speed at 16 different locations and load, conditionally on the ambient temperature, for 7 regions in the northeast. These models take into account spatial correlations and make it possible to simulate the uncertainty of potential wind generation and load for every hour in a specified day. In addition, the models of load distinguish between temperature-sensitive and non-temperature-sensitive load. These models simulate the stochastic inputs of wind and load for the multi-period SuperOPF that affect the amount of reserve generating capacity needed for ramping. However, it turns out that the effects of ramping on system costs are small compared to the effects of storage.

The main distinction in storage is between utility-scale storage located at wind farms and distributed storage in the form of deferrable (controllable) demand at load centers. The general framework for representing storage considers the charge and discharge power capacities, the energy capacity and the round-trip efficiency. For deferrable demand (e.g. thermal storage for space cooling), the discharge rate is, in practice, limited by the amount of load that is potentially deferrable, and for space conditioning, this amount depends on the ambient temperature. Models of space cooling, space heating, water heating and electric vehicles have all been modeled in the multi-period SuperOPF.

What was accomplished by this research? What were the contributions to the field?

The available capabilities of the models used to analyze operations on a power grid limit the scope of the analyses conducted. For example, the traditional Security Constrained Optimal Power Flow (SCOPF) models used by systems operators are deterministic, with a DC representation of power flows for a single period. These types of models make it difficult to analyze important new problems that are emerging, such as dealing with 1) the stochastic characteristics of generation from wind turbines and solar PV, 2) the effects of storage on system operations, and 3) greater participation by demand-side resources (e.g. distributed storage) in electricity markets.

A fundamental objective for developing the SuperOPF was to provide an optimizing model with new capabilities that make it feasible for researchers to study these emerging problems effectively. The two salient features of the multi-period SuperOPF that make this possible are 1) stochastic inputs are represented realistically, and 2) the optimization covers a 24-hour horizon. With these features, it is now practical to evaluate 1) how the uncertainty of wind generation, for example, affects the need for reserve capacity to provide ramping, and 2) the tradeoff for storage between a) shifting load from peak to off-peak periods, and b) providing ramping to mitigate the variability of renewable generation. Given the new capabilities of the multi-period SuperOPF, here are examples of the issues and insights that can now be addressed:

1. The reduction of fuel costs when wind capacity is added to the test network is much larger than the increase in ramping costs, but the amount of missing money for conventional generators is also increased. The lower cost of energy in the wholesale market should be compared with the higher additional costs of capacity in a capacity market to determine the net benefits [29].
2. For any hour in the planning horizon (24 hours), an optimal dispatch is determined for each possible system state, and in some states, it may be inconsistent with the established rules for clearing a deterministic wholesale market. For example, some wind may be spilled in high wind states even though more expensive generators are operating. The reason is that there is a tradeoff between reducing fuel costs by dispatching more wind and committing more capacity for ramping [16].
3. Utility-scale storage located at wind sites is an effective way to 1) flatten the daily dispatch of conventional generation by charging at night and discharging during the day, 2) mitigate the variability of wind generation by providing ramping services, and 3) spill less of the potential wind generation. Distributed storage, in the form of deferrable (controllable) demand, is slightly less effective at providing these three system benefits but it does have two other distinct advantages. First, it reduces congestion on the network and may reduce the need for transmission upgrades [5]. Second, the capital cost is likely to be lower because this cost is shared with delivering an energy service to customers, and as a result, the total cost to customers is reduced [2].

What are the current and/or future applications of this research?

The benefits to customers from using deferrable demand to lower total costs cited above [2] assumes that these devices are operated centrally by an aggregator and appear as a virtual battery. The aggregator receives instructions from the system operator about when to charge and discharge. Our current research has shown that similar benefits accrue to customers when the aggregator manages the devices locally by minimizing the expected cost of purchases from the grid and submitting bids into a day-ahead market that include trigger prices for charging and discharging deferrable demand [18]. Nevertheless, it is likely that the system operator's optimum plan will eventually violate the energy capacity of deferrable demand by the end of the 24-hour period. For this reason, a topic for future research is to compare operations using a rolling-horizon criterion for grid operations instead of a day-ahead market. This will allow aggregators to use updated price forecasts and provide the system operator with more realistic bids for the next 24-hours. In addition, the system operator will be able to take advantage of updated and more accurate forecast of stochastic inputs, such as potential wind generation [4].

Identify any products developed and any technology transfer activities

Other products	This project was in collaboration with Ray Zimmerman's project that developed the optimization code for the SuperOPF. The current public version of this model can be downloaded under a 3-clause BSD license at http://www.pserc.cornell.edu //matpower/. Our contribution was to provide different components for generating the stochastic inputs for and displaying results from a newer version of the SuperOPF model (called the Matpower Optimal Power Scheduler, MOPS) that is not yet publically available.

Publications

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19. Lu, Hao; Wooyoung Jeon, Alberto J. Lamadrid, Timothy D. Mount, and Jung Youn Mo, “Evaluating the Effectiveness of Demand Aggregators in Accommodating the Uncertainty of Wind Generation”, Proceedings of the 33nd Annual CRRI Eastern Conference, May 2014.
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25. Mount, Timothy D.; Alberto J. Lamadrid, Woo-Young Jeon, Carlos E. Murillo-Sánchez, and Ray Zimmerman. *How Will Customers Pay for the Smart Grid?* Presented at the 30th Annual Eastern Conference in Regulated Industries, Skytop, Pennsylvania, May 18-20, 2011.
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PI (Lead)	Shmuel Oren			Institution	Univ. of California, Berkeley
Project Title	Transmission Unit Commitment in Economic Dispatch				
Funding	FY	09	$	50,000	

Summary of project intent/scope

Explore the potential saving in economic dispatch cost from simultaneous economic dispatch of generation resources and switching off lines in a smart grid environment. Develop new models that capture the potential of line switching and new algorithmic procedure that can efficiently solve the challenging combinatorial optimization problems posed by such models. Ultimately, this project will lay the ground for introducing short run topology optimization to traditional unit commitment and optimal power flow dispatch and will demonstrate the potential value of such topology control in a smart grid environment with appropriate line switching technology.

Summary of project activities for the entire period of funding stated above

Current tools for unit commitment and security constrained economic dispatch treat the network topology as a fixed network in the short run that is subject to random outages. However, the long planning cycle of transmission system and the fact that the grid is designed to be robust under a multitude of condition implies that the network design may be suboptimal in many circumstances. It is well known and easy to demonstrate that switching out transmission lines may in fact increase transfer capability of the network and indeed in practice operators often switch lines on an ad hoc basis when overloaded or not needed during low load periods but there is no systematic effort to optimize the network topology on a short term basis. Project activities over the duration of the project continued the development and analysis in two directions that added realism to this study. We expanded expand the formulation of the optimization model to account for AC load flow with reliability constraints commonly used in short term economic dispatch. We will also expand the DC formulation to address the day ahead co-optimization of generation unit commitment and transmission-switching accounting for the nonconvexities in generation cost functions, ramp rates, reserve requirement etc. These formulations were tested on a stylized IEEE test problems and on real cases provided by CAISO and ISO-NE through FERC. The main difficulty in modeling the transmission system as switchable is that switchable lines need to be represented as binary variables and optimizing the network topology simultaneously with determining the optimal dispatch under reliability constraints becomes a very difficult combinatorial optimization problem. Experience so far shows that our proposed extensions pose significant challenges even to the most advanced commercial software packages such as CPLEX and DASH. Hence, we developed new heuristics and algorithmic advances to facilitate such solutions and improve algorithm's performance. Specifically we explored the development of new "cuts" that constrain the relaxed version of the combinatorial optimization problem and hence improved the bounds on the optimal objective generated as part of the branch and cut procedures.

In addition to the model formulation and computational work we also explored the economic implications of transmission switching. Specifically, we investigated how switching of transmission lines to reduce the social cost of congestion may impact the FTR market in terms of overall revenue adequacy and settlement to FTR holders.

What was accomplished by this research? What were the contributions to the field?

Our studies conducted in this project have demonstrated significant potential savings through co-optimization of economic dispatch and transmission switching on standard test systems and on a 5000 bus case based on ISO-NE data. In the test case of the IEEE118 bus network and IEEE76 (RTS 96) network we were able to show significant savings due to transmission switching while meeting N-1 security constraints. These results were obtained for DC approximations and without considering aspect of unit commitment such as fixed startup cost, no load cost, ramp rates etc. We have also developed new heuristics for identifying priority lists of lines that should be evaluated for switching and started work on large scale commercial systems. Our study of economic implications of transmission switching indicates that while such actions will improve social welfare by reducing dispatch cost, they may create winners and losers in the FTR markets and some form of side payments may be needed to account for such adverse consequences.

The results of this project were instrumental in increased interest throughout the research community and industry in the potential of topology control. It led to funding by ARPA E of two multimillion multi-million dollars projects under the GINI initiative focusing on the development and commercialization of topology control.

What are the current and/or future applications of this research?

ARPA E funded two large projects on topology control which includes the assembling of User Forums and various activities to promote the implementation of the technology in industrial setting including ISO-NE, PJM and ERCOT. In the follow-up work to this project, funded by ARPA E it was demonstrated that topology control could save, 100 Million dollars annually at PJM. We have also demonstrated significant benefits of post contingency topology control at TVA. PJM is in the process of issuing an RFP to explore and develop topology control strategies for its system and we are currently in negotiation with ERCOT to start a demonstration project on implementing topology control as part of their pre and post-dispatch procedures.

Identify any products developed and any technology transfer activities

Technologies/Techniques	Incorporating topology control in unit commitment

Publications

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PI (Lead)	Shmuel Oren			Institution	University of California, Berkeley
Project Title	**Interactions of Environmental Policies in a Transmission-constrained Competitive Electric Market**				
Funding	**FY**	10	**$**	60,000	
	FY	11	**$**	80,000	

Summary of project intent/scope

The project will addressed several emerging issues: 1) Will multiple concurrent market-based policies necessarily benefit renewable producers at the expense of consumers and coal-based producers? 2) What is the relationship among prices of electric energy, emissions permits, and renewable energy credits (RECs)? 3) Will multiple concurrent market-based policies grant a greater magnitude of incentive for companies to manipulate markets in their favor (i.e., market power)? 4) Do the designs of the current policies have adequate flexibility without sacrificing environmental integrity and interfering with competitive market operations? 5) Will any policy be redundant under certain conditions if their policy goals are to some extent overlapped? And 6) What are the implications to power producers if a) renewable used to meet RPS can be sold as green power to customers (referred to as double-counting) or b) utilities can bundle RECs with non-renewable and sell as green power (referred to as bundling) and c) RECs can be used to offset emissions obligations? This analysis of the above questions will focus on the Western US using a reduced model of the WECC.

Summary of project activities for the entire period of funding stated above

Energy policies, such as a RPS, can interact with electric market operations in several ways. For instance, policies can effectively limit the total amount of energy that could be produced or consumed from none-renewable sources, if the RPS is binding, equivalent to rendering renewable producers market power. In short run, an over-stringent RPS might crash emissions trading markets and might increase electricity price volatility. However, the extent to which these interactions affect market outcomes also depends on the ways renewable energy credits (RECs) and renewable energy are treated in the markets. This relates to 1) whether or not double counting of RECs is allowed; and 2) whether bundling of RECs and energy is allowed.

The lack of understanding about the interactions of these concurrent policies and their implied consequences could put the power sector and society as a whole on a costly and potentially irreversible path. Our research explored the interactions of multiple market-based policies. It improved understanding about the price dynamics among different commodities created by various instruments (e.g., emission permits, RECs), costs of compliance to the generating companies and implied emissions consequences. The answers to these questions depend on the transmission network configuration, the generation mix, the extent of congestion and the extent of ownership concentration. Hence, our analysis involved detailed modeling of the electricity system that represents both the economic and electrical features with reasonable accuracy.

We examined a variety of questions regarding the impact and efficacy of environmental regulation in the context of the Western US electricity system. The project complemented a parallel effort funded by CERTS and PSERC that focuses on the Eastern US. The ultimate goal was to put together a national model that will provide a tool for assessing the impact of emerging environmental regulation while accounting for economic and technical aspects of the electricity infrastructure in the US. The primary focus in this project was to develop and refine a reduced model of the WECC with enhanced details for California that captures network effects, congestion and market power and can serve as a tool for examining alternative proposal for environmental regulation.

In this project we collaborated with Dr. Yishu Chen of UC Merced (funded by other sources) who has extensive experience and has published several papers addressing environmental regulation issues in the context of electricity system.

What was accomplished by this research? What were the contributions to the field?

Carbon regulation policies, such as a RPS, carbon tax, or Cap & Trade interact with electric market operations that effect economic and environmental outcomes in several ways. For instance, by changing the relative cost of different resources such policies will impact the fuel mix in the dispatch. This in turn may impact congestion and the level of competition which will affect prices and ultimately the levels of energy production. In a paper (A. Downward, Energy Journal Vol 31, No. 4, (2010)) it was demonstrated how a carbon tax may result in an increase in emission due to reduced congestion increased causing competition which puts down pressure on prices and increases overall energy consumption. Likewise, in short run, an over-stringent RPS might crash emissions trading markets and might increase electricity price volatility. However, the extent to which these interactions affect market outcomes also depends on the ways renewable energy credits (RECs) and renewable energy are treated in the markets.

Our research focused on the Western US and complement a parallel effort co-sponsored by PSERC and CERTs for the Eastern US. We employed several methodological approaches based upon a reduced electrical model of the WECC electrical system developed in collaboration with CAISO. We have developed a market equilibrium framework employing a linear complimentarily model which was applied to an IEEE 24 bus test system and to a reduced 225 bus representation of the WECC. Computational experiments and sensitivity studies validated the capability of the model and demonstrated that indeed ownership structure and congestion may have significant impact on economic and environmental outcomes. Comparative studies for the 24 bus model also validated the use of a DC approximation in this policy context. We expanded the California test case to a 250 bus network which added details that capture the essential elements of the California electricity grid, and reflected the expected changes in proposed energy and environmental regulations. Extensive studies were performed to evaluate alternative policy options and understand the causes of the observed numerical results. We have also explored the interaction between electricity markets and emission trading. Specifically we have demonstrated the impact of initial emission permits allocation on electricity market outcomes when the market for emission permits is subject to imperfect competition.

What are the current and/or future applications of this research?

The results of the work have been disseminated through publications and presentations at professional meeting. Public policy on emission trading will hopefully account for the identified interactions and potential consequences.

