Final Report to the National Energy Technology Laboratory on FY14- FY15 Cooperative Research with the Consortium for Electric Reliability Technology Solutions

Power Systems Engineering Research Center
Empowering Minds to Engineer
the Future Electric Energy System

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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.

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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 over 30 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.

Phase I of the PSERC's research collaboration with CERTS was administered through a cooperative agreement, DE-FC26-09NT43321, between the National Energy Technology Laboratory and Arizona State University, PSERC's lead university and spanned the period from FY 2009 to FY 2013.

This report describes the research performed under the Phase II cooperative agreement, DE-OE0000670 that provided funding from FY 2014 through FY 2015 and included a no-cost extension through September 2017.

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.

Phase I of OE's funding for PSERC, under cooperative agreement DE-FC26-09NT43321, started in fiscal year (FY) 2009 and ended in FY2013. It 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 for OE, conducted through CERTS, from September 2015 through September 2017 utilizing FY 2014 to FY 2015 funding under cooperative agreement DE-OE0000670.

2. Background

2.1. Power Systems Engineering Research Center (PSERC)

PSERC is a thirteen-university consortium with over 30 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:

- ***Reliability and Markets (Area 1)***
  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.
- ***Real Time Grid Reliability Management (Area 2)***
  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.
- ***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

A 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 2014 through FY 2015). The performers were with Arizona State University (ASU), Cornell University (CU), University of California at Berkeley (UCB), and University of Illinois at Urbana-Champaign (UIUC).

3.1. Reliability and Markets

PSERC research activities in the area of reliability and markets 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. Real Time Grid Reliability Management

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 the CERTS research area of 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 CERTS-NETL Research Projects, FY14 to FY15 Funding
(project budgets shown in thousand dollars)

Lead	Project	FY14 ($k)	FY15 ($k)
Research Area: Reliability and Markets: Stochastic Planning, Optimization, and Markets Analysis			
Anderson (Cornell)	Benchmarking and Integrating Chance-Constrained Stochastic Unit Commitment Solution for Optimal Management of Uncertainty (Project B.1)	90	90
Varaiya (UC Berkeley)	Virtual Bids and Flexible Bids: Risk Mitigation and Congestion Relief (Project B.3)	175	120
Tong (Cornell)	Probabilistic Forecast of Congestion and Real-Time LMP (Project B.4)	170	90
Schulze (Cornell)	Mapping Energy Futures: The SuperOPF Tool (Project B.5(1))	100	10
Tylavsky (ASU)	Attribute-Preserving Optimal Network Reductions (Project B.5(2))		90
Reliability and Markets: Demand-Side Markets and Reliability			
Oren (UC Berkeley)	A Business Model for Retail Aggregation of Responsive Load (Project C.2)	125	100
Research Area: Reliability & Markets: Tools for Future Grid Engineering & Market Environment			
Overbye (UIUC)	Development of Attribute Preserving Network Equivalents	75	
Real-Time Grid Reliability Management: Advanced Applications Research and Development			
Sauer (UIUC)	Pre-and Post-disturbance Grid Reliability Monitoring (Project 3.1)		50
	Total	735	550

4. Summary of Major Accomplishments

PSERC led seven research projects listed in Table 1 under the CERTS Reliability and Markets research area under FY2014 through FY2015 funding. The major accomplishments are summarized in this section.

4.1. Reliability and Markets: Stochastic Planning, Optimization, and Markets Analysis

4.1.1. Benchmarking and Integrating Chance-Constrained Stochastic Unit Commitment Solution for Optimal Management of Uncertainty (Project B.1)

This project aimed to develop approximate optimization methods that have the flexibility to include renewable resource uncertainty in on the supply side, and responsive loads on the demand side. In conjunction with the development of stochastic optimization methods, improvements in uncertainty characterization are also essential, to properly represent spatially correlated renewable resources across the grid. The scope of this project was the development of flexible and scalable stochastic methods to enable higher penetration of renewables, while maintaining system reliability, in the future electric grid.

Key accomplishments of this research include:

1. The development of a data-driven stochastic unit commitment framework that is scalable to large power systems, and also capable of including very large scenario sets. This approach to stochastic unit commitment was a new direction, with other efforts in the literature mostly using stochastic programming and robust methods. This model is also very flexible – the initial model included stochastic constraints only the load balance, while a newer implementation intends to determine reserve margins endogenously based on risk criteria as well.
2. A novel scenario reduction method that can improve the accurate representation of potential wind patterns for decision making. This method, based on a band-depth metric, brings the ability to cluster scenarios on the shape of a time-series trajectory, which are extremely important inputs to power system operations.

In this project, one of the first algorithms for operation of distributed storage resources was developed, within the economic dispatch of a power system with renewable resource uncertainty; previous efforts have focused only on single-unit operations.

4.1.2. Virtual Bids and Flexible Bids: Risk Mitigation and Congestion Relief (Project B.3)

This project had two thrusts.

1. Limiting risk of renewable power supply through virtual bids (lead P. Varaiya)
A renewable power generator must make a firm commitment in the Day Ahead Market (DAM) and faces a penalty for failure to deliver in the spot or real time market (RTM).

The generator seeks to reduce the penalty risk by making use of virtual bids. Virtual bids are sell (supply) and buy (demand) energy bids made in the DAM with the explicit requirement that they be accompanied by buy and sell bids of the same energy in the RTM. Since the DAM and RTM virtual bids must exactly cancel out, these are purely financial transactions. However, the DAM virtual bids are included in the DAM price and schedule determination, so they do affect how physical resources are dispatched. Virtual bids are also called convergence bids because of the belief that large numbers of virtual bids narrows the gap between DA and RT prices.

To better understand the interactions between DAM and RTM, the researchers conducted analysis of historic data from PJM. They used this analysis to formulate a theoretical model of the two-settlement market. The model captures the following facts: most of the supply and demand is settled in DAM, while RTM functions as a balancing market; cost functions in DAM and RTM are quadratic, which correspond to affine supply functions; there are forecast errors on both demand and supply side; DAM and RTM are coupled by the no-arbitrage condition ex ante, while systematic nonzero spreads may exist ex post. They then developed a theory of virtual bidding, based on the two-settlement model. The main results have the following implications: [sufficient condition of spread convergence] when the average forecast of virtual bidders is better than the market, the magnitude of the spread is reduced after virtual bidding; [Cournot theorem for virtual bidding] as the number of virtual bidders increases, if the average forecast error of virtual bidders goes to zero, the spread also converges to zero; a virtual bidder makes a positive profit if and only if the spread is driven to zero by its participation. This model and the findings provide a framework to explore the data using more sophisticated machine learning techniques in the future work.

2. Congestion limiting dispatch through flexible bids (lead K. Poolla)

The study examined how temporal and spatial load shifting, combined with storage could reduce congestion in transmission networks. Specifically, how much flexibility is needed to ensure congestion free dispatch? How much congestion is relieved by a specified set of flexibility resources at various buses? What is the associated change in payments by loads, or to generators resulting from changes in locational marginal prices (LMPs) derived from load flexibility? The analyses of these questions was closely coupled with comprehensive simulation studies using historical data from PJM.