Publications

1. Limpaitoon, Tanachai; Yishu Chen, and Shmuel Oren. *The Impact of Carbon Cap and Trade Regulation on Congested Electricity Market Equilibrium*. Journal of Regulatory Economics, vol. 40, pp. 237-260, September 6, 2011.
2. Limpaitoon Tanachai, Yihsu Chen and Shmuel S. Oren, *The Impact of Imperfect Permit Market on Congested Electricity Market Equilibrium*, The Energy Journal*,* Vol 35, No. 3 (2014) pp. 145-166
3. Papavasiliou, Anthony; Y. Chen, and Shmuel Oren. *Environmental regulation in transmission-constrained electricity markets*. IEEE Power Energy Society General Meeting, pgs. 1–8, July 2009.
4. Tanachai Limpaitoon**,** *Cap-and-Trade Modeling and Analysis: Congested Electricity Market Equilibrium*, PhD. Dissertation, University of California at Berkeley, 2012

PI (Lead)	Shmuel Oren			Institution	University of California, Berkeley
Project Title	Business Model for Retail Aggregation of Responsive Load				
Funding	FY	12	$	90,000	
	FY	13	$	100,000	

Summary of project intent/scope

The project seeks to develop methods for assembling, managing, and valuing complementary portfolios of variable or intermittent power sources and applications, such as load curtailment, load shifting, renewable resources (wind, solar) and distributed storage (e.g., EV and PHEV batteries, UPS devices etc.). Aggregators can assemble portfolios of such resources to obtain wholesale resources that can be offered in the various ISO markets and exploit the complimentary aspects of these resources through portfolio structuring and dispatch strategies to mitigate the intermittent nature of load response and renewables. Variability can be further reduced by pooling uncertain retail level load response and distributed renewable and organizing the pool through product differentiation according to dispatch priorities.

Summary of project activities for the entire period of funding stated above

This work seeks to develop a sustainable business model for a utility or a third party aggregator who will interface with responsive loads on the retail side to produce wholesale demand side resources that can be offered in the day ahead, real time, reserves and regulation markets operated by the ISO. Retail demand response can also be augmented by distributed intermittent renewable resources and storage devices so that the aggregator would exploit the complimentary aspects of such resources. This project's activities focused on developing an end to end approach that will mobilize load flexibility on the retail side and bundle such flexibility into wholesale products that can compete in the ISO markets and improve overall system efficiency. Specifically we consider direct load control mechanisms where retail customers enter into service contracts that define the contingencies under which portions of their load can be shifted or curtailed and the financial terms for the service. We believe that such an approach is compatible with customer experience with other services and with public policy realities. As a special case such contracts can specify a threshold wholesale price above which a portion of the load or the use of specific appliances can be curtailed. Such contracts can capture the economic benefits of real time pricing if customer choices are sufficiently stable. However, the terms of service contracts may be more general like some bounds on curtailment frequency or a time window within which load can be shifted, allowing load to be controlled asynchronously, as opposed to synchronous control triggered by the wholesale spot price. Asynchronous load control may be advantageous when loads flexibility comes from inherent storage capability like EVs or thermostatically controlled loads. In such a case one would want to spread the load rather than have, for instance all EV's shifting their charging time in response to a high real time price.

Our general approach draws on the economic theory of efficient rationing and priority service that has been developed by the PI and his colleagues under the auspices of EPRI back in the 1980s and 1990s. These early developments that were theoretical in nature when introduced, have now become relevant to practice given the capabilities and cost of new metering and control technologies. Our research activities focused on developing a comprehensive end to end solution based on the fundamental load control idea described above that includes the following components:

1. Updating of underlying theory of efficient rationing and risk pooling.
2. Design of service terms and pricing for load control contract
3. Design of contract portfolio for load control aggregation
4. Algorithms for exercise of load control given a contract portfolio
5. Design of wholesale electricity products (and pricing) backed by aggregator portfolios.
6. Simulation studies of unit commitment and real time markets with load control products.
7. Planning tools for electricity systems with ubiquitous load control.

What was accomplished by this research? What were the contributions to the field?

We developed a model of the aggregator's problem: the aggregator owns a VER, faces a fixed wholesale market price, a given population of potential DR participants, and a fixed penalty for shortfall in production. It chooses quantity to commit to the market, and optimally designs a menu of contracts that DR participants can choose from. The contract structure is based on a fuse control paradigm where customers can select service levels from a menu differentiated by price and probability of curtailment for capacity increments. These increments are stacked in order of service priority. Customers are assumed to make their selection according to their private valuation of capacity increments which reflect behind the meter optimization of electricity usage subject to the capacity constraint. The contract menu is structured so as to elicit the customers private information (valuations) following the theory of mechanism design. The simplest abstract model is a one-period model: wholesale market prices are known and fixed, the characteristics (in particular, the value of consumption) of population of demand response consumers are constant and deterministic, and the VER production follows a single arbitrary but known probability distribution. We have updated the relevant theory to apply it in this setting, characterized the solution to the aggregator's optimization problem, and solved a concrete instance of this model to develop qualitative insight into the economics of the problem. We show that the optimal contract menu has a threshold structure, where the threshold is characterized by fairly simple first order condition. We also have derived two expressions for the optimality conditions characterizing the supply function VER backed by DR which specifies the quantity of power offered to the wholesale market as a function of the wholesale price, the VER nameplate capacity and the DR total capacity.

In addition, we developed a framework to validate our fuse control paradigm by investigating the efficiency loss due to a hierarchical control scheme, whereby the household valuation of incremental fuse capacity can be captured by an average supply function for incremental capacity curtailments. An analytical model was developed and was incorporated in a stochastic, optimization-based framework, where stochasticity arises due to forecast errors in photovoltaic power output representing net load variability. By means of simulation studies we then compared the cost to the household when incremental fuse curtailments are based on such an average supply function upon which contracts can be based, as compared to an idealized setting where individual appliance are interrupted directly based on a real time price signal replicating the wholesale price. We also enhanced this model to include storage devices and performed a rigorous analysis to construct a probabilistic envelope, inside which the valuations of the incremental fuse capacity are confined to lie. Our simulation studies indicate that the hierarchical load control approach incurs about 15% efficiency losses compared to an ideal benchmark based on controlling each device in the household via real time wholesale price signals.

What are the current and/or future applications of this research?

The proposed paradigm offers a viable approach to coupling VER with demand response but it has not been implemented yet.

Publications

1. Oren, Shmuel. *A Business Model for Residential Load Control Aggregation*. 2014 IEEE Power & Energy Society General Meeting, National Harbor, Maryland, July 27-31, 2014.
2. Oren, Shmuel. *A Historical Perspective and Business Model for Demand Response Aggregation Based on Priority Service*. Proceedings of Hawaii International Conference on Systems Sciences 46 (HICSS 46), Maui, Hawaii, January 7-11, 2013.
3. Campaigne, C.; Shmuel Oren. *A Mechanism Design Model for Firming Intermittent Renewable Generation with Curtailable Demand*. INFORMS Annual Meeting, Cluster Session on Energy, Natural Resources and the Environment; San Francisco, California, November 9-12, 2014.
4. Margellos, Kostas; and Shmuel Oren. *Capacity constrained demand side management: A stochastic pricing analysis.* Accepted for publication in the IEEE Transaction on Power Systems. 2015.
5. Margellos, Kostas; Shmuel Oren. *A fuse control paradigm for demand side management: Formulation and stochastic pricing analysis*. American Control Conference, Chicago, Illinois, July 1-3, 2015.
6. Papavasiliou Anthony, Shmuel S. Oren, "Large-Scale Integration of Deferrable Demand and Renewable Energy Sources in Power Systems", IEEE Transaction on Power System, Vol. 29, No. 1, (2014) pp. 489-499

PI (Lead)	Hsiao-Dong Chiang			Institution	Cornell
Project Title	SuperOPF Optimization Solver Enhancement/SuperOPF Framework				
Funding	FY	09	$	70,000	
	FY	11	$	31,000	
	FY	13	$	60,000	

Summary of project intent/scope

The stochastic contingency-based security constrained AC OPF formulation behind the SuperOPF makes it very applicable to a variety of problems arising in power system planning and operations under deregulation. The intent of this work was to develop a commercial-grade SuperOPF in the context of co-optimization framework that correctly accounts for contingencies, ancillary services, static and dynamic constraints in determining both dispatch and price.

Summary of project activities for the entire period of funding stated above

The objective of the SuperOPF project is to develop a framework that will provide proper allocation and valuation of resources through true co-optimization across multiple scenarios. Instead of solving a sequence of simpler and approximate sub-problems, the SuperOPF approach combines as much as possible into a single mathematical programming framework with a full AC network and simultaneous co-optimization across multiple scenarios with stochastic costs.

This effort involved development of the problem formulations, implementation of research grade software code, and testing of the methods and algorithms on a range of case studies to demonstrate their added value over currently available tools.

The main activities of year 1 were the following:

- develop an effective OPF tool as a foundation for SuperOPF's stochastic co-optimization framework
- Develop an OPF solver which can handle practical large power systems (> 10,000 buses)
- Develop a robust and efficient OPF solver which can converge well under heavy loading conditions
- Develop an OPF solver that can determine optimal values for discrete control variables
- Support the extensible modeling capability of the SuperOPF Framework
- Evaluate on the PJM's 13,000-bus system
- Support utility industry standard network models
- Support improvements of load modeling, DC line modeling and generator capability curve modeling
- Data Format and modeling improvement: PSS/E version 30 (PJM) and CIM compliance format (CAISO)

Year 2 focused on the following: (i) enhancing SuperOPF (into SuperOPF-contingency) in its capability to deal with a large set of contingencies subject to voltage stability constraints, (ii) adjusting (or re-dispatching) both real and reactive power control variables so that Super-OPF-contingency can perform the application functions needed in a ISO/RTO-scale Energy Management System (EMS), (iii) enhancing SuperOPF in its capability to deal with different objective functions needed in power system operation and planning, (iv) enhancing SuperOPF in its capability to deal with optimal load shedding, (v) continuing development toward a commercial-grade SuperOPF-contingency package.

Year 2 work featured following activities:

- Develop a commercial-grade core SuperOPF-Contingency software equipped with a commercial Power flow Solver and a homotopy-based interior point based solver and support various industrial-grade power system models such as 13,000-bus EMS models in Common Information Model (CIM) and Siemens' PSS/E data formats.
- Develop a commercial-grade core SuperOPF-Contingency software equipped with a commercial voltage stability solver capable of handling the voltage stability constraint of a large set of contingencies, such as 2500 contingencies.

- Develop a commercial-grade core SuperOPF-Contingency software equipped with an optimal load shedding solver capable of handling up 10,000 loads.
- Develop a comprehensive Automatic Voltage Control (AVC) formulation using the SuperOPF Framework.
- Develop an effective solution methodology for solving the AVC formulation.

The Year 3 focus was to develop a commercial-grade Co-optimization Stochastic SuperOPF-renewables with the following features:

- Co-optimize multiple base-cases
- Uncertainties of wind generation
- A large set of contingencies
- Security-constrained OPF (contingencies, static security constraints)
- Stochastic cost
- AC power flow (under contingency constraints)

This stage developed the single-period, stochastic optimal power flow (OPF) solver and program to deal with the uncertainty of operating conditions. Such uncertainty stems from the possible occurrence of contingences and from limited knowledge about future model parameters (e.g., the uncertainty of predicting load, climate, wind availability and river flow.) Uncertainties were described as a set of probability distributions for involved contingencies and uncertain parameters and were materialized as multiple scenarios (sets of system states) with associated probabilities. The objective of the OPF computation is thus a probability-weighted sum of the objectives of the materialized scenarios.

What was accomplished by this research? What were the contributions to the field?

Security constrained optimal power flow programs are important tools for ensuring correct dispatch of supply while respecting the many constraints imposed by the delivery system power grid. Current state-of-the art production-grade tools typically break the relevant optimization problems down into sequences of sub-problems, often using DC approximations to model the transmission and replace voltage and adequacy requirements with corresponding proxy constraints.

The SuperOPF framework provides proper allocation and valuation of resources through true co-optimization across multiple scenarios with a full AC network implemented in software.

The SuperOPF production-grade software is a fast, robust implementation of a core solver integrated in the SuperOPF Framework. The work includes handling utility industry standard network models, data management for SuperOPF constructs, handling of control variables for real and reactive power and support for objective functions of cost, losses and minimum violations of target voltage profiles.

What are the current and/or future applications of this research?

Research under this project included presentation of the production-grade SuperOPF software to in power industry ISOs and RTOs to gather information about industry applications of the technology. A summary of identified areas follows.

Operations:

- Static stability constraints with contingency
- Setting voltage schedules
- Minimizing number of controls for reliability
- Co-optimizing transfer capability and generation dispatch
- Co-optimization of worst scenarios especially with renewables
- Inclusion of AGC response into SuperOPF to deal with renewable integration
- State Estimation Improvements
- Setting transfer limits based on margins to limits (thermal, voltage, stability)

Planning:

- Help addressing NERC requirements
- Dynamic stability constraints with contingency

• Peak Load Reduction • Reserve requirements with renewables Power Market: • Look-ahead (short–term up to 4 hours) for renewables using co-optimization • Application to the day-ahead to address renewable intermittency and pre-planning of reserve generation

Identify any products developed and any technology transfer activities

Website(s)	www.bigwood-systems.com

Networks/collaborations	Presentations and discussions of the technology were held at the California Independent System Operator, PJM Interconnection, Tennessee Valley Authority, Independent System Operator – New England, Net York Independent System Operator, DOE Office of Electricity Transmission and Energy Reliability

Inventions, Patent Application, licensing agreements, etc.	Patent Application: METHOD AND APPARATUS FOR OPTIMAL POWER FLOW with VOLTAGE stability FOR LARGE-SCALE ELECTRIC POWER SYSTEMS, Application Number: 14/459,960, Filing Date: 08/14/2014

Publications

1. Chiang, Hsiao-Dong; and Ray Zimmerman. Project Final Report, *Commercialization of the SuperOPF Framework*, User Manual 1.0, final and Design Manual 1.0, March 30, 2012.
2. Chiang, Hsiao-Dong. *Locational Marginal Pricing under Composite Dynamic Load Models: Formulation and Computation.* Final Project Report. October 2009.

PI (Lead)	Bernie Lesieutre			Institution	University of Wisconsin-Madison
Project Title	Proxy Limits				
Funding	FY	09	$	80,000	

Summary of project intent/scope

The purpose of this study is to determine the best way to incorporate “proxy-limits” in a DCOPF to preserve features of the solution of a more detailed ACOPF. Specific voltage and stability limits cannot be directly represented in a DCOPF and are indirectly included as line flow limits. This research sets out to determine the best way to set proxy limits to preserve the dispatch and prices of the ACOPF, in a DCOPF representation.

Summary of project activities for the entire period of funding stated above

The traditional engineering approach to establishing proxy limits is to impose line limits that preserve dispatch and line flows in a solution. For a typical and important example, consider the effect of a voltage constraint at a bus. As the power demand at the bus increases the voltage will drop, eventually reaching a minimum limit. In a physical sense the amount of power the can be delivered to the bus is limited by the voltage constraint. An effective first choice for representing this limit in a DCOPF with no voltage representation is to impose flow limits on the lines incident on the bus. This method is simple, and it can meet the dispatch and physical flows in the solutions. However, it is observed that this approach of limiting flows on incident lines does not preserve prices well. That is, the Lagrange multipliers of the more detailed ACOPF are not preserved. While the absolute dispatch and flows can be met this way, the incremental model is substantially different (and prices are set by incremental changes).

In order to determine the best way to represent proxy limits we start by examining small systems over which we can essentially perform an exhaustive search of possible line combinations. Specifically we pose the study as an optimization problem to minimize a weighted measure of differences between generator dispatches and system prices for a detailed ACOPF and proxy-limited DCOPF. Then by brute force we find the best one-line proxy limit, the best two-line proxy limit, the best three-line proxy limit, etc. The results showed a compelling pattern. To best fit both dispatches and prices, placing limits on lines close to generators was most effective, even when the corresponding voltage constraint was physically and electrically distant from generation. Although this result was not anticipated prior to the study, it has a simple explanation. The flow and prices are ultimately determined by the controllable resources in the optimization problem, i.e. the ACOPF. The controllable resources are typically the generators whose dispatch is determined as a result of the ACOPF. Placing direct limits on the generators is the most effective and direct way to manage these resources via constraints. With proxy limits on lines, the most effective lines are close to the controllable resources.

What was accomplished by this research? What were the contributions to the field?

This research proved fundamental understanding into the nature of proxy-limits, that they are most effective when they limit the controllable resources in the model. In that regard the results are intuitive; however we note there is a real difference between this observation and the previously held (and intuitive) expectation that proxy limits should be located near the physical limit. Given the results of this research we provide the following recommendations: A. Try not to rely on proxy limits and use the more detailed ACOPF over a DCOPF. B. If a DCOPF is to be used for practical reasons, consider implementing the limits directly in terms of generator injected powers instead of line flow limits. In a manner similar to the calculation of generator distribution factors associated with line flow limits, one could compute generator distribution factors associated with voltage limits. However there is a perception that this approach of representing proxy limits directly in terms of generation could be opposed by generation as placing artificial limits on their output. In that case recommendation C. is to perform some scoping studies similar to ours for the system of interest to find the lines most effective for mimicking ACOPF voltage constraints by proxy limits. Among these options we strongly recommend the ACOPF approach, and we note that there is considerable on-going research on methods for robustly solving the ACOPF problem.

What are the current and/or future applications of this research?

The best use of future research in this area is to enable the reliable use of the ACOPF for all problems of interest. This avoids the inherent approximations that are introduced by artificial proxy limits in a DCOPF. Within the problem of proxy limits for the DCOPF, assuming the need may persist for some time in the future, we recommend that research be directed to the development of calculations for generator affine distribution factors associated with voltage constraints. These types of distribution factors will be the most direct and most effective means for implementing voltage-based proxy limits in the DCOPF.

Identify any products developed and any technology transfer activities

Networks/collaborations	University of Wisconsin-Madison; Cornell University

Technologies/Techniques	Optimization, Sensitivity Analysis, ACOPF, DCOPF

Publications

1. Lesieutre, B.C., M. Schlindwein, and E.E. Beglin, "DC Optimal Power Flow Proxy Limits," presented at the 43rd-Annual Hawaii International Conference on System Sciences, January 2010.
2. Edward Beglin, "Representing Voltage Constraints in a Proxy-Limited DC Optimal Power Flow," Master's Thesis, December 2008 (UW-Madison).
3. Michael Schlindwein, "Optimal Proxy-Limited Lines for Representing Voltage Constraints in a DC Optimal Powerflow," Master's Thesis, December 2009 (UW-Madison).

PI (Lead)	Bernie Lesieutre			Institution	University of Wisconsin-Madison
Project Title	Market Power Monitoring Metrics				
Funding	FY	09	$	80,000	
	FY	10	$	135,000	

Summary of project intent/scope

Market power gives certain market participants the ability to manipulate the market to their advantage. In our research we identify resources which have the potential for market power either individually or within a small group based on sensitivity information that can be obtained from an optimal power flow. Specifically we cluster generators with the ability to adjust prices without affecting dispatch, potentially enabling them to set prices. We develop and demonstrate robust algorithms that can be applied to ISO-scale systems.

Summary of project activities for the entire period of funding stated above

We have developed a sensitivity-based metric for identifying market participants with potential market power in an energy market. The overall approach is to seek a small number of suppliers that are not substitutable in some portion of the grid for a given operating condition. This is a form of local market power usually due to system constraints that create load pockets. While a single supplier or small group of suppliers may not be pivotal in total supply, they can potentially have market power control over a smaller network-constrained region.

The mathematical technique computes sensitivity matrices relating revenue/offer price and dispatch/offer price. Using these matrices, groups of participants are identified with the ability to simultaneously raise energy offer prices and revenues. Importantly, the influence of networks and their limitations are explicitly included in the analysis, implicitly identifying affected load pockets. Our prior work has proven the effectiveness of this methodology on smaller systems and has been corroborated with experimental economic studies at Cornell University in which students representing generators in an energy auction have been able to determine and exploit market power potential. The purpose the research is to scale up methods for practical real time application to ISO-scale systems.

The challenges in fast large scale applications involve the fast computation of the sensitivity matrices, and the ability to analyze these matrices to identify small groups with market power potential. To appreciate this latter point, note that there are may be many possible combinations of suppliers who may control prices, but cases that require coordination of a large number of participants pose little risk to the market. The challenge is to identify the potential of a small number of suppliers that may control the market in a load pocket through the analysis of a large sensitivity matrix. As demonstrated in the earlier Cornell studies, a small number of suppliers can discover their market power potential without direct collusion.

The necessary mathematical advances for large-scale implementation are reported in our IEEE transactions paper. This describes an efficient means to construct the sensitivity matrix using generator distribution factors. We then pose a two-stage algorithm for identifying small groups with market power potential. The first stage uses a clustering algorithm to group generators. The second stage uses an eigen-analysis approach to isolate price perturbation properties, and guide subsequent refinement to the clustering. The paper presents results on an IEEE test system, and we have applied the method to ISO-scale models.

At the end of this project, the algorithm is shown to practical for large scale implementation.

What was accomplished by this research? What were the contributions to the field?

In this stage of our research on market power monitoring we developed practical algorithms for large scale implementation. The first challenge involved the calculation of the sensitivity matrices, which was aided through the use of generation distribution factors that are routinely calculated by commercial tools. The second challenge was to examine the sensitivity matrix to identify small groups of suppliers with the potential to exploit local market power. This was challenging due to the large number of possible combinations from a single supplier, to the combination of all suppliers. We applied a two-stage process to group generators and subsequently compute viable market power price perturbations. Further refinement was used to regroup generators based on these initial results of the algorithm.

The method is ready for deployment in the power industry as another tool for the identification of local market power. One of the primary researchers developed a prototype software tool for this purpose.

We also find it worth noting that another contribution to the field: the methodology developed under this program was applied to to the study of important facilities in the power grid for the Federal Energy Regulatory Commission (FERC). The sensitivity approach is basis for the Topological and Impedance Element Ranking (TIER) developed for FERC to inform their analysis of elements of the bulk power grid. It is a direct extension of this research.

What are the current and/or future applications of this research?

The research focused the analysis of market power potential considered in a traditional framework involving large generators in an energy market. Consideration of demand response potential, and coupled markets for energy and various forms of reserves, the sensitivity approach could be applied to larger coupled problems for which market power potential may be harder to detect.

Identify any products developed and any technology transfer activities

Networks/collaborations	University of Wisconsin-Madison, University of Illinois Urbana-Champaign
Technologies/Techniques	Optimization, Sensitivity Analysis, Clustering
Other products	Prototype software was developed by research partner Tom Overbye.

Publications

1. Rogers, K.M., and T.J. Overbye, “Clustering of Power System Data and its use in Load Pocket Identification,” 44th Hawaii International Conference on System Sciences, January 2011.
2. Lesieutre, B.C., K.M. Rogers, T.J. Overbye, A.R. Borden, “A Sensitivity Approach to Detection of Local Market Power Potential,” IEEE Transactions on Power Systems, Vol. 26, No. 4, pp. 1980-1988, November 2011.
3. Alex Borden, “Real Time Market Power Analysis Tool for Electric Generation Markets,” MS Thesis, May 2010, University of Wisconsin-Madison.

PI (Lead)	**Dan Tylavsky**			**Institution**	**Arizona State University**
Project Title	**ESP Network Reductions for Engineering and Economic Analysis of High Penetration of Renewables**				
Funding	**FY**	11	**$**	175,000	
	FY	12	**$**	121,000	
	FY	13	**$**	90,000	

Summary of project intent/scope

Economic simulation of large and highly complex engineering systems is sometimes impossible or impractical because of the computational demands of these simulations. To that end, smaller models must be developed that preserve certain, but not all, attributes of the system. The objective of this work has been to 1) develop methods for producing reduced electrical network models that preserved different sets of attributes, 2) develop a reduced equivalent model of the North American electric power system and 3) develop a Network Reduction Toolbox which incorporates the best of the methods developed for use by other researchers in this field.

Summary of project activities for the entire period of funding stated above

The activities of this project have been wide-ranging, but may be broken down into following categories: advancement of network reduction techniques, development of the Network Reduction Toolbox, development of backbone equivalents for the three major electric-power network interconnections in North America. These interconnections are the Eastern Interconnection (EI), Western Electricity Coordinating Council (WECC) interconnection and Energy Reliability Council of Texas (ERCOT) interconnection. The national network model was designed to be used with applications, such as the Engineering, Economic and Environmental Electricity Simulation Tool (E4ST), for analyzing policy options, impacts on reliability, costs and emissions for the North American electric power system.

We have also worked to support other research teams funded by DOE doing related research. Specifically, we have worked closely with the E4ST group at Cornell and Resources for the Future and provided them with multiple network equivalents for their studies and have work with Ben Hobbs and his Johns-Hopkins group as this group was the first to use our Network Reduction Toolbox. While we have coached them on the use of the Toolbox, Ben and his group have provided important feedback that has allowed us to make improvements to the speed and memory requirements of the Network Reduction Toolbox.

We have also worked with Hyungseon Oh at the SUNY Buffalo, who has helped us understand his bus-aggregation technique and who has help us develop an independent software implementation of the bus aggregation approach, allowing us to independently verify his network reduction method.

We have also worked with Tom Overbye at the University of Illinois to help validate his method of assigning branch flow limits to fictitious branches in reduced networks.

What was accomplished by this research? What were the contributions to the field?

One of the more tangible outcomes of this project was the development of Network Reduction Toolbox that is currently being distributed with MATPOWER 5.1 and will shortly be available through the E4ST website, E4ST.com. What makes this toolbox unique is that, unlike Ward reduction which splits generators into many pieces in the equivalent model, this application moves generators whole to buses using a closest-electrical-distance metric and then distributes loads using an inverse-power-flow algorithm to retain the accuracy of the retained-branch flows under base case conditions. For economic simulations, retaining generators whole rather than splitting them is important since most simulation programs are incapable of modeling split generators.

In the process of developing the Network Reduction Toolbox, it was found expedient to develop a module to convert PSSE formatted power-flow data into MATPOWER formatted data. This module was modified by Ray

Zimmerman of Cornell and is now distributed with this public domain application.

A second tangible outcome is the development of reduced backbone equivalent models for the North American power grid. These models include a 4853 bus model of the EI, a 389 bus model of ERCOT and a 2305 bus model of WECC. These models are being used by the E4ST team at Cornell, who are also being funded by DOE to perform related research. Because of the many data errors in the supplied data, assembling these models from multiple inconsistent sources was a task we underestimated when we began. To achieve acceptable models, several metrics—including locational marginal price and line-flow accuracy—were used to right-size these models. Selecting which branches and buses to retain in the model was an iterative process with significance guidance provided by the DOE commissioned National Electric Transmission Congestion Study and industry collaborators listed below.

In addition to working with the Cornell team, we have worked with Ben Hobbs team at Johns Hopkins who are using our Network Reduction Toolbox to produce a network equivalent with specific needs for the WECC system.

Most models used for economic analysis simplify the ac model with a dc approximate. One outcome of this research has been to identify the so-called "alpha-matching" model as the most appropriate model for generating a dc equivalent for an ac network and identifying an appropriate method for accounting for losses, as loss accounting is critical to model accuracy. In the process of validating dc equivalent reductions using PowerWorld, we identified bugs in the PowerWorld code and worked with the accommodating people at PowerWorld to fixed those bugs.

We've also worked with Tom Overbye at the University of Illinois to help validate his line-limits model.

Finally we've produced an independent application for the bus aggregation method developed by Hyungseon Oh and improved upon the implementation by decreasing memory requirements, which are substantial, and improving execution speed.

What are the current and/or future applications of this research?

The most recent release of the Network Reduction Tool Box, is being distributed internationally with MATPOWER version 5.1. This toolbox will allow any user to create a reduced network which will retain generators as whole in their models and match the base-case branch flows. While this toolbox is primarily expected to be used in conjunction with the E4ST application, it also functions as a standalone toolbox. It is impossible to know how many groups are now using the application. We are aware that it is being used by Ben Hobbs' group at Johns Hopkins in research on power system transmission expansion planning. To achieve wider distribution, this application will soon be available through E4ST.com.

The reduced backbone equivalent models for the North American power grid developed through this funding are expected to be made available in the public domain; however since the reduced models were built using proprietary data, it is expected that the user will need to purchase a license from the suppliers of the unreduced network data, Energy Visuals. These models are expected to be used by ISO's and utilities wanting to study the effects of government regulations on their expansion plans and by DOE for providing feedback on the effects of proposed government regulations to regulators.