The researchers developed a generalized framework for analysis of flexible bids in multi-period economic dispatch and showed that in the marginal case of small amounts of flexibility, every load benefits. With larger amounts of flexibility, they showed that loads may exhibit pathologies when the loads pay more as a collective, dis-incentivizing them from offering their flexibility. Empirical studies using PJM data showed that flexible bidding offers substantial economic rewards to participants by reducing congestion. Specifically, their empirical studies suggest that loads acting cooperatively can increase the social welfare by 3X over simple LMP arbitrage.

4.1.3. Probabilistic Forecast of Congestion and Real-Time LMP (Project B.4)

This project developed computationally tractable techniques for the *short-term probabilistic forecast* of congestion and real-time locational marginal price (LMP) for large utility-size networks under a multi-area SuperOPF framework. The developed techniques are intended for the service operator to (i) anticipate congestion situations for operation planning; (ii) scheduling flows with neighboring operators; and (iii) provide real-time (non-binding) price forecast to aid operation decisions of its participants and facilitate demand response decisions. To this end, the forecast algorithms were developed with the objective of becoming an integral component of the real-time market operation.

The project made two specific contributions:

1. **Probabilistic forecasting of real-time LMP and network congestions**
   The researchers developed an online machine learning technique for the large scale simulation and probabilistic forecasting of locational marginal prices, power flow, congestions, and reserve levels. The method provides several orders of magnitude improvement in computation efficiency.

2. **Multiarea interchange scheduling and tie-line scheduling**
   The researchers also developed a new decentralized multi-area economic dispatch and robust optimization technique that provides a finite step convergence to optimal tie-line schedules. They also examined the first stochastic optimization of interchange among neighboring independently operated service regions.

4.1.4. Mapping Energy Futures: The Super OPF Tool (Project B.5(1))

The purpose of this project was to develop a simulation tool (the (E4ST) of the three interconnections that serve the United States that incorporates engineering, economics, and the environmental impacts of the power system. Thus, for example, someone could choose a sequence of fast rising natural gas prices over the next twenty years and an optimistic, declining path for investment costs for solar generation and examine the implications for the market penetration of solar as well as the resulting environmental impacts. For comparison, that individual might decide to see what happens if natural gas prices rise slowly and look at how much extra CO2 is emitted, etc.

The project goal was accomplished and the simulation tool is available at e4st.com. The project also developed Fast E4ST Predictor, which is an interface that allows anyone to try different policy combinations for the U.S. electric power system under different assumptions and obtain approximate results. As a result of this research, much more sophisticated simulation model of power systems is now available to researchers, government, and industry to forecast the response to policies, products, new investments in lines, generation and new technologies.

4.1.5. Attribute-Preserving Optimal Network Reductions (Project B.5(2))

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 project was to develop methods for producing reduced electrical network models that preserved different sets of attributes.

The project developed a Network Reduction Toolbox that is currently being distributed with MATPOWER 5.1 and is also 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 addition, the project developed 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. 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.

4.2. Reliability and Markets: Demand-Side Markets and Reliability

4.2.1. A Business Model for Retail Aggregation of Responsive Load (Project C.2)

This project sought 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.). The focus was on mobilization of DR at the low end retail level to firm up VERs that will participate in the ISO wholesale energy markets, ancillary service and in providing capacity resources for revenue adequacy. The researchers focused on third party aggregators (and possibly traditional utilities) and on DR resources that might be too small to meet the ISO threshold for participating as supply side DR resources. Such aggregated DR participation in the market will complement ISO mechanisms to mobilize DR resources for supplying flexible ramping products and peak load energy relief. Aggregators can assemble portfolios exploiting the complementarity of these resources to create wholesale products that can be offered in the various ISO markets, assuming that the ISO will not perform such aggregation functions internally. Research in portfolio structuring, correlation modeling and dispatch strategies may further mitigate intermittency and uncertainty of DR and VERs. The portfolio structure was co-optimized in terms of the mix of DR population and VER nameplate capacity, the day commitment, and the contract design in order to induce efficient self-selection of DR in an asymmetric information setting.

The contribution to the field was to verify through theoretical modeling and simulation the validity of the fuse control demand response paradigm and to develop a theoretical foundation and illustrative case study that for an end to end business model that accounts for an aggregator's contracting with customers and the bidding of the aggregated demand response into the wholesale market.

4.3. Reliability and Markets: Tools for Future Grid Engineering & Market Environment

4.3.1. Development of Attribute Preserving Network Equivalents

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 were 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.

The researchers examined three approaches and found that could assign a meaningful limit to equivalent lines with each of them. In doing so, the research provides a better understanding of the issues associated with the creation of equivalent lines. For example, the researchers found that when buses are eliminated one by one sequentially, the results are dependent on the bus elimination order. To tackle this, they 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 Max-Hungarian approach and the QP program, 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. They found that they could reduce this 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. Previously, no equivalencing algorithms had this capability.

4.4. Real-Time Grid Reliability Management: Advanced Applications Research and Development (AARD)

PSERC led one research project under the CERTS RTGRM/AARD research area from FY2014 through FY2015 as listed Table 1. The major accomplishment of this project is summarized below.

4.4.1. Pre- and Post-Disturbance Grid Reliability Monitoring (Project 3.1)

This project demonstrated the feasibility of using measurement-based analysis to provide improved online monitoring and control of the grid. It included the development and integration of model-less post-contingency grid reliability performance metrics and temporal and zonal reliability composite indices. The overall project sought to work with MISO during the development and integration of the extended prototype in their real time phasor monitoring infrastructure led by a private firm, ASR. The research provided an application for utilizing SCADA or PMU data to compute sensitivities that could be used in contingency analysis or any online algorithm that needs linear power flow computation. It also proposed the use of Thevenin equivalents to relate current loading conditions relative to St. Clair curve limitations.

5. Individual Project Reports

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

5.1. Reliability and Markets: Stochastic Planning, Optimization, and Market Analysis

5.1.1. Benchmarking and Integrating Chance-Constrained Stochastic Unit Commitment for Optimal Management of Uncertainty (Project B.1)

PI Lead	**Lindsay Anderson**	**Institution**	**Cornell University**
Funding	**FY14**	$90k	
	FY15	$90k	

Summary of project intent/scope

To realize the benefits of significant wind penetration into existing power systems, new methods are required to ensure the most effective use of this resource, while preserving system reliability and security. Traditional stochastic optimization frameworks for security constrained unit commitment can be solved numerically in realistic time for moderately-sized systems with a very small number of scenarios and contingencies. However, power system optimization is characteristically of high dimension, exacerbated by the addition of multi-location sources of uncertainty due to variable generation and demand-side resources. Specifically, the spatial aspect of wind generation is extremely important, and the appropriate correlations are not represented effectively with a small number of scenarios. On the demand side, there exist uncertainties in both quantity and response time that are critical to their effective use. As a result, there does not exist a stochastic unit commitment formulation that is a viable option for adoption for system operations. To meet this need, we are faced with the challenge of developing stochastic optimization methods that are tractable, scalable, flexible and accurate.

This project aimed to develop approximate optimization methods that have the flexibility to include renewable resource uncertainty in on the supply side, and responsive loads on the demand side. In conjunction with the development of stochastic optimization methods, improvements in uncertainty characterization are also essential, to properly represent spatially correlated renewable resources across the grid. The scope of this project was the development of flexible and scalable stochastic methods to enable higher penetration of renewables, while maintaining system reliability, in the future electric grid.

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

In FY 2014, efforts focused on identifying key characteristics of the problem formulation that are desirable for ensuring scalability, as well as useful approximation methods that will guarantee faster solutions. Results from the first year of the project illustrated the applicability of data-driven chance-constrained optimization for the stochastic unit commitment problem, which enabled the solution of moderately-size test networks with 10^6 scenarios, solvable in reasonable (~1 hour) computation time on a standard desktop computer [3,4,6]. A key feature of this approach is the ability to customize spatial and temporal "risk" levels within the network; allowing the system operator to identify specific times or locations that are particularly critical to operations, and ensure the highest level of robustness in those cases. While this framework has significant advantages for application to unit commitment decisions, a key concern of all approximate methods is ensuring that solutions obtained are also highly accurate. Potential inaccuracy of these solutions stems from two areas: representing the uncertainties accurately with the minimal cardinality, and the ability of the solution method to reach optimal solution using approximate function evaluations.

In addition, FY2014 brought forth the EPA's new Clean Power Plan (CPP), which set out to regulate carbon emissions from both new and existing power plants across the United States. In order to provide an assessment of potential impacts of the CPP on power system operations, wind utilization, and emission impacts, we conducted an empirical simulation-based study implementing the CPP rules on IEEE test systems under various conditions and implementations. The results of this effort are summarized in [5].

FY 2015 effort was directed at improving and extending the stochastic unit commitment and dispatch models developed in FY2014. Activities we directed at two primary aims; 1) the development of robust scenario reduction methods with assessment of impact optimality of the SCUC solution, and 2) the implementation of the approximate solution methods to solve larger systems, including distributed storage, while maintaining reasonable solution times.

In the context of scenario reduction, a new method based-on band-depth statistics was developed. This approach provides a novel algorithm for clustering 24-hour time-series of observations which identifies similar daily patterns in clusters. We describe this approach and its application to wind in [1]. The primary advantage of this method is that the band depth measure emphasizes the shape of time series or functional observations relative to other members of a dataset, and allows clustering of observations without reliance on pointwise Euclidean distance. This is in contrast to the more common k-means clustering, which emphasizes the "level" of the diurnal pattern, instead of the shape. Results demonstrate the utility of the new method in simulation studies and an application to the MOST power grid algorithm, where the band distance improves reliability over standard methods at a comparable cost [2].

While many believe that efficient and in-expensive energy storage is the key to renewable resource integration, the literature provides very little guidance on the optimal operation or management of these resources, specifically in the case of multiple storage units distributed across the grid. Therefore, efforts in FY2015 were also directed at developing a solution to the optimal dispatch problem, in the face of spatially correlated renewables and distributed storage. The optimal utilization of storage, in particular is a complex problem, due to its dynamic nature. The natural approach for thus type of problem is the use of dynamic, or stochastic dynamic, programming. However, it is well known that the SDP approach is inherently limited to very small scale problems, due to the 'curse of dimensionality'. To address this issue, we adapted the tools of stochastic dual dynamic programming, well established in the area of hydrothermal optimization, to the problem of optimal dispatch of power systems with renewables and utility-scale storage [1].

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

Key accomplishments of this research include:

1. The development of a data-driven stochastic unit commitment framework that is scalable to large power systems, and also capable of including very large scenario sets. This approach to

stochastic unit commitment was a new direction, with other efforts in the literature mostly using stochastic programming and robust methods. This model is also very flexible – the initial model included stochastic constraints only the load balance, while a newer implementation intends to determine reserve margins endogenously based on risk criteria as well.

2. A novel scenario reduction method that can improve the accurate representation of potential wind patterns for decision making. This method, based on a band-depth metric, brings the ability to cluster scenarios on the shape of a time-series trajectory, which are extremely important inputs to power system operations.
3. While the issue of optimal storage dispatch is an important problem for the future grid, previous efforts have focused on single-unit operations. In this project, one of the first algorithms for operation of distributed storage resources was developed, within the economic dispatch of a power system with renewable resource uncertainty.

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

This work provided the groundwork in flexible and scalable models for operations at the transmission level. Future applications of the research are directed at the integration of the developed methods [1, 2, 4, 6] into an integrated model for co-optimization of transmission and distribution systems to enable demand response as a power system resource. With the solution of this next stage of research, the highest levels of renewables penetration could be achieved through leveraging of individual and/or aggregated retail consumers in power system operations.

Identify any products developed and any technology transfer activities

Website(s)	The new (follow on) project directed at co-optimization of transmission and distribution will provide an outlet for open-source codes for band-depth clustering algorithms, and the chance-constrained unit commitment model, appearing after streamlining of the code and user instructions. Located at https://blogs.cornell.edu/sidr/
Networks/ Collaborations	New collaborations based on this work include Prof. J. Mathieu (University of Michigan) and Prof. D. Matteson (Cornell University, Department of Statistics)

Publications

1. Zéphyr, L., Anderson, C. L. (2017) Integrating Storage with Power System Management: A Stochastic Dual Dynamic Programming Approach. Computational Management Science (accepted for publication) http://arxiv.org/abs/1604.08189

2. Laura L. Tupper, David S. Matteson, C. Lindsay Anderson & Luckny Zephyr (2017). Band Depth Clustering for Nonstationary Time Series and Wind Speed Behavior. Technometrics (In Press) http://dx.doi.org/10.1080/00401706.2017.1345700

3. Liu, J., Martínez, M.G., Li, B., Mathieu, J. & Anderson, C.L. (2016) A Comparison of Robust and Probabilistic Reliability for Systems with Renewables and Responsive Demand. Proceedings of the 49th Hawaii International Conference on System Sciences. (8 pages) https://doi.org/10.1109/HICSS.2016.297

4. Martínez, M. G., & Anderson C. L. (2015). A Risk-averse Optimization Model for Unit Commitment Problems, Proceedings of the 48th Hawaii International Conference on System Sciences (9 pages)

http://dx.doi.org/10.1109/HICSS.2015.31

5. Cardell, J. B., & Anderson, C. L. (2015). Targeting existing power plants: EPA emission reduction with wind and demand response. Energy Policy, 80, 11–23. http://dx.doi.org/10.1016/j.enpol.2015.01.021
6. Martínez, M. G. & Anderson, C. L. (2014) Toward a Scalable Chance-Constrained formulation for unit commitment to manage high penetration of variable generation. Proceedings of the 52nd Annual Allerton Conference on Communications, Computing and Control. (8 pages).