Identify any products developed and any technology transfer activities

Networks/collaborations	Our closest collaborations have been with Hyungseon Oh (SUNY Buffalo), Tom Overbye (University of Illinois), Ben Hobbs (Johns Hopkins), and the E4ST team at Cornell (Bill Schulze, Dick Schuler, Ray Zimmerman) and at Resources for the Future (Dan Shawhan). During the North American electric power network model building phase of this project, we worked with many people in industry to verify model elements and retained bus/branch selection. Our collaborators included Navin Bhatt (AEP); Vince Ordax (FRCC); Xiaochuan Luo and Eugene Litvinov (ISO NE); Rao Konidena, Mark Westendorf, Ryan H. Westphal and Loren Mayer (MISO); Michael Swider and Steve Corey (NYISO); Mahendra Patel (PJM); John Idzior (RFC); Joe

	Spencer (SERC); Doug McLaughlin and Wyne Gambe (Southern Company); Mak Nagle (SPP); Dejim Lowe (TVA).

Other products	The Network Reduction Toolbox developed through this funding is being distributed with version 5.1 of MATPOWER.

Publications

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2. P. Sood, D. J. Tylavsky, Y. Qi, "Improved dc Network Models for Contingency Analysis," North American Power Symposium 2014, Pullman Washington, Sep. 2014, pgs. 6.
3. Y. Zhu, D. J. Tylavsky, "An Optimization-Based Generator Placement Strategy in Network Reduction," North American Power Symposium 2014, Pullman Washington, Sep. 2014, pgs. 6.
4. D. L. Shawhan, J. T. Taber, D. Shi, R. D. Zimmerman, J. Yan, C. M. Marquet, Y. Qi, B. Mao, R. E. Schuler, W. D. Schulze, D. J. Tylavsky, "Does a Detailed Model of the Electricity Grid Matter? Estimating the Impacts of the Regional Greenhouse Gas Initiative," Resource and Energy Economics, Volume 36 Issue 1, January 2014, pp. 191–207.
5. Y. Qi, D. Shi, D. J. Tylavsky, "Impact of Assumptions on dc Power Flow Accuracy," North American Power Symposium 2012, Champaign Illinois, Sep. 2012, pgs. 6.
6. N. Li, D. Shi, D. Shawhan, D. J. Tylavsky, J. Taber, R. Zimmerman, "Optimal Generation Investment Planning: Pt 2:, Application to the ERCOT System," North American Power Symposium 2012, Champaign Illinois, Sep. 2012, pgs. 6.
7. D. Shi, D. Shawhan, N. Li, D. J. Tylavsky, J. Taber, R. Zimmerman, "Optimal Generation Investment Planning: Pt 1:, Network Equivalents," North American Power Symposium 2012, Champaign Illinois, Sep. 2012, pgs. 6.
8. D. Shi, D. J. Tylavsky, "An Improved Bus Aggregation Technique for Generating Network Equivalents," 2012 IEEE Power Engineering Society General Meeting, San Diego, CA, Jul. 2012, pgs. 8.

PI (Lead)	Richard Schuler			Institution	Cornell
Project Title	Transmission Investment Assessment under Uncertainty				
Funding	FY	11	$	10,000	
	FY	12	$	10,000	

Summary of project intent/scope

Collaborate with Prof. Hobbs in developing multi-stage investment decision-making tools with recourse that provide realistic outcomes in an uncertain (realistic) environment, and coordinate that work with the efforts of Profs. Schulze, Shawhan and Zimmerman on developing a SuperOPF Planning Tool that might also be used as energy and environmental policy analysis tools.

Summary of project activities for the entire period of funding stated above

Two-way interactions were achieved between separate research groups in the development of both methodologies and a modeling tool that is publicly available.

What was accomplished by this research? What were the contributions to the field?

Advances were made by Hobbs' group on planning methodology, and Schulze's group developed a multi-period planning/simulation tool with realistic network reductions provide by Tylavsky's group, that incorporates, endogenously, generation investment and retirement, by energy source and location, and customer demand response to the consequent prices. These tools are now ready to perform realistic transmission investment planning, on top of simulations reflecting the long-run consequences of a range of energy and environmental policies.

What are the current and/or future applications of this research?

Simulate, realistically, the effects of the development of new transmission (e.g. the Quebec-NYC HVDC line), that reflect the consequences on electricity price, by location, and therefore on retirements of old and construction of new generation and on the demand for electricity, including the feedback on the economic viability of the new line. A whole range of different energy (e.g. nuclear and fracking policies) and environmental (e.g. carbon and fine-particulate policies, through regulation, emission fees or cap and trade) policies can be simulated more realistically, including their effects, by location.

Identify any products developed and any technology transfer activities

Website(s)	E4ST.com
Networks/collaborations	Hobbs @JHU, Schulze & Zimmerman @ Cornell, Shawhan @ RPI, and Tylavsky @ ASU
Technologies/Techniques	Analyticic models and numerical simulations.

Publications

1. Schuler, R.E., "Efficient Pricing and Capital Recovery for Infrastructure over Time Incentives and Applications for Electric Transmission Expansion", <u>Proceedings of the Hawaii International Conference on Systems Science 44</u>, Kauai, HI, Jan. 4-7, 2011.
2. Schuler, R.E., "Planning, Investment and Markets in the Electric Supply Industry", <u>Proceedings of the Hawaii International Conference on Systems Science 45</u>, Maui, Hawaii, Jan. 5, 2012.
3. Schuler, R.E., "Pricing the Use of Capital Intensive Infrastructure over Time and Efficient Capacity Expansion: Illustrations for Electric Transmission Expansion", <u>Journal of Regulatory Economics</u>, <u>41</u>,1, 30th Anniversary Edition, Feb. 2012, 80-99.

4. Taber, J., Shawhan, D., Zimmerman, R., Marquet, C., Zhang, M., Schuler, R., Schulze, W., and Whitley, S., "Mapping Energy Futures Using the SuperOPF Planning Tool: An Integrated Engineering, Economic and Environmental Model," Proceedings of the Hawaii International Conference on Systems Science 46, Maui, Hawaii, Jan. 8, 2013.
5. Shawhan, D., Taber, J., Shi, D., Zimmerman, R.,Yan, J., Marquet, C., Qi, Y., Mao, B., Schuler, R., Schulze', W., and Tylavsky, D., "Does a detailed model of the electricity grid matter? Estimating the impacts of the Regional Greenhouse Gas Initiative", Resource and Energy Economics, 36, 1, Jan. 2014, 191–207.
6. Hyman, L. & Schuler, R., "Electricity Restructuring, Consumer Prices and the Cost of Capital: Lessons for the Modeling of Future Policy," Proceedings of the Hawaii International Conference on Systems Science 47, Waikaloa, Hawaii, Jan. 6-9, 2014, (Awarded Best Paper in the Electricity, Markets and Policy Minitrack - - Electric Energy Systems Track).
7. Shawhan, D., Taber, J., Schuler, R., Schulze, W., Thomas, R., Tylavsky, D., Jewell, W., Mao, B., Yan, J., and Zimmerman, R., "A Detailed Power System Planning Model: Estimating the Long-Run Impact of Carbon-Reducing Policies", Proceedings of the Hawaii International Conference on Systems Science 48, Kauai, Hawaii, Jan. 5-8, 2015

PI (Lead)	Pravin Varaiya			Institution	University of California, Berkeley
Project Title	Renewable Integration through Risk-Limiting Dispatch				
Funding	FY	11	$	120,000	
	FY	12	$	125,000	
	FY	13	$	175,000	

Summary of project intent/scope

This project deals with enabling deep penetration of renewable generation. The principal difficulty with renewable generation is its variability. The current practice to balance this variability is through reserve (or back-up) generation. This approach is economically untenable and defeats emissions benefits of renewables. We have studied two distinct zero-emissions approaches to mitigating renewable variability: (a) *Risk-limiting dispatch* (RLD), which exploits improved forecast information in intermediate markets to economically gather balancing resources, and (b) *Coordination of Distributed Resources* (CDR), which exploits the flexibility in many end loads such as HVAC systems and Electric Vehicles to tailor demand to match intermittent supply.

Summary of project activities for the entire period of funding stated above

Project activities include:

(a) Education. We have supported 3 PhD Students, 5 post-docs, and 1 visiting student in the course of this project. All of them have gone on to assume positions in academia or industry (Toronto, University of Southern California, Cornell, etc).

(b) Lectures/Keynote addresses. We have given over 15 lectures at various conferences on the research results from this project. Notable among these is the Plenary lecture at the 2012 Conference on Decision and Control in Maui with over 1200 attendees.

(c) Comprehensive report of Risk-limiting Dispatch. We have completed a 138 pp draft report entitled "Extensions of Risk Limiting Dispatch." The report reflects contributions of Prof Ram Rajagopal and Junjie Qin of Stanford, Christoph Trabert of ETH, and Pravin Varaiya of Berkeley. Here is the abstract: For single- bus systems with one delivery period and multiple markets, Chapter 1 provides the optimal dispatch rule under stochastic prices and proves that the optimal cost is linear in the level of uncertainty. The sensitivity, termed price of uncertainty, is calculated explicitly. Chapter 2 extends RLD to a setting with storage operating over the delivery period for regulation. To understand the role of ramping constraints, Chapter 3 studies the simplest setting with ramping constraints without network constraints. Chapter 4 provides structural and computational results for two-bus network systems. Extending the intuitions in Chapter 4, Chapter 5 gives theoretical analysis for the problem of dispatch in a general congested network.

What was accomplished by this research? What were the contributions to the field?

We proposed risk-limiting dispatch (RLD) that optimizes the purchase of forward energy and reserve capacity in an arbitrary sequence of markets. The decision in each market depends on the information about net load (load - variable generation) available at the time. Algorithms are given to calculate RLD very efficiently. Examples show that RLD requires much lower levels of reserve than the current "decoupled" dispatch process in which a decision taken in one market (say 24-hr ahead) does not take into account the fact that future decisions can compensate for the "errors" made in current decisions. RLD is described in [15].

We developed a proposal to sell wind energy as a commodity with variable reliability. The wind power availability profile is divided into tranches of variable reliability. Higher reliability power fetches a larger price. The scheme requires no reserves to compensate for wind variability. The pricing scheme is optimal. The work is summarized in [1].

We have considered a collection of distributed resources such as residential HVAC system, Electric Vehicles, and Storage. Our first accomplishment is to model the aggregate flexibility offered by such a collection. We have shown that a collection of TCLs can be coordinated to offer regulation or other ancillary services. The aggregate flexibility offered can be compactly modeled as a stochastic battery. The capacities and charge rates of this battery can be forecasted in advance. Our stochastic battery model is exact when we have identical TCLs. For a diverse collection of TCLs, we show through simulations that the model is modestly conservative. We developed a run-time control strategy for CDR using two priority stacks. Simulation results suggest strongly that this strategy is extremely effective in following typical AGC commands from the SO. These results are summarized in [6].

We have developed a technique to quantify the flexibility of power consumption of HVAC systems in commercial buildings. Our tool for quantifying flexibility of loads is the virtual battery, which is a simple, succinct, and well-understood model. In this context, we have developed a method to identify virtual battery model parameters for these more complex flexible loads. The method extracts the parameters of the virtual battery model by stress-testing a detailed software model of the physical system. This work is summarized in [8].

Distributed resources can be coordinated with variable renewable generation via scheduling policies that greatly reduce net load variability and the need for reserve generation. Several scheduling algorithms were investigated. Simulation examples show dramatic reduction is possible. The details are provided in [18].

What are the current and/or future applications of this research?

We are confident that our research will eventually be productized. The power systems industry is very slow moving, and this may take several more years, and productizing research results requires a serious investment of time, money and effort. In particular, there are two components that we believe are ripe for translation to industrial practice: (a) our approach to modeling the aggregate flexibility of distributed resources as virtual batteries, and (b) priority stack control strategies that extract ancillary services from these resources based on these virtual battery models. We are actively exploring industrial collaborations (C3Energy, OhnConnect, Virtual Power Systems) as possible outlets for commercializing our research products.

Identify any products developed and any technology transfer activities

Networks/collaborations	SinBerBest, National Research Foundation, Singapore.

Inventions, Patent Application, licensing agreements, etc.	Provisional Patent Disclosure: *Token Based Scheduling for Energy Efficient Operation of Building HVAC systems*

Publications

1. Bitar, E.; Poolla, K.; P. Khargonekar; R. Rajagopal; P. Varaiya; F. Wu. *Selling Random Wind*. 45th Hawaii International Conference on System Science (HICSS), pgs. 1931-1937, Maui, Hawaii, January 2012.
2. Dominguez-Garcia, Alejandro D.; S. T. Cady, and C. N. Hadjicostis. *Decentralized Optimal Dispatch of Distributed Energy Resources*. IEEE Conference on Decision and Control, Maui, HI, December 2012.
3. Hao, He; Borhan M. Sanandaji, Kameshwar Poolla, Tyrone L. Vincent. *Potentials and Economics of Residential Thermal Loads Providing Regulation Reserve*. Energy Policy, 2015. In final revision.
4. Hao, He; Borhan M. Sanandaji, Kameshwar Poolla, Tyrone L. Vincent. *Frequency Regulation from Flexible Loads: Potential, Economics, and Implementation*. Proceedings of the American Conference on Decision and Control, Portland, OR, June 4-6, 2014.
5. Hao, H.; B. Sannadaji, K. Poolla, T. Vincent. *A Generalized Battery Model of a Collection of Thermostatically Controlled Loads for Providing Ancillary Service*. Allerton Conference, October 2013.
6. Hao, H.; B. Sannadaji, K. Poolla, T. Vincent. *Aggregate Flexibility of Thermostatically Controlled Loads*. IEEE Transactions on Power Systems, vol. 30, no. 1, pp:189-98, April 2014.
7. B. Sanandaji, H. Hao, and K. Poolla, *Fast Regulation Service Provision via Aggregation of Thermostatically Controlled Loads.* Hawaii International Conference on System Sciences, pp: 2388- 2397, Kona, January 2014.