5.1.2. Virtual Bids and Flexible Bids: Risk Mitigation and Congestion Relief (Project B.3)

PI Lead	**Pravin Varaiya**	**Institution**	**University of California--Berkley**
Funding	**FY14**	$175k	
	FY15	$120k	

Summary of project intent/scope

This project had two thrusts interconnected by the shared analytical tools and modeling methods used:

1. Limiting risk of renewable power supply through virtual bids (lead P. Varaiya)

A renewable power generator must make a firm commitment in the Day Ahead Market (DAM) and faces a penalty for failure to deliver in the spot or real time market (RTM).

The generator seeks to reduce the penalty risk by making use of virtual bids. Virtual bids are sell (supply) and buy (demand) energy bids made in the DAM with the explicit requirement that they be accompanied by buy and sell bids of the same energy in the RTM. Since the DAM and RTM virtual bids must exactly cancel out, these are purely financial transactions. However, the DAM virtual bids are included in the DAM price and schedule determination, so they do affect how physical resources are dispatched. Virtual bids are also called convergence bids because of the belief that large numbers of virtual bids narrows the gap between DA and RT prices.

2. Congestion limiting dispatch through flexible bids (lead K. Poolla)

The study examined how temporal and spatial load shifting, combined with storage could reduce congestion in transmission networks. The following questions were investigated:

- How much flexibility is needed to ensure congestion free dispatch.
- How much congestion is relieved by a specified set of flexibility resources at various buses?
- What is the associated change in payments by loads, or to generators resulting from changes in locational marginal prices (LMPs) derived from load flexibility?

The analyses of these questions was closely coupled with comprehensive simulation studies using historical data from PJM.

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

The researchers conducted analysis of historic data from PJM. They used this analysis to formulate a theoretical model of the two-settlement market. The model captures the following facts: most of the supply and demand is settled in DAM, while RTM functions as a balancing market; cost functions in DAM and RTM are quadratic, which correspond to affine supply functions; there are forecast errors on both demand and supply side; DAM and RTM are coupled by the no-arbitrage condition ex ante, while systematic nonzero spreads may exist ex post.

The researchers then developed a theory of virtual bidding, based on the two-settlement model. The main results have the following implications: [sufficient condition of spread convergence] when the average forecast of virtual bidders is better than the market, the magnitude of the spread is reduced after virtual bidding; [Cournot theorem for virtual bidding] as the number of virtual bidders increases, if the average forecast error of virtual bidders goes to zero, the spread also converges to zero; a virtual bidder makes a positive profit if and only if the spread is driven to zero by its participation.

This model and the findings provide a framework to explore the data using more sophisticated machine learning techniques in future work.

The researchers developed a generalized framework for analysis of flexible bids in multi-period economic dispatch and showed that in the marginal case of small amounts of flexibility, every load benefits.

With larger amounts of flexibility, they showed that loads may exhibit pathologies when the loads pay more as a collective, dis-incentivizing them from offering their flexibility. Empirical studies using PJM data showed that flexible bidding offers substantial economic rewards to participants by reducing congestion. Specifically, their empirical studies suggest that loads acting cooperatively can increase the social welfare by 3X over simple LMP arbitrage.

Publications

- “Model and Data Analytics of Two-Settlement Wholesale Electricity Market with Virtual Bidding”, W. Tang, R. Rajagopal, K. Poolla, P. Varaiya, IEEE Conference on Decision and Control.
- “A cooperative game for the realized profit of an aggregation of renewable energy producers”, P. Chakraborty, E. Baeyens, P. Khagonekar, K. Poolla, IEEE Conference on Decision and Control.
- “The Sharing Economy for Electricity Storage”, C. Wu, D. Kalathil, K. Poolla, P. Varaiya, IEEE Conference on Decision and Control.
- “The Geometry of Locational Marginal Prices”, J. Mather, E. Baeyens, D. Kalathil, K. Poolla, IEEE Transactions on Power Systems.

5.1.3. Probabilistic Forecast of Real-Time Locational Marginal Price (Project B.4)

PI Lead	**Lang Tong**	**Institution**	**Cornell University**
Funding	**FY14**	$170k	
	FY15	$90K	

Summary of project intent/scope

The objective of the proposed research is to develop computationally tractable techniques for the *short-term probabilistic forecast* of congestion and real-time locational marginal price (LMP) for large utility-size networks under a multi-area SuperOPF framework. The developed techniques are intended for the service operator to (i) anticipate congestion situations for operation planning; (ii) scheduling flows with neighboring operators; and (iii) provide real-time (non-binding) price forecast to aid operation decisions of its participants and facilitate demand response decisions. To this end, the forecast algorithm will be an integral component of the real-time market operation.

The problems of real-time congestion and LMP forecast have been considered by major system operators, motivated by the fact that short-term forecasts of the real-time LMP are potentially beneficial for making effective demand response decisions. Such forecasts can also play an important role in congestion relief, thus reducing the overall system operating cost. Congestion forecasts are also important for coordination of multi-region operators when power flows on tie lines are to be scheduled in real-time.

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

1. *Probabilistic forecasting of real-time LMP and network congestions*
   We investigated the problem of probabilistic forecasting of locational marginal prices, power flows, contingency events, and level of reserves. Such techniques provide the system operator a useful tool to make operation decisions under uncertainty.

2. *Multiarea interchange scheduling and tie-line scheduling*
   We investigated the problem of interchange scheduling when there are significant stochastic generation and other operation uncertainties.

3. *Market approach to seamless interfaces*
   We investigated the effects of using proxy bus model for interchange scheduling, the presence of loop flows, and the cost of market based approaches.

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

1. *Probabilistic forecasting of real-time LMP and network congestions*
   We developed an online machine learning technique for the large scale simulation and probabilistic forecasting of locational marginal prices, power flow, congestions, and reserve levels. The method provides several orders of magnitude improvement in computation efficiency.
2. *Multiarea interchange scheduling and tie-line scheduling*
   - We developed a new decentralized multi-area economic dispatch and robust optimization technique that provides a finite step convergence to optimal tie-line schedules.
   - We obtain the first stochastic optimization of interchange among neighboring independently operated service regions.

3. *Market approach to seamless interfaces*
   We developed a generalized coordinate transmission scheduling (CTS) that eliminates proxy bus approximations and loop flows in the interchange scheduling problem. We establish also that the generalized CTS provides revenue adequate guarantee for participating system operators and price convergence of interface bids.

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

The developed probabilistic forecasting techniques has the potential to become of very useful tool for system operator in making operating decisions.