8. Hughes, Justin T.; Alejandro D. Dominguez-Garcia, Kameshwar Poolla. *Virtual Battery Models for Load Flexibility from Commercial Buildings*. 48th Annual Hawaii International Conference on System Sciences, Kauai, Hawaii, January 5-8, 2015.
9. Maasoumy, Mehdi; Borhan M. Sanandaji, Alberto Sangiovanni-Vincentelli, and Kameshwar Poolla. *Model Predictive Control of Regulation Services from Commercial Buildings to the Smart Grid*. Proceedings of the American Control Conference, Portland, OR, June 4-6, 2014.
10. Mather, J.; E. Baeyens, K. Poolla, and P. Varaiya. *The Real Value of Load Flexibility - Congestion Free Dispatch*. American Control Conference, Chicago, Illinois, 2015.
11. Nayyar, A.; M. Negrete-Pincetic, K. Poolla, P. Varaiya. *Rate-constrained Energy Services: Allocation Policies and Market Decisions*. Submitted to IEEE Transactions on Automatic Control, October 2014.
12. Nayyar, A.; M. Negrete-Pincetic, K. Poolla, P. Varaiya. *Duration-differentiated Energy Services with a Continuum of Loads*. To be published, IEEE Transactions on Networked Systems, 2015.
13. Nayyar, A.; K. Poolla, and P. Varaiya. *A statistically robust payment sharing mechanism for an aggregate of renewable energy producers*. European Control Conference, pp: 3025- 3031, Zurich, July 2013.
14. Nayyar, A.; J. Taylor, A. Subramanian, K. Poolla, and P. Varaiya. *Aggregate Flexibility of a Collection of Loads*. Conference on Decision and Control, pp:5601-7, Florence, Italy, December 2013.
15. Rajagopal, R.; E. Bitar, P. Varaiya, F. Wu. *Risk-Limiting Dispatch for Integrating Renewable Power*. International Journal of Electrical Power & Energy Systems, vol. 44, issue 1, pp. 615-628, January 2013.
16. Sanandaji, Borhan; A. Tascikaraoglu, K. Poolla, P. Varaiya. *Low-dimensional Models in Spatio-Temporal Wind Speed Forecasting.* Proceedings of the American Control Conference}, Chicago, June 2015.
17. Sanandaji, Borhan M.; He Hao, Kameshwar Poolla, Tyrone L. Vincent. *Improved Battery Models of an Aggregation of Thermostatically Controlled Loads for Frequency Regulation*. Proceedings of the American Control Conference, Portland, OR, June 4-6, 2014.
18. Subramanian, A.; M. Garcia, D. Callaway, K. Poolla, and P. Varaiya. *Real-time Scheduling of Distributed Resources*. IEEE Transactions on Smart Grid, vol.4, no. 4, pp: 2122- 2130, 2013.
19. Subramanian, A.; J.A. Taylor, E. Bitar, D. Callaway, K. Poolla, P. Varaiya. *Optimal Power and Reserve Capacity Procurement Policies with Deferrable Loads*. Proceedings of the Conference on Decision and Control, pp. 450-456, Maui, Hawaii, December 2012.
20. Subramanian, A.; M. Garcia, A. Dominguez-Garcia, D. Callaway, K. Poolla, and P. Varaiya. *Real- time Scheduling of Deferrable Electric Loads*. Proceedings of the American Control Conference, pp. 3643-3650, Montreal, Canada, June 2012.

PI (Lead)	Lang Tong			Institution	Cornell
Project Title	Understanding Effects of Data Quality on Market Functions				
Funding	FY	11	$	95,000	
	FY	12	$	90,000	
	FY	13	$	90,000	

Summary of project intent/scope

This project focuses on data quality on the real-time market operations of a power system. In particular, the project addresses the following pertinent issues: (i) in the presence of bad data, to what degree that real-time locational marginal prices are affected? (ii) What are the worst scenarios of bad data that have the most significant impact on real-time prices of electricity? (iii) What are the effects of analog and digital forms of bad data? (iv) What are the potential risks on market operations from cyber data attacks?

Summary of project activities for the entire period of funding stated above

During the project period, our activities are focused on aspects of data qualities. First is on effects of bad data on power system state estimation. In particular, we investigate two different types of bad data: one corresponds to the type that are undetectable by any detection techniques, the other are those that can be detected with a level of probability of error. We investigated conditions under which bad data cannot be detected. We also investigated effects of topology data errors coupled with power measurement bad data on power system state estimation. Effects of nonlinearity in state estimation on bad data are also studied.

The second area of activities focused on characterizing effects of bad data on locational marginal prices. This included analyzing how state estimates perturbed by bad data affect real-time economic dispatch and the calculation of locational marginal prices. To this end, we studied the geometric characteristics of locational marginal prices, which allows us to characterize the type of bad data that can cause significant price fluctuations.

What was accomplished by this research? What were the contributions to the field?

This project has led to a number significant contributions:

- We obtained a precise characterization of and a method of computing the so called security index defined by the smallest number of bad data measurements that render the network unobservable.
- We developed new techniques to localize and identify bad data based on the generalized likelihood ratio test (GLRT) procedure and sparse recovery procedure based on convex relaxation techniques
- We obtained a geometric characterization of locational marginal prices from which effects of bad power and topology measurements are quantified.
- We demonstrated that nonlinear state estimation has mitigating effects on bad data.
- We obtained conditions under which topology changes may be masked by the presence of bad data. We developed an authentication mechanism that enhances network observability against topology attacks.
- We obtained results that demonstrate the possibility that data measurements may allow the construction of unobservable cyber-attacks on power system state estimates.
- We showed that standard bad data removal procedure can be misled to remove good data so that the network becomes unobservable.

What are the current and/or future applications of this research?

The results obtained in this project provide theoretical understanding and practical insights into the effects of bad data on power system and market operations. The techniques developed in this paper also have applications for enhancing cyber security of a power grid. In particular, the bad data detection and localization techniques can be applied to intrusion detection in cyber defense, and the authentication method against topology estimation error can be used for protecting against topology attacks

Publications

Journal Publications:

[1] Jinsub Kim, Lang Tong, and Robert J. Thomas "Subspace Methods for Data Attack on State Estimation: A Data Driven Approach," *IEEE Transactions on Signal Processing.* Vol. 63, no. 5, pp 1102-1114, May, 2015, DOI: 10.1109/TSP.2014.2385670

[2] Jinsub Kim, Lang Tong, and Robert J. Thomas, "Data Framing Attack on State Estimation," *IEEE Journal on Selected Areas in Communications,* vol. 32, no. 7, July 2014. DOI: 10.1109/JSAC.2014.2332032

[3] Liyan Jia, Jinsub Kim, Robert J. Thomas, and Lang Tong, "Impact of Data Quality on Real-Time Locational Marginal Price," *IEEE Transactions on Power Systems,* vol. 29, no. 2, March 2014 DOI: 10.1109/TPWRS.2013.2286992

[4] Jinsub Kim and Lang Tong, "On Topology Attack of a Smart Grid: Undetectable Attacks and Counter Measures," *IEEE Journal on Selected Areas in Communications,* vol. 31, no. 7, July 2013. DOI: 10.1109/JSAC.2013.130712

[5] Oliver Kosut, Liyan Jia, Robert J. Thomas, and Lang Tong, "Malicious Data Attacks on the Smart Grid" *IEEE Trans. Smart Grid Special Issue on Cyber, Physical, and System Security for Smart Grid,* vol. 2, no. 4, December, 2011. DOI: 10.1109/TSG.2011.2163807

Conference publications:

[1] Jinsub Kim, Lang Tong, and Robert J. Thomas, "Dynamic attacks on power systems economic dispatch," 2014 48th Asilomar Conference on Signals, Systems and Computers, Pages: 345 - 349, 2014. DOI: 10.1109/ACSSC.2014.7094460

[2] Jinsub Kim and Lang Tong,"On topology attack of a smart grid," 2013 IEEE PES Innovative Smart Grid Technologies (ISGT), Pages: 1 - 6, 2013. DOI: 10.1109/ISGT.2013.6497834

[3] Jinsub Kim and Lang Tong, "On phasor measurement unit placement against state and topology attacks," 2013 IEEE International Conference on Smart Grid Communications (SmartGridComm), Pages: 396 - 401, 2013. DOI: 10.1109/SmartGridComm.2013.6687990

[4] Liyan Jia, Robert J. Thomas, and Lang Tong, "Impacts of Malicious Data on Real-Time Price of Electricity Market Operations, 45th Hawaii International Conference on System Science (HICSS), Pages: 1907 - 1914, 2012. DOI: 10.1109/HICSS.2012.313

[5] Liyan Jia, Robert J. Thomas, and Lang Tong, "On the nonlinearity effects on malicious data attack on power system," 2012 IEEE Power and Energy Society General Meeting,

Pages: 1 - 8, DOI: 10.1109/PESGM.2012.6345685

[6] Liyan Jia, Robert J. Thomas, and Lang Tong, "Malicious data attack on real-time electricity market," 2011 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Pages: 5952 - 5955, 2011. DOI: 10.1109/ICASSP.2011.5947717

PI (Lead)	Tom Overbye			Institution	Univ. of Illinois at Urbana Champaign
Project Title	Development of Attribute Preserving Network Equivalents				
Funding	FY	12	$	75,000	
	FY	13	$	75,000	

Summary of project intent/scope

This goal of the project was to develop algorithms that can preserve attributes of the original power system in the reduced equivalent system. Among important attributes of the original system that becomes unavailable in the equivalent system, thermal line limits are the focus on this project. When an equivalent system is constructed, equivalent lines are created without any associated limit and it is common practice in the field that they have no limit, which is equates to infinite limits. Hence, the goal of the project is to assign a meaningful value for the limits of equivalent lines.

Summary of project activities for the entire period of funding stated above

The starting hypothesis for the project was that it would be always possible to find exact equivalent line limits. However, we soon realized that there are cases for which exact limit were not possible. Therefore we came up with a new algorithm, a Min/Max approach, which can calculate an upper limit and a lower limit for non-exact cases. The core idea of the algorithm and its application to a 4-bus case were introduced in the CERTS annual review in August 2012. Based on this initial work, the algorithm was applied to the IEEE 118-bus case and its result was presented in the PSERC IAB meeting in December 2012 and the full description of the algorithm was presented in the IEEE Power and Energy Conference at Illinois (PECI) in February 2013.

One problem with this Min/Max method was when bracketing the limits for the lines without an exact solution, the limits bounds could eventually become quite large. To overcome this drawback a Quadratic Program (QP) based algorithm was developed. The QP method is a continuous optimization problem that had the advantage that it could provide both upper and lower bounds along with a best estimate of equivalent line limits. Also, the sequential calculation based on single bus elimination was replaced by parallel calculation from sub-group elimination, which reduces the overall computational requirements. The QP method was tested with the IEEE 118-bus case. The algorithm was introduced in the PSERC IAB meeting in May 2013 and in the CERTS annual review in August 2013. Also, it was presented in the PSERC webinar in February 2014. We submitted a journal paper on this algorithm to the IEEE transaction on Power Systems in July 2013 and it was published in September 2014.

However, a key problem with the QP method was it was not fast enough for large systems as its computation increased exponentially with respect to the number of first neighbors of the sub-groups being eliminated. Therefore, we modified the QP algorithm so the new algorithm, a Top-down method was developed. The Top-down approach constructs an equivalent system from the system-level and proceeds downwards, while the previous algorithms started from the bus level and proceeded upwards. As it has much simpler problem formulation compared to the QP, its computation is linear with respect to the number of equivalent lines. This method was applied to the Eastern Interconnection case to preserve the structural integrity of the original system by retaining only one bus in each substation. The detailed procedure and simulation results were presented in the CERTS annual review in August 2014 and in the Hawaii International Conference on System Sciences in January 2015. We also worked with the Tylavsky group at the Arizona State University. We have assigned equivalent line limits in the reduced Eastern Interconnect (EI) case, which they have used in their power system planning package.

What was accomplished by this research? What were the contributions to the field?

We have developed three algorithms that calculate thermal limits of equivalent lines in the equivalent system: a Min/Max approach, a Quadratic Program approach, and a Top-down approach. All three algorithms utilize the same criteria for success. That is, the total transfer capability (TTC) of the equivalent system for different directions matches that of the original system.

The accomplishment by this research was that we could assign a meaningful limit to equivalent lines other than leaving the limit blank (the same as an infinite limit). Especially, we are able to assign equivalent line limits to a case with any size as the Top-down method has been developed. While the Min/Max approach and the QP method are bottom-up processes that start from the bus level and proceed upward, the Top-down method starts from the system level by aggregating adjacent buses and proceeds downwards. The problem formulation is simple and its computation is linear with respect to the number of equivalent lines. This allows the method to be used effectively on larger systems, such as the EI case.

However, the QP method has its own merit when the area to eliminate is small enough to apply it. For those case, the QP method can provide equivalent line limits with the least TTC mismatch among all three algorithms since the QP method normalizes the TTC mismatches and formulate an optimization problem whose objective is to minimize the sum of squares of all the mismatches. Most of the power system models are practically an equivalent case where only the area of interest is presented and the external area is approximated at boundary buses. Thus, the QP method can provide the most accurate line limits to those cases with a relatively small equivalenced area.

The research provided a better understanding of the issues associated with the creation of equivalent lines. We found that when buses are eliminated one by one sequentially, the results are dependent on the bus elimination order. To tackle this, we came up with the sub-group elimination in which contiguous buses, which are connected through lines, are grouped and eliminated together during the process. With this sub-group elimination method, which can be applied to both the Min/Max approach and the QP method, the dependency on bus elimination order was removed and parallel sub-group elimination made simulations more accurate and much faster. Another important observation was that negative reactance lines from already existing equivalent lines or the modelling of three-winding transformers have a bad impact on the accuracy of the algorithms. We could reduce their impact by wye-delta conversion of three winding transformers.

All three algorithms can be used as a complementary tool for any equivalent applications from the very first Ward equivalent to the latest backbone type equivalent. This is our key contribution since previously no equivalencing algorithms had this capability.

What are the current and/or future applications of this research?

The main application of this research is the development equivalent line limits for backbone type network equivalents for use in optimal power flow (OPF) and SuperOPF studies. The EI case with the equivalent line limits assigned with the Top-down method has been provided to the Tylavsky group for the power system planning tool being developed at Cornell. The development of any attribute preserving network equivalent is ultimately application dependent. However, any existing equivalencing algorithms may use the algorithms from this research to assign equivalent line limits in their reduced system regardless of their application since these algorithms just need the original case and the reduced case with equivalent lines as inputs.

Publications

W. Jang, S. Mohapatra and T. J. Overbye, “Towards a Transmission Line Limit Preserving Algorithm for Large-scale Power System Equivalents,” in *Proc. Hawaii International Conference on System Sciences (HICSS)*, Kauai, Hawaii, 5-8 Jan, 2015.

S. Mohapatra, W. Jang and T. J. Overbye, “Equivalent Line Limit Calculation for Power System Equivalent Networks,” *IEEE Trans. Power Systems*, Vol. 29, No. 5, pp. 2338-2346, Sep. 2014.

W. Jang, S. Mohapatra, T. J. Overbye and H. Zhu, “Line Limit Preserving Power System Equivalent,” in *Proc. 2013 IEEE Power and Energy Conference at Illinois (PECI)*, Champaign, IL, 22-23 Feb. 2013.