Publications

Journal Publications

1. Y. Ji, R. J. Thomas, L. Tong, "Probabilistic forecasting of real-time LMP and network congestion," *IEEE Trans. Power Systems*, vol 32, no. 2, March, 2017
2. Y. Ji, T. Zheng, and L. Tong, "Stochastic Interchange Scheduling in the Real-Time Electricity Market," *IEEE Trans. Power Systems*, vol 32, no. 3, March, 2017
3. Y. Guo, L. Tong, et. al., "Coordinated multi-area economic dispatch via critical region projection," Probabilistic forecasting of real-time LMP and network congestion," *IEEE Trans. Power Systems*, vol PP, no. 99, January, 2017
4. Y. Ji and L. Tong, "Multi-area interchange scheduling under uncertainty," IEEE Transactions on Power Systems, vol PP, issue 99, July 2017
5. Y. Guo, S. Bose, and L. Tong, "Robust tie-line scheduling in multi-area power systems," submitted to IEEE Transactions on Power Systems, to appear in IEEE Transactions on Power Systems, July, 2017.
6. Y. Guo, Y. Ji, and L. Tong, "Generalized Coordinated Transaction Scheduling: A Market Approach to Seamless Interfaces," submitted to IEEE Transactions on Power Systems, (under second review), July 2017

Conference publications

1. Y. Guo, Y. Ji, and L. Tong, "Incorporating Interface Bids in the Economic Dispatch for Multi-area Power Systems," IEEE PESGM, July 2017.
2. Y. Guo and L. Tong, "Robust tie-line scheduling for multi-area power systems with finite-step convergence," IEEE PESGM, July 2017.
3. Y. Guo, L. Tong, T. Doan, C. Beck, and S. Bose, "Tie-line scheduling in power networks: an adjustable robust framework," 2017 Information Theory & Applications Workshop, Feb, 2017
4. Weisi Deng, Yuting Ji, and Lang Tong, "Probabilistic forecasting and simulation of electricity markets via online dictionary learning," Proc the 50th Hawaii International Conf on System Sciences (HICSS), January 4-7, 2017. Best paper award.
5. Y. Ji and L. Tong, "Multi-proxy interchange scheduling under uncertainty," IEEE Power & Energy Society General Meeting (PESGM), 2016. Best paper nomination.

6. Y. Guo, L. Tong, et. al., “Multi-area economic dispatch via state space decomposition,” IEEE American Control Conf. (ACC), 2016
7. Y Ji, R.J. Thomas, and L. Tong, ”Probabilistic Forecast of Real-Time LMP via Multiparametric Programming,” 2015 48th Hawaii International Conference on System Sciences (HICSS), 2015.
8. Y. Ji and L. Tong, ”Stochastic coordinated transaction scheduling via probabilistic forecasting,” IEEE Power & Energy Society General Meeting (PESGM), 2015.
9. Y. Guo, L. Tong, et. al., “Coordinated multi-area economic dispatch via multi-parametric programming,” IEEE Power & Energy Society General Meeting (PESGM), 2015.

5.1.4. Mapping Energy Futures: The SuperOPF Tool (Project B.5 (1))

PI Lead	**William Schulze**	**Institution**	**Cornell**
Funding	**FY14**	$100k	
	FY15	$10k	

Summary of project intent/scope

The purpose of this project was to develop a simulation tool (the (e4st) of the three interconnections that serve the United States that incorporates engineering, economics, and the environmental impacts of the power system. That has been accomplished and the simulation tool is available at e4st.com.

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

The final three tasks for this overall project have completed. First we have made available a Fast E4ST Predictor on the E4ST website by providing an interface that allows anyone to try different policy combinations for the U.S. electric power system under different assumptions and obtain approximate results. Thus, for example, someone could choose a sequence of fast rising natural gas prices over the next twenty years and an optimistic, declining path for investment costs for solar generation and examine the implications for the market penetration of solar as well as the resulting environmental impacts. For comparison, that individual might decide to see what happens if natural gas prices rise slowly and look at how much extra CO2 is emitted, etc. Second, we collaborated on economic design issues to develop a new second generation planning tool that addresses limitations of the current framework. Third, in collaboration with Ben Hobbs' group, we worked on transmission planning and collaborated and provided inputs to that effort.

Task 1: Development of a Fast E4ST Results Predictor

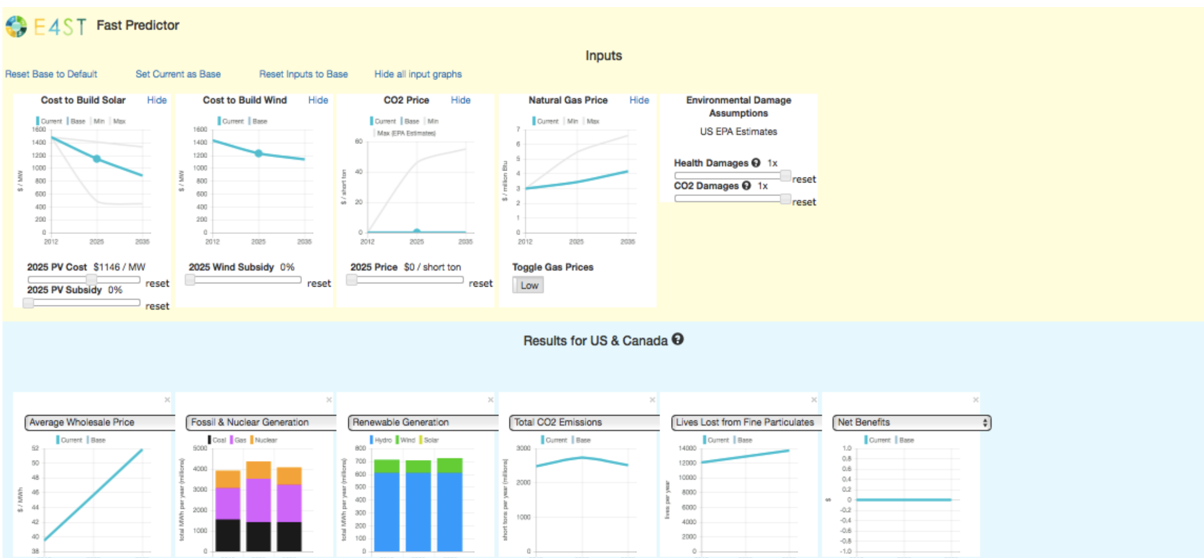
Users who wish to use the E4ST with our network models and generator information must purchase some of the necessary data from Energy Visuals, Inc, since substantial parts of the overall data set are the property of Energy Visuals. To make the E4ST website of more interest to potential users, we conducted a large number of simulations for different alternative energy prices, as well as different policies to promote alternative sources of generation, energy efficiency, and pollution reduction. We used the output data from these simulations, such as average LMP, emissions of CO2, NOx and SO2, fine particulate pollution levels, health effects, investment in alternative sources of generation and energy efficiency, etc., to interpolate the response to alternative energy prices and energy and environmental policies.

Thus, instead of users purchasing transmission and generator data and then using Gurobi to solve the very large optimization problem to answer a specific question with the model, which then takes many hours to solve, we have placed our statistically estimated model of the response of the electric power system to various policies online on the E4ST website and call it, for short, the Fast Predictor. Thus, users can vary energy prices for natural gas, capital costs, energy policies such as subsidies for renewables, and CO2 price, and instantly obtain output by using the Fast Predictor that gives outcomes by interconnection, or for the contiguous United States and parts of Canada and Mexico.

The predicted results closely approximate the output of running the full optimization model. This not only provides a usable policy tool but also provides a platform that can be used in the classroom and by the public. Hopefully, researchers with questions that cannot be answered by the online platform will be motivated to download the full model and acquire the necessary data to run the full E4ST.

An important component was development of a website with useful graphics to show output from the Fast Predictor. In addition, the output data from running the many simulations will be used for publication on a wide range of issues, such as the effects of changes in emission prices, technology costs, fuel prices, load growth/energy efficiency, and demand response. Furthermore, with the Fast Predictor, extensive sensitivity analysis to account for uncertainty about future conditions is fast and easy.

The Fast Predictor can be accessed at E4ST.com. A screen shot of the Fast Predictor is shown below.



Task 2: Support for Development of a New Generation Investment Planning Tool

Ray Zimmerman and Carlos Murillo-Sanchez (Project 1A) have developed a second generation planning tool that incorporates AC power flows, discrete investment, and a time dimension. These changes address important limitations in the current version of the E4ST that is based on the first generation SuperOPF. The economists working on the E4ST assisted in developing the economic modeling aspects of the design of the second generation version.

Task 3: Support for Transmission Planning

Ben Hobbs' group at Johns Hopkins University has developed a dynamic transmission planning tool (Project 2B) that uses the outputs from the full E4ST as described in Task 1 for the Eastern Interconnection to simplify the problem of dynamic planning while retaining the accuracy of the full E4ST. The support involved adding a new line to the Eastern Interconnection part of the E4ST model and estimating the response for changes in such variables as natural gas prices, and energy and environmental policies

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

A much more sophisticated simulation model of power systems is now available to researchers, government, and industry to forecast the response to policies, products, new investments in lines, generation and new technologies.

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

(see above)

Identify any products developed and any technology transfer activities

Website(s)	e4st.com
Networks/ Collaborations	We collaborated with Ben Hobbs project on optimal transmission planning.
Technology/ Techniques	The e4st has been adopted by Altenex, Microsoft Renewables, the Edison Electric Institute, Resources for the Future and other companies and researchers.

Publications

See e4st.com for a list of project publications.

In particular the paper by *Biao Mao, Daniel Shawhan, Ray Zimmerman, Jubo Yan, Yujia Zhu, William Schulze, Richard Schuler, Daniel Tylavsky. "The Engineering, Economic and Environmental Electricity Simulation Tool (E4ST): Description and an Illustration of its Capability and Use as a Planning/Policy Analysis Tool." Proceedings of the 49th Hawaii International Conference on System Sciences (HICSS), Koloa, HI, 2016, pp. 2317-2325 DOI: 10.1109/HICSS.2016.290* was the winner of the **best paper award** in the Electric Power Systems track.

5.1.5. Attribute Preserving Optimal Network Reductions (Project B.5(2))

PI Lead	Dan Tylavsky		Institution	Arizona State University
Funding	FY14	$0		
	FY15	$ 90k		

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 is also 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.

In addition 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. Finally, we developed a nonlinear voltage-preserving network reduction technique for ac systems using holomorphic embedding methods which promises to have wide ranging applications in the future.

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 is also 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. The advantage of the holomorphic-embedding methods for ac network reductions which preserve voltage are expected to have wide application as the preserved with high precision the nonlinear behavior of the full network in the reduced network model.

Identify any products developed and any technology transfer activities

Website(s)	E4st.com
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).
Technology/ Techniques	Nonlinear voltage-preserving network reduction methods using the holomorphic embedding technique.
Other products	The Network Reduction Toolbox developed through this funding is being distributed with version 5.1 of MATPOWER and at the e4st.com website.

Publications

1. A. Lamadrid, D. Shawhan, C. E. Murillo-Sanchez, R. Zimmerman, Y. Zhu, D. Tylavsky, A. Kindle and Z. Dar, "Stochastically Optimized, Carbon-Reducing Dispatch of Storage," *IEEE PES Trans on Power Systems*, Vol. 30, no. 2, Mar. 2015, pp. 1064-1075.
2. D. Shawhan, J. Taber, R. Zimmerman, J. Yan, C. Marquet, W; Schulze, R. Schuler, R. Thomas, D. Tylavsky, D. Shi, N. Li, W. Jewell, T. Hardy & Z. Hu, "A Detailed Planning Model: Estimating the Long-Run Impact of Carbon Reducing Policies," Hawaii International Conference on System Sciences, Manao, Hawaii, Jan. 2015, pgs. 10.
3. S. Rao, D. J. Tylavsky, "The Holomorphic Embedding Method Applied to a Newton Raphson Power Flow Formulation," *IEEE Trans on Power Systems*, (In Preparation), pp. 1-.
4. S. Rao, D. J. Tylavsky, "Maximum Power Transfer Theorem for Saddle-Node-Bifurcation-Point-Preserving Nonlinear Network Reductions," *IEEE Trans on Power Systems*, (In Preparation), pp. 1.
5. S. Li, D. J. Tylavsky, "Analytic Continuation and the Aha! Moment," *IEEE Trans on Power Delivery*,

(Submitted), pp. 1-9.