PI (Lead)	Max Zhang			Institution	Cornell
Project Title	Dynamic Energy and Environmental Dispatch of Power Systems				
Funding	FY	11	$	90,000	
	FY	12	$	90,000	
	FY	13	$	90,000	

Summary of project intent/scope

The scope of the project was to develop strategies to achieve the co-benefits of maintaining power systems reliability and protecting public health (from air pollution) during high electricity demand days (HEDDs). HEDDs are typically hot summer days when the demand for electricity is highest and the atmosphere is conductive to pollution formation such as ozone. Meeting high electricity demand during HEDDs requires dispatch of all generation resources, and demand response programs often lead to firing up of diesel backup generators. Those generation resources lead to high NOx emissions contributing to exceedingly high ozone pollution during HEDDs.

Summary of project activities for the entire period of funding stated above

First, we identified the research gaps in the nexus of power systems reliability, economics and air quality. Second, we investigated a number of strategies to address the gaps. The specific strategies include discharging plug-in electric cars to meet peak demand, dynamically managing thermal storage to meet peak demand and provide spinning reserves services. Third, we systematically analyzed the impacts of diesel backup generators participating in demand response programs on regional and local air quality.

What was accomplished by this research? What were the contributions to the field?

There are a number of accomplishments by this research. First, one of our papers on discharging plug-in electric cars to meet peak demand published on Journal of Power Sources has been cited over 95 times according to Google Scholar. In this paper, we argued for a program to enable plug-in electric vehicles to provide frequency regulation and peak load reduction services to achieve economic and societal benefits. The high citation numbers indicate that our research has resulted in significant impact in designing programs for plug-in electric vehicles, and widely read by researchers and policy makers.

Second, we discovered that building thermal energy storage systems can be easily managed to provide spinning reserve services, and that the economic return for building operators to provide spinning reserve services in the current markets is attractive. We have applied for a conditional patent for our finding.

Third, our paper on diesel backup generators participating in demand response programs has attracted media attention, and is featured on several media channels. Third, we showed the power system operation cost reduction in the range of 0.9–1.5% per every 10% thermal energy storage penetration level increase. Finally, we proposed a new concept called “Green DR”, i.e., defined as those that not only provide power systems reliability services, but also have verifiable environmental benefits or minimal negative environmental impacts. We argue that Green DR programs are key to solving the “peak” problem described in the Introduction, when almost all EGUs are dispatched to meet the demand, leaving little room for other strategies such as environmental dispatch. In essence, Green DR resources hold promise for ensuring resource adequacy and reducing emissions at the same time, thus achieving the cobenefits of power system reliability and protecting public health during periods with peak electricity demand.

What are the current and/or future applications of this research?

Moving forward, we recommend that Green DR resources should be differentiated from the polluting ones, and incentivized for their societal and economic benefits. Furthermore, the participation of low-emitting hydrocarbon-fueled generation in DR programs should not hinder the deployment of non-emitting generation that can reduce the electricity demand during the “peak” periods.

Identify any products developed and any technology transfer activities

Website(s)	http://energy.mae.cornell.edu

Networks/collaborations	New York Independent System Operator (NYISO), Consolidated Edison, Inc., New York Department of Environmental Conservation (NYSDES).

Technologies/Techniques	Model Predictive Control in Buildings with Convex Optimization

Inventions, Patent Application, licensing agreements, etc.	A novel building control method, Provisional patent application, 62/105,340

Publications

Palacio, S., Kircher, K. J., and Zhang, K. M. On the Feasibility of Providing Spinning Reserves from Thermal Storage. Accepted by *Energy and Buildings*

Kircher, K. J., and Zhang, K. M. (2015) Model Predictive Control of Thermal Storage for Demand Response, *Invited Paper, American Control Conference, Chicago, July 2015*

Zhang, X. and Zhang, K. M. (2015) Demand Response, Behind-the-Meter Generation and Air Quality, *Environmental Science & Technology, 49* (3): 1260–1267

Palacio, S., Valentine, K., Wong, M., and Zhang, K. M. (2014) Reducing Power System Cost with Thermal Energy Storage. *Applied Energy,* 129: 228-237

Valentine, Keenan F., William G. Temple, and Zhang, K.M. Electric vehicle charging and wind power integration: Coupled or decoupled electricity market resources? In IEEE *Power and Energy Society General Meeting, 2012,* pp. 1-7

White, C.D., and Zhang, K. M. (2011) Using Vehicle-to-Grid technology for frequency regulation and peak-load reduction in the New York Metropolitan Area. *Journal of Power Sources*, 196(6): 3972-3980

Valentine, K., Temple, W. and Zhang, K. M. (2011) Intelligent electric vehicle charging: Rethinking the valley fill. *Journal of Power Sources, 196 (24)*: *10717-10726*

Valentine, K., Foster, E.J., Acquaviva, J. and Zhang, K. M. (2011) Transmission Network- based Energy and Environmental Assessment of Plug-in Electric Hybrid Vehicles. *Journal of Power Sources*, 196(6): 3378-3386

PI (Lead)	Lindsay Anderson			Institution	Cornell
Project Title	Advanced Stochastic Unit Commitment Solution for Optimal Management of Uncertainty				
Funding	FY	13	$	75,000	

Summary of project intent/scope

The objective of this project is the development of a method for the day-ahead commitment of power generation assets under uncertain forecasts for wind and solar generation. The primary challenge of existing approaches to this problem has been the computational burden of solving for power networks of realistic size. A secondary, though critically important, problem has been the selection of the appropriate set of input scenarios to ensure that the solutions obtained are reliable, with minimal increase in computational burden. In this project, a new algorithm was developed to accelerate the problem solution, which performs well in simulations on existing test systems.

Summary of project activities for the entire period of funding stated above

During FY13, this project was initiated and two separate but synergistic activities were pursued; first, the development of a flexible and scalable formulation for unit commitment under uncertain forecasts of renewable generation, and second an effective process for identifying the most important scenarios to include in the optimization to ensure a secure and effective unit commitment and generation dispatch plan. The specific tasks completed were as follows:

1. Formulation and implementation of risk-limiting unit commitment models

During this quarter, robust stochastic models have been explored for power systems with thermoelectric power units, wind turbine generators, solar generators, and storage units. The uncertainty considered in these models comes from the power generated by the wind and solar sources. In particular, methods were explored to determine ways to handle the ambiguous nature of the uncertainty surrounding wind and solar power generation. In this aim the following models have been analyzed:

a) Formulation of a chance-constrained unit commitment model wherein the balance between generation and demand is satisfied with a prescribed (very high) probability level, This is a very robust model and results in reliable solutions that tend to avoid dispatching renewable resources due to their uncertainty.

b) An alternative method for enforcing reliable solutions is through minimizing "risk" of decisions, measured with the conditional value-at-risk metric. This approach requires the optimization to minimize both cost of providing electricity, and the risk of the solution. Since we have limited information about the probability distribution driving the uncertain wind power generation, the uncertainty of wind and solar power are represented with large sets of historical data relevant to the test system.

2. Development of improved methods for classifying scenarios

Toward the goal of developing improved methods for representing uncertainty in renewable generation, we have pursued clustering algorithms that can represent both spatial and temporal correlations between and within wind farm sites. The most promising approach is the use of hybrid statistical-heuristic methods that capture the shape of daily patterns and the correlations among sites.

What was accomplished by this research? What were the contributions to the field?

During the reporting period, we implemented a new algorithm for managing the uncertainty of the wind and solar resources through probabilistic constraints on the optimization problem. This approach has several advantages, with primary characteristics as follows:

1. The method allows adjustment of risk at each time period and node in the power network, providing flexibility for system operators to incorporate system-specific information, such as nodes which are less critical, and hours of the planning horizon which are less tightly constrained,
2. the specific formulation decomposes the stochastic (uncertain) part of the problem from the computationally intensive network optimization problem. This decomposition is essential in providing

scalability, because the computational expense of solving these two difficult problems together is prohibitive for larger networks, and

3. this approach is data-driven, in that no assumptions are required about the underlying distribution of the uncertainty in renewable generation. A very large number of samples (on the order of a million) can be used from the data to represent the possible scenarios. As a result, the solutions obtained are very reliable and perform well in out of sample testing.

In addition to algorithm development, the issue of scenario reduction was addressed directly from a statistical perspective. Specifically, initial work on scenario analysis included clustering historical data to identify representative scenarios for use in optimization models. The standard approach this has been unsupervised clustering, based on generation level, and has proven unsatisfactory due to the important spatial component of wind generation across the system. Therefore we are investigating an alternative method, based on band depth statistics. In initial tests, it is shown that this method is capable of capturing spatial components and inter-temporal patterns in the data and is under further development.

What are the current and/or future applications of this research?

Current applications of this work are limited to test systems with historical data inputs, in order to select the most effective formulation for future development. From the work performed in FY13, the preferred approach has been identified and is under development leading to future applications that include rapid and reliable solutions to the unit commitment problem under uncertainty for realistic-sized systems. Future versions will also integration with Matpower™ and/or the SuperOPF software to leverage AC solutions for the economic dispatch sub-problem.

Publications

Martínez, M. G., & Anderson C. L. (2015). A Risk-averse Optimization Model for Unit Commitment Problems, Presented at the System Sciences (HICSS), 2015 48th Hawaii International Conference on System Sciences (9 pages). *Submitted June 2014*

Martinez, G. & Anderson, L., "Toward a scalable chance-constrained formulation for unit commitment to manage high penetration of variable generation," Communication, Control, and Computing (Allerton), 2014 52nd Annual Allerton Conference on, pp.723,730, Sept. 30 2014-Oct. 3 2014 . doi: 10.1109/ALLERTON.2014.7028526

6.2. Advanced Applications Research and Development

Advanced Applications Research and Development (AARD) is a subgroup of activities in the Real Time Grid Reliability Management CERTS research area that works to develop advanced applications and tools to more effectively operate the electricity delivery system, by enabling advanced analysis, visualization, monitoring and alarming, and decision support capabilities for grid operators.

PI (Lead)	Mladen Kezunovic				Institution	Texas A&M
Project Title	Synchronized Sampling Uses for Real-Time Monitoring and Control					
Funding	FY	09	$	80,000		

Summary of project intent/scope

The scope of this project was to investigate the potential benefits of integrating information obtained by phasor measurement units (PMU) and other intelligent electronic devices (IED) into the control center real-time monitoring and control solution.

Summary of project activities for the entire period of funding stated above

The project focused on development of new software aimed at automated fault location and visualization. The phases below show the activities for the entire period:

- The first phase was software preparation, including Java project establishment and generic classes development. This lasted about 2 months;
- The second phase was the core part, which includes GUI programming, equipment modeling, 2-D and 3-D images creation. This lasted about 7 months;
- The final phase was software testing and on-site demonstration using field cases. This lasted about 1 month.

What was accomplished by this research? What were the contributions to the field?

The following is a summary of the progress achieved:

- The overall implementation flow chart of the software has been developed and explained;
- Both external and internal logic of the software represented in the implementation flow chart have been specified;
- The Object-oriented Programming (OOP) technique has been selected as the primary programming technique;
- The software programming flow chart has been defined and general programming sequence has been established;
- Two types of data interpreters have been explained; detailed inputs and outputs of the interpreters have been specified;
- The programming specification of all GUI modules within the graphical software has been outlined and block diagrams for each module has been specified;
- Options for receiving satellite images from commercial providers have been investigated;
- The hierarchical view, which is for normal state monitoring purpose, is set to be a combination of four other views: model, equipment, aerial and topological.
- Implementation plans for software maintenance and security considerations during development have been specified;
- A general schedule for developing the graphical software is established, which has specified three phases throughout the programming process.

What are the current and/or future applications of this research?

Since the specification and design work for the software has been completed, the future activity should focus now on the development of the control center visualization tools as the next step. Field installation and in-service demonstration of visualization tools should be carried out soon after the software is developed.

Publications

1. Kezunovic, Mladen; C. Zheng, and C. Pang. *Merging PMU, Operational, and Non-operational Data for Interpreting Alarms, Locating Faults and Preventing Cascade.* Hawaii International Conference on System Sciences (HICCS 43), Hawaii, January 2010.
2. Kezunovic, Mladen; C. Zheng, O. Gonen, and J. Ren. *Synchronized Sampling Uses for Real-Time Monitoring and Control/RTGRM.* Annual Report for Fiscal Year 2009 Project Work. January 15, 2010.
3. Zheng, C., and Mladen Kezunovic. *Synchronized Sampling Uses for Real-Time Monitoring and Control*. North American Power Symposium (NAPS), Starkville, Mississippi, October 2009.

PI (Lead)	**Jim McCalley**			**Institution**	**Iowa State University**
Project Title	**New Security Tools for Real-Time Operations**				
Funding	**FY**	09	**$**	120,000	
	FY	10	**$**	120,000	
	FY	11	**$**	120,000	
	FY	12	**$**	90,000	

Summary of project intent/scope

The objective of this work was to create new security assessment tools for real-time operations. Two areas of work were pursued including (1) risk-based security assessment; (2) high-speed extended term time domain simulation. The work resulted in new concepts for security assessment as well as developments which improve security-related computation.

Summary of project activities for the entire period of funding stated above

For each of the work areas specified above, there were four types of activities. These activities are summarized for each of these two work areas below.

Work area 1: Risk-based security assessment:

(a) Personnel supported: One Ph.D. student, Qin Wang, was supported from 2009, graduating in 2013. Dr. Wang is now working for the National Renewable Energy Laboratory (NREL) in their Transmission Grid Integration group. In addition, one post-doctoral researcher, Renchang Dai, was supported from 2009-2011. Dr. Dai is now a senior engineer for Alstom Grid.

(b) Publications: In this work area, there have been 6 journal publications (see "Publications" below).

(c) Industry interactions: We interacted closely with engineers at ISO New England. Ph.D. student Qin Wang spent two internships deploying risk-based security assessment on datasets characterizing their system.

(d) Presentations: Presentations were made each year at the annual NETL review meeting. Two other important presentations made were the following:

- J. McCalley, "New approaches to balancing security and economy: risk-based security-constrained economic dispatch (RB-SCED)," PSERC Webinar, January 21, 2014.
- J. McCalley, "Online Risk-based Security-Constrained Economic Dispatch and Market Operation," at the Federal Energy Regulatory Commission's technical conference, *Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software*, Washington DC, June 25, 2012.

Work area 2: High-speed extended term time-domain simulation:

(a) Personnel supported: One Ph.D. student, Chuan Fu, was supported from 2009-2011. Dr. Fu is now employed as a Sr. Transmission Engineer at Dynegy. A second Ph.D. student was supported from 2010-2014 and is now a transmission business analyst with NextEra Energy Resources. A post-doctoral researcher, Siddhartha Khaitan, was supported from 2009-2013; Dr. Khaitan is now a research faculty at Iowa State University.