6. S. Rao, D. J. Tylavsky, "Two-Bus Holomorphic Embedding Method-Based Equivalents and Weak-Bus Determination," *arxiv.org/ftp/arxiv/papers/1706/1706.01298.pdf*, Aug. 2017, pp. 1-4.
7. Y. Zhu, D. J. Tylavsky, "An optimization-based dc-network reduction method," *IEEE PES Trans on Power Systems*, (Accepted), pp. 1-9.
8. Y. Zhu, S. Rao, D. J. Tylavsky, "Nonlinear structure-preserving network reduction using holomorphic embedding," *IEEE Trans on Power Systems*, (Accepted), pp. 1-10.
9. S. Rao, D. J. Tylavsky, "Theoretical convergence guarantees versus numerical convergence behavior of the holomorphically embedded power flow method," *International Journal of Electrical Power and Energy Systems*, (Accepted), pp. 1-22.
10. S. Rao, D. J. Tylavsky, Y. Feng, "Estimating the saddle-node bifurcation point of static power systems using the holomorphic embedding method," *International Journal of Electrical Power and Energy Systems*, Vol. 84, Jan. 2017, pp. 1-12.
11. Y. Zhu, and D. J. Tylavsky, "Bivariate Holomorphic Embedding Applied to the Power Flow Problem," 2016 North American Power Symposium, Sep. 2016, pgs. 6.
12. S. Rao, and D. J. Tylavsky, "Nonlinear Network Reduction for Distribution Networks using the Holomorphic Embedding Method," 2016 North American Power Symposium, Sep. 2016, pgs. 6.
13. S. Rao, Y. Feng, D. J. Tylavsky, M. Subramanian, "The Holomorphic Embedding Method Applied to the Power-Flow Problem," *IEEE PES Trans on Power Systems*, Vol. 31, no. 5, Sep. 2016, pp. 3816-3828.
14. (HICSS 2016 Best Paper Award for Electric Energy Systems) B. Mao, D. Shawhan, R. Zimmerman, J. Yan, Y. Zhu, W. Schulze, R. Schuler, D. J. Tylavsky, "The Engineering, Economic and Environmental Electricity Simulation Tool (E4ST): Description and an Illustration of its Capability and Use as a Planning/Policy Analysis Tool," Hawaii International Conference on System Sciences, Manao, Hawaii, Jan. 2016, pgs. 8.
15. Y. Zhu, and D. J. Tylavsky, "An optimization based network reduction method with generator placement," 2015 North American Power Symposium, Oct. 2015, pgs. 6.
16. D. Shi and D. J. Tylavsky, "A Novel Bus-Aggregation-Based Structure Preserving Power System Equivalent," *IEEE PES Trans on Power Systems*, Vol. 30, no. 4, Jul. 2015, pp. 1977-1986.
17. D. Shi and D. J. Tylavsky, "A novel bus aggregation based network reduction for market analysis and system planning studies," *IEEE PES Trans on Power Systems*, Vol. PP, no. 99, Oct. 2014, pp. 1-10 (DOI: 10.1109/TPWRS.2014.2359447.)
18. M. K. Subramanian, Y. Feng, D. J. Tylavsky, "PV Bus Modeling in a Holomorphically Embedded Power-Flow Formulation," North American Power Symposium 2013, Manhattan Kansas, Sep. 2013, pgs. 6.
19. Y. Feng, D. J. Tylavsky, "A Novel Method to Converge to the Unstable Equilibrium Point for a Two Bus System," North American Power Symposium 2013, Manhattan Kansas, Sep. 2013, pgs. 6.
20. D. Shi and D. J. Tylavsky, "A novel bus aggregation based network reduction for market analysis and system planning studies," *IEEE PES Trans on Power Systems*, Vol. PP, no. 99, Oct. 2014, pp. 1-10 (DOI: 10.1109/TPWRS.2014.2359447.)
21. P. Sood, D. J. Tylavsky, Y. Qi, "Improved dc Network Models for Contingency Analysis," North

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22. 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.
23. 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.
24. 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.
25. 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.
26. 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.
27. 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.

5.2. Reliability and Markets: Demand-Side Markets and Reliability

5.2.1. A Business Model for Retail Aggregation of Responsive Load to Produce Wholesale Demand-Side Resources (Project C.2)

PI Lead	Shmuel S. Oren	Institution	UC Berkeley
Funding	FY14	$125k	
	FY15	$100k	

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.). The focus is on mobilization of DR at the low end retail level to firm up VERs that will participate in the ISO wholesale energy markets, ancillary service and in providing capacity resources for revenue adequacy. We focus on third party aggregators (and possibly traditional utilities) and on DR resources that might be too small to meet the ISO threshold for participating as supply side DR resources. Such aggregated DR participation in the market will complement ISO mechanisms to mobilize DR resources for supplying flexible ramping products and peak load energy relief. Aggregators can assemble portfolios exploiting the complementarity of these resources to create wholesale products that can be offered in the various ISO markets, however, we do not foresee the ISO performing such aggregation function internally. Research in portfolio structuring, correlation modeling and dispatch strategies may further mitigate intermittency and uncertainty of DR and VERs. In our model we co optimize the portfolio structure in terms of the mix of DR population and VER nameplate capacity, the day commitment, and the contract design that will induce efficient self-selection of DR in an asymmetric information setting. We also will continue a validation study and efficiency loss assessment of our fuse control approach, as outlined above.

Our overall research agenda is to develop a comprehensive end-to-end solution based on the fundamental “fuse 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 contracts
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) Simulation study of household response to fuse control
8) Planning tools for electricity systems with ubiquitous load control.

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

We have conducted a simulation study in 2014, of a household response to a fuse limit signal. The household is represented by a random collection of flexible and firm loads and a stochastic supply e.g. PV solar power. We formulated the household response to a fuse limit as a stochastic control problem under a pricewise affine control strategy. By optimizing the allocation of fuse reduction and stochastic supply shortfall we obtain an average supply curve for fuse increments derived from the shadow prices of the fuse constraint. We compared the total disutility of flexible load curtailments based on the average supply function in response to a day ahead price profile from CAISO with that of direct response by each flexible load to corresponding real time price signal. The results show a modest efficiency loss of 14% due to the hierarchical control which validates the premise of the proposed "fuse control" paradigm.

In FY 2015 we continued this line of research to account for temporal load shifting capability due to storage and EV load in the household. The work focused on developing a general theoretic framework for the end to end aggregator business model and on constructing and analyzing a stylized case of our more general model. In our detailed analysis we discovered that there are six cases which we document a large table. Because of the complexity of this simplest illustrative example, we have put substantial work into simplifying the problem by re parameterization and we have been able to reduce the number of parameters describing the problem data from six to three, by expressing the problem in terms of the ratio of the density of DR participants by valuation to the VER nameplate capacity, and considering valuation of service as net of the retail rate of service. We have derived case-wise analytical formulas, implemented in the Mathematica language, for: the optimal menu of contracts; the information rent that accrues to participants by virtue of their private information; the optimal offer curve for the aggregator to offer into the wholesale market; as well as the value added by aggregating VER and DR resources--the dollar value of their complementarity, or synergy. We also show how to calibrate the simple model parameters based on economic data, including demand elasticity. These formulas, and particularly their graphical display, give us more general managerial insight into the aggregator's problem.

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

The contribution to the field was to verify through theoretical modeling and simulation the validity of the fuse control demand response paradigm and to develop a theoretical foundation and illustrative case study that for an end to end business model that accounts for an aggregator's contracting with customers and the bidding of the aggregated demand response into the wholesale market.

Several papers and presentations based on this work were given, one Ph.D dissertation funded by this project was completed and one postdoc internship was funded whose recipient is currently a faculty member at Oxford.

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

The results of the work are being disseminated through lecture at academic and industrial institutions. We are seeking funding for implementing the developed concepts.

Identify any products developed and any technology transfer activities

Technology/ Techniques	Business Model for Load Control Aggregation to Firm up Renewable Resources
Other products	Publications, conference presentation, keynotes and plenary talks at workshops, Ph.D dissertation at UC Berkeley.

Publications

1. Margellos, Kostas and Shmuel Oren, "Capacity Controlled Demand Side Management: A Stochastic Pricing Analysis", IEEE PES Transactions, Vol 31, No 1, (2016) pp 706-717.