(b) Publications: In this work area, there have been 3 journal publications, 5 book chapters, and 7 conference papers (see "Publications" below).

(c) Industry interactions: We interacted with engineers at PJM in this work area, deploying various algorithms on datasets characterizing their system.

(d) Presentations: Presentations were made each year at the annual NETL review meeting. Three other important presentations made were the following:

   a. S. Khaitan, "Outlook for Parallel Computing in the Electric Power Industry," PSERC Webinar, March 19, 2013.

b. S. Khaitan, "An Efficient Load Balancing Approach For Massive Dynamic Contingency Analysis in Power Systems," 2nd High Performance Computing, Networking and Analytics for the Power Grid Workshop, Salt Lake City, SC12, November 11, 2012.

c. Khaitan, S. "TDPSS: A Scalable Time Domain Power System Simulator For Dynamic Security Assessment," 2nd High Performance Computing, Networking and Analytics for the Power Grid Workshop, Salt Lake City, SC12, November 11, 2012.

What was accomplished by this research? What were the contributions to the field?

There were two main accomplishments of this research:

1. Risk-based security assessment: We formulated the risk-based security-constrained economic dispatch (RB-SCED) and illustrated its value relative to the existing security-constrained economic dispatch (SCED) underpinning today's real-time electricity markets. Its value is that it provides more secure operating conditions at lower cost. Contributions to the field resulting from this work include:
    a. Conceptual: We provided a conceptually new conceptualization of transmission system security. For many decades, redispatch control is exerted for post-contingency loadings that exceed a designated post-contingency flow limit; the re-dispatch must be enough to satisfy all post-contingency flow limits. This is the standard approach within the industry today, and it is embedded in the SCED. In contrast, the RB-SCED exerts redispatch control for all post-contingency loadings in proportion to the level of post-contingency flow and the probability of the contingency which caused it. Thus, a given operating condition is modified by a re-dispatch effort which more heavily weights higher and more likely post-contingency flows.
    b. Practical: We used a number of test systems to compare operating conditions obtained by RB-SCED with operating conditions obtained by SCED, showing that the former were both more economic (due to relief of constraints imposed by unlikely contingencies) and more secure (due to reduction of all "heavy" post-contingency flows and not just those which exceed their long-term emergency ratings), and we provided independent tests to illustrate improvements in terms of cascading, voltage stability, and angular stability. We also showed that RB-SCED produces locational marginal prices that are more uniform through space and less volatile through time.
    c. Computational: A new algorithm was developed to solve the computationally intense RB-SCED in which a nested two-stage Benders decomposition was employed.
2. High-speed extended-term time-domain simulation (HSET-TDS): We developed design principles for numerical solvers of differential algebraic systems (DAE) associated with power system time-domain simulation, focusing on DAE construction strategies, integration methods, nonlinear solvers, and linear solvers. We applied three ways of enhancing computational speed associated with time-domain simulation for power system electromechanical stability assessment; each is a contribution to the field:
    a. Multifrontal linear solvers: We applied unsymmetric multifrontal methods for the linear solve step in integrating the differential algebraic equations encountered in power system dynamic simulation. The method achieves computational efficiency as compared to conventional linear sparse solvers due to the inherent parallel hierarchy present in multifrontal methods.
    b. HH4 Integration: We identified an integration method called Hammer-Hollingsworth 4 (HH4) that can accelerate time domain simulation especially for extended-term, because it enlarges the integration step while still maintaining numerical precision. We assessed the HH4 algorithm in terms of computational efficiency and accuracy, using the New England 39 buses system, an expanded 8775 buses system, and a PJM 13029 bus system.
    c. Parallelized contingency analysis: We developed a "work-stealing" scheduling algorithm to perform real time parallelized dynamic contingency analysis. Simulations of thousands of contingencies on a large system were conducted; computational savings and scalability results were attractive.

What are the current and/or future applications of this research?

There are three current applications of this research:

1. Risk-based constraint relaxation: We are currently completing the end of a two-year PSERC-funded project to develop risk-based constraint relaxation. This need is driven by the fact that the conventional SCED often results in an infeasible solution, and to obtain feasibility, certain constraints are relaxed. However, today, such constraint relaxation is performed on an ad-hoc basis, and so we are applying risk-based security assessment to provide feasibility while maintaining security and reducing spikes in LMPs.
2. Enhancements to high-speed extended-term time domain simulation (HSET-TDS): We have partnered with Lawrence Livermore National Laboratories (LLNL) to enhance HSET-TDS by employing both shared and distributed memory parallelism by interfacing LLNL integration packages with our time-domain simulators. Findings to-date indicate that parallelization over contingencies with MPI gives the best use of a high performance machine.
3. Dynamic security assessment processing system (DSAPS): We have designed a DSAPS which is built around the high-speed extended-term time domain simulator (HSET). We are further developing DSAPS under a two-year project funded by the Southern California Edison company. The DSAPS automates the design of remedial action schemes and enables real-time support for operator action during extreme events.

Identify any products developed and any technology transfer activities

Networks/collaborations	We have developed the following collaborations as a result of this funding: • Arizona State University in our work on risk-based constraint relaxation; • Lawrence Livermore National Laboratory in our work on high-speed extended-term time domain simulation (HSET-TDS); • Southern California Edison company in our work on deploying HSET-TDS.

Publications

Work Area (1) Risk-Based Security Assessment:

JOURNAL PAPERS:

1. Q. Wang, J. McCalley, T. Zheng, and E. Litvinov, "Solving Corrective Risk-based Security-Constrained OPF with Lagrangian Relaxation and Benders Decomposition," to appear in International Journal of Electrical Power and Energy Systems.
2. *Q. Wang, *G. Zhang, J. McCalley, T. Zheng, and E. Litvinov, "Risk-based locational marginal pricing and congestion management," *IEEE Transactions on Power Systems*, Vol. 29, Is 5, 2014, pp. 2518-2528.
3. *Q. Wang and J. McCalley, "Risk and 'N-1' Criteria Coordination for Real-time Operations," *IEEE Transactions on Power Systems*, Vol. 28, No. 3, August 2013, pp. 3505-3506.
4. *Q. Wang, J. McCalley, T. Zheng, and E. Litvinov, "A Computational Strategy to Solve Preventive Risk-based Security-Constrained Optimal Power Flow," Digital Object Identifier: 10.1109/TPWRS.2012.2219080, *IEEE Transactions on Power Systems*, Vol. 28, I. 2, 2013, pp. 1666-1675..
5. *R. Dai, *H. Pham, *Y. Wang, and J. McCalley, "Long term benefits of online risk-based optimal power flow," *Journal of Risk and Reliability* (Part O of the Proceedings of the Institution of Mechanical Engineers): Special Issue on "Risk and reliability modeling of energy systems," Vol. 226, Issue 1, Feb, 2012.
6. *F. Xiao and J. McCalley, "Power System Risk Assessment and Control in a Multi-objective Framework," *IEEE Transactions on Power Systems*, Vol. 24, No. 1, Feb. 2009, pp 78-87.

Work Area (2) High-Speed Extended Term Time-Domain Simulation:

JOURNAL PAPERS:

1. *L. Tang and J. McCalley, "Quantitative Transient Voltage Dip Assessment of Contingencies using Trajectory

Sensitivities International Journal of Electrical Power and Energy Systems," *International Journal of Electrical Power and Energy Systems*," DOI: 10.1016/j.ijepes.2014.03.063, Vol. 61, 2014, pp. 298-304.

2. *C. Fu, J. McCalley, and J. Tong, "A Numerical Solver Design for Extended-Term Time-Domain Simulation," Digital Object Identifier: 10.1109/TPWRS.2011.2177674, Vol. 28, Issue 4, *IEEE Transactions on Power Systems*, 2013, pp. 4926-4935.
3. *S. Khaitan, J. McCalley, and A. Somani, "Proactive Task Scheduling and Stealing in Master-Slave Based Load Balancing for Parallel Contingency Analysis", *Electric Power Systems Research*, Vol. 103, October 2013, pp. 9-15.

BOOK CHAPTERS:

1. S. Khaitan and J. McCalley, "PARAGON: An Approach for Parallelization of Power System Contingency Analysis Using Go Programming Language," *International Transactions on Electrical Energy Systems*, DOI: 10.1002/etep.1999, 2014.S. Khaitan and J. McCalley, "Cyber Physical Systems: A Review", Book chapter in *Encyclopedia of Business Analytics and Optimization (EBAO),* IGI Global 2013.
2. S. Khaitan and J. McCalley, "MASTER: A JAVA Based Multithreaded Work-Stealing Technique for Parallel Contingency Analysis in Power Systems", Book chapter in *High Performance Computing, Grids and Clouds*, Published by IOS Press, 2013.
3. S. Khaitan and J. McCalley, "Dynamic Load Balancing and Scheduling for Parallel Power System Dynamic Contingency Analysis" Book chapter in *High Performance Computing in Power and Energy Systems*, Springer-Verlag Inc., 2012.
4. S. Khaitan and J. McCalley, "High Performance Computing for Power System Dynamic Simulation" Book chapter in *High Performance Computing in Power and Energy Systems*, Springer-Verlag Inc., 2012.
5. *S. Khaitan and J. McCalley, "A Class of New Preconditioners for Linear Solvers used in Power System Time domain Simulation," *IEEE Trans on Power Systems*, Vol. 25 , I. 4, 2010, pp. 1835-1844.

CONFERENCE PAPERS:

1. *S. Khaitan, J. McCalley, and *C. Fu, "Fast Parallelized Algorithms for On-Line Extended-Term Dynamic Cascading Analysis," Proc. of the Power Systems Conference & Exhibition, Seattle, March 15-18, 2009, pp.1-7.
2. *L. Tang and J. McCalley, "Transient Stability Constrained Optimal Power Flow for Cascading Outages," Proc. of the IEEE PES General Meeting, July 2014.
3. S. Khaitan and J. McCalley, "Parallelizing power system contingency analysis using D programming language," DOI: 10.1109/PESMG.2013.6672115, *Proc. of the 2013 IEEE Power and Energy Society General Meeting*, 2013.
4. *L. Tang and J. McCalley, "Trajectory Sensitivities: applications in power systems and estimation accuracy refinement," in 2013 IEEE PES General Meeting, Vancouver, BC, Canada, 2013, pp. 1-5.
5. *S. Khaitan and J. McCalley, "TDPSS: A Scalable Time Domain Power System Simulator For Dynamic Security Assessment" *2nd International Workshop on High Performance Computing, Networking and Analytics for the Power Grid*, SC12, Salt Lake City, UT, USA, November 11, 2012.
6. *S. Khaitan and J. McCalley, "EmPower: An Efficient Load Balancing Approach For Massive Dynamic Contingency Analysis in Power Systems" *2nd International Workshop on High Performance Computing, Networking and Analytics for the Power Grid*, SC12, Salt Lake City, UT, USA, November 11, 2012 .
7. *L. Tang and J. McCalley, "An efficient transient stability constrained optimal power flow using trajectory sensitivity," Proc. of the North American Power Symposium, pp. 1-6, 2012.

PI (Lead)	**Vijay Vittal**			**Institution**	**Arizona State University**
Project Title	**Adaptive Islanding Demonstration in the Western Electricity Coordinating Council**				
Funding	**FY**	09	**$**	125,000	
	FY	10	**$**	165,000	
	FY	11	**$**	165,000	

Summary of project intent/scope

This project developed an integrated algorithm to identify a cutset for a large power system for the application of a slow coherency based controlled islanding scheme. Controlled islanding is employed as a corrective measure of last resort to prevent cascading outages caused by large disturbances. The large scale power system is represented as a graph and a simplification algorithm is used to reduce the complexity of the system. Generators belonging to the same slowly coherent group are collapsed into a dummy node, and a graph partition library is used to split the graph into a given number of parts. Some extra islands formed by the partition library are merged into their adjacent large islands and the original cutset of the actual power system is recovered from the highly simplified graph. A software package was developed to test the efficiency of the algorithm, and dynamic simulations were run on the WECC system to verify the effectiveness of the cutset obtained. To test the islanding performance, four extreme contingencies under two different operating conditions of the WECC system are tested using time domain simulations. Time domain simulation results for the four contingencies with controlled islanding and uncontrolled islanding are shown, and the dynamic performance in each case is analyzed. Further analyses are conducted to examine the amount of load shed in each case, and a discussion of the cutset sensitivity and time sensitivity of islanding are provided.

Summary of project activities for the entire period of funding stated above

Cascading outages have resulted in significant disruptions to power systems all over the world. Controlled islanding can provide a corrective measure of last resort to alleviate the impact of large disturbances. This project provides detailed demonstrations of using slow coherency based controlled islanding to prevent cascading outages in bulk power systems. Improvements and extensions over existing slow coherency theory are developed. In the extended theory, the number of slow modes does not have to be equal to the number of groups, and the weight of each slow mode is considered. A tightness index is introduced to exclude boundary or loosely coherent machines from identification. The impact of the initial conditions on slow coherency determination is also discussed.

In addition, an integrated algorithm is developed to identify cutsets for large scale power systems for the application of slow coherency based controlled islanding schemes. The large scale power system is represented as a graph and a simplification algorithm is used to reduce the complexity of the system. Generators belonging to the same slowly coherent group are collapsed into a dummy node, and a graph partition library is used to split the graph into a given number of parts. Some extra islands formed by the partition library are merged into their adjacent large islands and the original cutset of the actual power system is recovered from the highly simplified graph. A software package was developed based on the algorithm, and dynamic simulations were run on the Western Electricity Coordinating Council (WECC) system to verify the effectiveness of the cutsets obtained.

Finally, to test the islanding performance, four extreme contingencies under two different operating conditions of the WECC system are tested using the time domain simulations. The cutsets used in the controlled islanding cases are obtained from the software package developed using the graph partition library. The time domain simulation results for the four contingencies with controlled islanding and uncontrolled islanding are shown, and the dynamic performance in each case is analyzed. Further analyses are conducted to examine the amount of load shed in each case, and a discussion of the cutset sensitivity and time sensitivity of islanding are provided. Finally, a discussion of practical implementation issues and conclusions are provided.

What was accomplished by this research? What were the contributions to the field?

The contributions of this project include three major aspects: 1) extension and improvement of slow coherency theory and application in power systems; 2) introduction of an integrated cutset determination algorithm for large scale power systems, and development of a software package for controlled islanding; 3) simulation of comprehensive time domain dynamic analyses to verify the effectiveness of controlled islanding strategies. Details of the three aspects will be described as follows.