2. Campaign Clay and Shmuel Oren, “Firming Renewable Power with Demand Response: An End to End Aggregator Business Model”, Journal of Regulatory Economics, Vol 50, No. 1, (2016), pp. 1-37.
3. Margellos Kostas and Shmuel Oren, “A Fuse Control Paradigm for Demand Side Management: Formulation and Stochastic Pricing Analysis”, Proceedings of the American Control Conference, July 1-3, 2015, Chicago, Ill.
4. IEEE, PES GM, Invited Panelist, “A Business Model for Residential Load Control Aggregation”, Harbor Bay, MD, July 27-31, 2014.
5. Bergen Business School Workshop on Intermittent Renewables, Balancing Power and Electricity Market Design, Plenary Talk, “A Business Model for Load Control Aggregation to Firm up Renewable Capacity”, Hardingasete, Norway, August 25-27, 2014.
6. American Control Conference “A Fuse Control Paradigm for Demand Side Management: Formulation and Stochastic Pricing Analysis”, with Margellos Kostas (presenter), Chicago, Ill, July 1-3, 2015.
7. EPFL Conference on Demand Response, Plenary “A Historical Perspective and Business Model for Load Control Aggregation”, Lausanne, Switzerland September 10, 2015.
8. KIT Institute for Industrial Production, Chair of Energy Economics, Invited Lecture, “A business Model for Load Response Aggregation to Firm up Renewable Resources”, Karlsruhe, Germany, November 11, 2015.
9. KIT Institute for Industrial Production, Chair of Energy Economics, Invited Lecture, “A business Model for Load Response Aggregation to Firm up Renewable Resources”, Karlsruhe, Germany, November 11, 2015.
10. IEEE PES GM, Invited Supersession, “Firming Renewable Power with Demand Response: An End-to End Aggregator Business Model,” (with Clay Campaign), Boston MA, July17-21, 2016.
11. Clay Campaign, “On Demand Response in Electricity Markets”, Ph.D. Dissertation, UC Berkeley, December 2016.

5.3. Reliability & Markets: Tools for Future Grid Engineering and Market Environment

5.3.1. Development of Attribute Preserving Network Equivalents

PI Lead	Thomas Overbye		Institution	University of Illinois at Urbana-Champaign
Funding	FY14	$75K		
	FY15	$0k		

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.

The overall research plan for the funding period stated above is to further develop the algorithm to allow for its application to large-scale system. Special emphasis will be placed on applying the algorithm to the "backbone" equivalents of large networks, such as the Eastern Interconnect, being created by the group led by Dan Tylavsky. Special characteristics of these equivalents include 1) retaining a rather small subset of buses scattered throughout the entire system, and 2) explicitly retaining the large generators.

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

During the above period, we had a second round of revision of the journal paper on the second algorithm, Quadratic program. After the final revision, the journal paper was accepted to the IEEE Transactions of Power Systems in 2014. In addition, during the stated funding period, we have developed the third algorithm, a Top-down approach. This method also uses total transfer capability and power transfer distribution factor in assigning limits to equivalent lines just like the previous algorithms. However, unlike the two previous algorithms (Max-Hungarian method and Quadratic program), this algorithm is able to be applied with larger cases such as Eastern Interconnect with more than 60,000 buses. This algorithm was applied to the EI case and the detailed explanation of the algorithm and the application results with the EI case was accepted to the HICCS conference in 2014 and presented there in Jan. 2015.

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

The accomplishment by this research was that we could assign a meaningful limit to equivalent lines other than just zero or infinity with all the three approaches. 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 Max-Hungarian approach and the QP program 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.

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 Max-Hungarian approach and the QP program, 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 developed 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

1. 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. URL: https://www.computer.org/csdl/proceedings/hicss/2015/7367/00/7367c759.pdf
2. 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. URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6730712

5.4. Real-Time Grid Reliability Management: Advanced Applications Research and Development

5.4.1. Pre- and Post- Disturbance Grid Reliability Monitoring and Visualization (Project 3.1)

PI Lead	Peter W. Sauer		Institution	University of Illinois at Urbana-Champaign
Funding	FY14	$0		
	FY15	$50,000		

Summary of project intent/scope

The project consisted of showing the feasibility of using measurement-based analysis to provide improved online monitoring and control of the grid. This included the development and integration of model-less post-contingency Grid reliability performance metrics and temporal and zonal reliability composite indices in support of the GARR prototype for MISO and ATC or FPL. The overall project was to work with MISO during the development and integration of the extended prototype in their real time phasor monitoring infrastructure led by ASR.

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

The project provided new concepts for improved fast solutions to contingency analysis using online monitoring data to compute sensitivities that could be used to avoid error-prone models which could be out of date at the time the analysis. The model-less techniques could also be used to find errors in the stored model data. The technique was also demonstrated for use with security-constrained economic dispatch and other sensitivities such as line outage angle factors and related applications.

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

The research provided an application for utilizing SCADA or PMU data to compute sensitivities that could be used in contingency analysis or any online algorithm that needs linear power flow computation. It also proposed the use of Thevenin equivalents to relate current loading conditions relative to St. Clair curve limitations.

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

The concept of using data-driven analysis can be used to improve model-based computation through the discovery of model errors. Since the data-driven analysis utilizes actual measurements of the system condition it has the correct topology and voltages of the grid. As such, it is not subject to the impact of unplanned outages or varying conditions.

Identify any products developed and any technology transfer activities

Networks/ Collaborations	Results of this work were presented to the MISO for use in various applications requiring improved linear power flow solutions.
Technology/ Techniques	The researchers met with the MISO on two occasions to transfer the techniques for their use and to propose testing with real PMU data.

Publications

1. 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.
2. P. W. Sauer and A. Dominguez-Garcia, "Data Driven Dynamic Security Assessment", Proceedings, 2014 IEEE/PES General Meeting, Washington, DC, July 27-31, 2014.
3. 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.
4. 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. 30, No. 4, pp. 1727-1738, July 2015.
5. Yu Christine Chen, Jianhui Wang, Alejandro D. Dominguez-Garcia, and Peter W. Sauer, "Measurement-Based Estimation of the Power Flow Jacobian Matrix," IEEE Transactions on Power Systems, Vol. 7, No. 5, pp. 2507-2515, September, 2016.
6. Kai Van Horn, A. Dominguez-Garcia, and P. Sauer, "Measurement-based real-time economic dispatch," Proceedings, IEEE PES General Meeting, Denver, CO, July 26-31, 2015.
7. Kai E. Van Horn, Alejandro Dominguez-Garcia, and Peter W. Sauer, "Measurement-Based Real-Time Security-Constrained Economic Dispatch," IEEE Transactions on Power Systems, Vol. 31, No. 5, pp. 3548-3560, September, 2016.
8. Kai E. Van Horn, Alejandro D. Dominguez-Garcia, and Peter W. Sauer, "Sensitivity-Based Line Outage Angle Factors," Proceedings, North American Power Symposium, University of North Carolina at Charlotte, Charlotte, NC, pp. 1-5, October 4-6, 2015.
9. Yu Christine Chen, Sairaj V. Dhople, Alejandro D. Dominguez-Garcia, and Peter W. Sauer, "Generalized Injection Shift Factors," IEEE Transactions on Smart Grid, Vol. 8, No. 5, pp. 2071-2080, September, 2017.