1) Contributions on slow coherency theory:
   - 1.1) Extended the slow coherency theory. In the extended slow coherency theory, the number of slow modes does not have to be equal to the number of groups, and the weight of each slow mode is considered in grouping determination.
   - 1.2) Introduced the boundary relaxation method in slow coherency identification. After excluding boundary machines or loosely coherent machines from slow coherency identification, more stable grouping results could be obtained.
   - 1.3) Analyzed the impact of the initial conditions, or contingency location and duration, on slow coherency identification. It has been shown in the dissertation that the determination of slow coherency grouping results in realistic application of power systems will be influenced by the initial conditions.
2) Contribution on the cutset identification algorithm:
   - 2.1) An integrated cutset determination algorithm is introduced, and a suite of software packages based on the algorithm is developed to determine cutsets for specified contingencies under different operating conditions. The software packages are computationally efficient for large power systems. Except for the graphical user interface, three major libraries are developed for the slow coherency based cutset determination software package.
   - 2.2) A power system library is developed to handle power flow data and dynamic data, including the reading of power flow data in IEEE format and PSSE v30 format, reading dynamic data in PSLF format, reading and writing power flow data and dynamic data in a self-defined binary format, forming the admittance matrix and Jacobian matrix, solving power flow by Newton-Raphson method and fast decoupled (PQ decoupled) method, checking mismatches of buses, equivalencing of generators and loads, reducing the system to a network with only generators and forming the system matrix of the reduced network, forming the graph representation of a power system, analyzing the load shedding and generation tripping results in each island from TSAT output messages.
   - 2.3) A graph library is developed to analyze the system structure, including removing unnecessary nodes and branches in the graph, checking the status of the graph, breadth first search of the whole graph, building a minimal spanning tree and collapsing the tree into a dummy node, partitioning the graph into certain number of isolated parts, merging small isolated partitions to their adjacent large partitions, recording all the performance in graph simplification, tree collapse, merging, etc., and recovering the original graph with the recovery records.
   - 2.4) A sparse matrix library is developed to perform power engineering related computations, including adding two matrices, multiplying a matrix with a vector, transposing a matrix, permuting a matrix, balancing a matrix, Gaussian elimination, LU factorization, solving linear equations, minimum degree ordering, tri-diagonal reduction, QR decomposition with Householder transformation, eigenvalue computation of a tri-diagonal matrix with Givens rotation, eigenvector calculation using power iteration, saving a matrix in Matlab binary format (.mat file) and some other input and output interfaces.
3) Contributions on verification of controlled islanding by dynamic simulations:
   - 3.1) Comprehensive dynamic simulations are conducted to verify the effectiveness of those

cutsets obtained from the slow coherency based cutset determination software package.

3.2) Controlled islanding is verified to be plausible in preventing the WECC system from losing stability after severe disturbances, such as COI TLO/SDLO and P15 TLO/SDLO. Moreover, controlled islanding can be used to prevent severe voltage swings and minimize generation tripping and load shedding after severe disturbances.

3.3) The impact of the disturbance is analyzed in a new way that the total electrical power increase is employed as a parameter to estimate the rate of average frequency declines caused by the disturbance. The estimation will be accurate even when the system is not in steady state before the disturbance. The rate of frequency decline can be used to estimate the load shedding amount caused by a disturbance.

Cutset sensitivity and time sensitivity of controlled islanding is discussed for the first time. It has been shown that a practical cutset which generally has a high R value will be insensitive to the changing of a few non-contingency lines in the cutset.

What are the current and/or future applications of this research?

The developed approach has been demonstrated on four different cases of the WECC systems and shown to work effectively. Several utilities around the world are exploring controlled islanding as a corrective measure. The WECC does have an existing islanding scheme but have not used the scheme recently.

Identify any products developed and any technology transfer activities

Networks/collaborations	The demonstration was done in collaboration with PG&E and the Western Electricity Coordination Council.
Other products	An integrated tool to develop the islands has been written using sparse matrix technology. The tool can accept both PSS/E and PSLF format data as input.

Publications

Xu, G., V. Vittal, "Slow Coherency based Cutset Determination Algorithm for Large Power Systems," *IEEE Transactions on Power Systems*, Vol. 25, No. 2, pp. 877-884, May 2010.

Xu, G., V. Vittal, A. Meklin, J.E. Thalman, "Controlled Islanding Demonstrations on the WECC System," *IEEE Transactions on Power Systems*, Vol. 26, No. 1, pp. 334-343, February 2011.

PI (Lead)	Anjan Bose			Institution	Washington State University
Project Title	Real-Time Wide-Area Control				
Funding	FY	09	$	25,000	

Summary of project intent/scope

Work with industry leaders to frame potential demonstrations of emerging real-time control concepts on bulk power systems. These concepts would then be presented to stakeholders for potential funding in FY10 and beyond.

Summary of project activities for the entire period of funding stated above

All the different types of real time applications were examined to determine their communication needs. Then different scenarios were developed using different numbers of these applications for each area of the grid. Hierarchical needs between Balancing Areas and Reliability Areas were taken into account. The aggregated communication needs were translated into communication hardware and software specifications at the substations and between substations.

What was accomplished by this research? What were the contributions to the field?

Many discussions were held with power companies (e.g. Bonneville Power Administration, Southern Services, etc.) to establish the communication needs of fast wide-area protection and controls.

What are the current and/or future applications of this research?

The applications are numerous as it has opened applications in whole classes of problems like wide-area protection, wide-area controls, and other PMU applications like linear state estimation.

Identify any products developed and any technology transfer activities

Networks/collaborations	Many new international collaborations.

Publications

Bose, A. “Smart Transmission Grid Applications and Their Supporting Infrastructure,” Invited Paper, IEEE Transaction on Smart Grid, vol. 1, No. 1, June 2010.

Bakken, D.E, Hauser C.H, Bose. A, Whitehead, D.E. and Zweigle, G.C, “Smart Generation and Transmission with Coherent, Real-Time Data,” Proceedings of the IEEE, vol. 99, No. 6, pp. 928-951, June 2011.

Kansal, P and Bose, A, “Bandwidth and Latency Requirements for Smart Transmission Grid Applications,” IEEE Transaction on Smart Grid, vol. 3, No. 3, pp.1344-52, 2012.

PI (Lead)	Peter Sauer			Institution	Univ. of Illinois at Urbana-Champaign
Project Title	Automatic Reliability Reports Research and Implementation, and Transmission Adequacy Performance Metrics				
Funding	FY	10	$	75,000	
	FY	11	$	165,000	
	FY	12	$	86,000	
	FY	13	$	60,000	

Summary of project intent/scope

Investigate mechanisms and associated metrics to quantify grid reliability performance. The emphasis is on using the proper measurement data to evaluate performance. Define the needs and requirements for reports on grid adequacy during all of the system states (Normal, Alert, emergency, and restorative) plus pre-contingency and post-contingency.

The work focuses on the use of PMU data for model-less performance metrics. Performance is evaluated based on distance from boundaries identified through consideration of thermal, voltage, and stability limits. These three limits are key components of the traditional St. Clair curves.

Summary of project activities for the entire period of funding stated above

Since the project focused the use of PMU data to quantify grid reliability, an initial effort looked at sources of PMU data error and potential improvements to provide reliable and clean data. We worked with PNNL (using SitAAR – Situational Awareness and Alerting Report) to identify the types of errors in typical data obtained from the American Transmission Company. The results of that work were reported in references [1] and [6].

Also since the project focused on the use of PMU data, we initiated an effort to build a low-cost PMU for distribution systems. This was valuable for developing an understanding of the issues associated with time stamping with GPS signals, and in filtering of measured data. The results of that work were reported in references [7] and [12].

The primary effort of the project was aimed at determining the metrics to assess grid reliability in the various operational states. The effort worked on three phenomena of interest – thermal constraints, voltage constraints, and stability constraints. This work involved the computation of Thevenin equivalents on each end of monitored transmission lines to observe the total angle across the system for each transmission line. The concept of two Thevenin equivalents came from a practical application of several papers involving the long-time established St. Clair curves to quantify acceptable line loadings. The results of this effort were reported in references [2], [5], and [8].

A major focus of the entire project effort was on the utilization of data rather than a mathematical model for quantifying grid reliability. This began with an extensive investigation into the use of real-time sensitivities from real-time data. The results of this work were reported in references [a], [3], [4], [9], [10], [11], and [13].

The project plan was to evaluate our grid performance metrics using actual MISO PMU data and corresponding EMS planning models for comparisons. Field tests have not been possible due to a lack of actual data and associated model from the MISO.

What was accomplished by this research? What were the contributions to the field?

This research proposed several fundamental concepts for quantifying operational reliability of the electric grid using PMU data as the primary input to the metrics of interest. The first concept had to do with the quality of the PMU data which involved both the measurement technology and the communication network from the PMU to the point of use. Techniques to clean poor data were considered and are still be examined for possible options to results in useful information.

Another concept included the conjecture of 90 degrees across at least one line in a network at the point of maximum system loadability. This concept emerged after numerous simulations and generalization of the St. Clair curve ideas to include a network of lines, generators, and loads. This concept has the potential to provide useful information from PMU data which can provide the real-time situational conditions which would produce the metric which quantifies the closeness to this 90 degree system limit. The Thevenin equivalents needed for this work were not traditional simple voltage sources behind impedance. They were equivalents which reflected the three-terminal characteristic of a transmission line with shunt capacitance. These equivalents include current-dependent voltage sources in addition to the normal voltage source behind impedance.

Perhaps the most promising concept that was produced by this research was the creation of real-time sensitivities that can be used to evaluate operational reliability and help design new algorithms for real-time control. The primary value of this is that the measurements are real-time and therefore include the impact of topology changes and are not subject to errors from model inaccuracies. As such, this improves situational awareness and gives a mechanism to provide improved control systems and to identify model errors. This concept has been extended to include Line Outage Distribution Factors (LODFs) and Line Angle Outage Factors (LOAFs) in addition to standard generation shift distribution factors. Current work is using this to compute system loss sensitivities, and economic sensitivities.

This work also found techniques to provide PMU applications when not every bus is equipped with a PMU. The so-called "sparse" representation exploits the fact that some buses are more important than others when it comes to sensitivity analysis. This is related to the concept of electrical distance and how that can impact sensitivities.

What are the current and/or future applications of this research?

There is still a need to field validate the concepts that have been developed. We hope to eventually obtain consistent data and model cases from the MISO to complete these field tests to validate the results of the research on a real system. We will continue to consider other options for validating the results, such as utilizing local system data and model cases or more realistic simulations.

Identify any products developed and any technology transfer activities

Website(s)	Some reports and documents are on the CERTS and UIUC web sites.
Networks/collaborations	Collaboration with PNNL, ATC, and MISO is continuing.
Technologies/Techniques	Data-based analysis seems to be a promising technology.
Other products	Software and concepts are fully documented in the publications provided.

Publications

1. K. E. Reinhard, "On Data Quality and Availability Modeling of Power Grid Phasor Measurements", Proceedings, 2012 North American Power Symposium, University of Illinois at Urbana-Champaign, Urbana, IL, pp. 1-5, September 9-11, 2012.
2. Karl E. Reinhard, Peter W. Sauer, and Alejandro D. Dominguez-Garcia, "On Computing Power System Steady-State Stability Using Synchrophasor Data", Proceedings, 46th Hawaiian International Conference on System Science (HICSS), pp. 2312-2318, January 7-10, 2013, Maui, Hawaii.
3. Y. C. Chen, A. D. Dominguez-Garcia and P. W. Sauer, "Online Computation of Power System Linear Sensitivity Distribution Factors", Proceedings, 2013 IREP Symposium – Bulk Power System Dynamics and Control – IX Optimization, Security and Control of the Emerging Power Grid, Crete, Greece, August 25-30, 2013.

4. Y. C. Chen, A. Domínguez-García, and P. W. Sauer. "*Online Estimation of Power System Distribution Factors—A Sparse Representation Approach"*. Proceedings, 2013 North American Power Symposium, Kansas State University, Manhattan, Kansas, pp. 1-5, September 22-24, 2013, .
5. J. Zhang, A. D. Dominquez-Garcia, P. W. Sauer, "Online Transmission Line Loadability Assessment Using Synchrophasor Measurements", Proceedings, 2013 North American Power Symposium, Kansas State University, Manhattan, Kansas, pp. 1-5, September 22-24, 2013.
6. K. Kirihara, K. E. Reinhard, A. K. Yoon, and P. W. Sauer, "Investigating Synchrophasor Data Quality Issues", Proceedings, Power Engineering Conference Illinois, University of Illinois at Urbana-Champaign, Champaign, IL, February 28 – March 1, 2014.
7. B. Pinte, M. Quinlan, A. Yoon, K. E. Reinhard, and P. W. Sauer, "A One-phase, Distribution-Level Phasor Measurement Unit for Post-Event Analysis", Proceedings, Power Engineering Conference Illinois, University of Illinois at Urbana-Champaign, Champaign, IL, February 28-March 1, 2014.
8. P. W. Sauer and A. Dominguez-Garcia, "Data Driven Dynamic Security Assessment", Proceedings, 2014 IEEE/PES General Meeting, Washington, DC, July 27-31, 2014.
9. Y. C. Chen, A. Domínguez-García, and P. W. Sauer. "*Measurement-Based Estimation of Linear Sensitivity Distribution Factors and Applications"*. IEEE Transactions on Power Systems, Vol. 29, No. 3, pp. 1372-1382, May 2014.
10. Y. C. Chen, A. Domínguez-García, and P. W. Sauer. "*Generalized Injection Shift Factors and Application to Estimation of Power Flow Transients",* Proceedings of the North American Power Symposium (NAPS), Pullman, Washington, September 7-9, 2014.
11. Y. C. Chen, A. D. Dominguez-Garcia, and P. W. Sauer, "A Sparse Representation Approach to Online Estimation of Power System Distribution Factors", IEEE Transactions on Power Systems, vol. PP, Issue 99, pp. 1-12, October 2014.
12. K. Kirihara, K. E. Reinhard, Y. Liu, and P. W. Sauer, "Synchrophasor visualizer." Proc. Power and Energy Conference at Illinois (PECI), pp. 1-4, February, 2015.
13. Y. C. Chen, J. Wang, A. D. Dominguez-Garcia, and P. W. Sauer, "Measurement-Based Estimation of the Power Flow Jacobian Matrix", Submitted to the IEEE Transactions on Smart Grid.