PSERC Power Systems Engineering Research Center
Empowering minds to engineer the future electric energy system

Overview of Accomplishments and Results from Work in the Future Grid Initiative

April 10, 2013

This document provides an overview of the accomplishments and results from on-going work in the PSERC Future Grid Initiative funded by the U.S. DOE. Research tasks are divided into six thrust areas:

	Thrust Area	Leader
1	Electric energy challenges of the future	Gerald Heydt, Arizona State
2	Control and protection paradigms of the future	Chris DeMarco, Univ. of Wisconsin-Madison
3	Renewable energy integration – technological and market design challenges	Shmuel Oren, Univ. of California, Berkeley
4	Workforce development	Chanan Singh, Texas A&M
5	Computational challenges and analysis under increasingly dynamic and uncertain electric power system conditions	Santiago Grijalva, Georgia Tech
6	Engineering resilient cyber-physical systems	Tom Overbye, Univ. of Illinois at Urbana-Champaign

The Future Grid Initiative also had white papers on the broad analysis topics "The Information Hierarchy for the Future Grid" (Peter Sauer, Univ. of Illinois at Urbana/Champaign, Lead) and "Grid Enablers of Sustainable Energy Systems" (Jim McCalley, Iowa State Univ., Lead). A list of products to date for the thrust area work and the broad analysis white papers is available on the PSERC website.

There were cross-cutting themes for the thrust area work, including:

- Enhancing and Monitoring Power System Stability and Operational Reliability with Diverse Resources
- Controlling and Protecting the System with Diverse Generation, Load, and Energy Storage Resources
- Designing, Planning, and Investing in the Power System to Support Sustainable Energy Systems
- Using Markets to Help Integrate Renewables
- Educating the Engineering Workforce through Courses, Professional Training, and Online Tools.

In this document, the thrust area tasks are organized by these themes, although the task numbers are also provided for reference.

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I. Enhancing and Monitoring Power System Stability and Operational Reliability with Diverse Resources

Hierarchical Coordinated Control of Wind Energy Resources and Storage for Electromechanical Stability Enhancement of the Grid *(task 2.2)*
Christopher DeMarco, Univ. of Wisconsin-Madison,
Collaborators: Bernard Lesieutre and Yehui Han, Univ. of Wisconsin-Madison

Accomplishments: With the underlying objective of maintaining stable grid frequency regulation and electromechanical response, developed control designs to make best possible use of the new characteristics of power-electronically-coupled wind energy and electrical storage resources. The controllers are complemented with a distributed estimation architecture to inform control actions. Each controller/observer uses local measurements, enhanced by a very modest number of remote synchrophasor measurements when available.

Results: Tools are designed to enable wind generation resources to be more effective contributors to grid frequency control. Control designs could also apply to responsive loads and other new, power-electronically-coupled resources.

Operational and Planning Considerations for Resiliency *(task 6.2)*
Ian Dobson, Iowa State Univ.

Accomplishments: Developed first practical method to quantify cascading line outage risk from one year of standard utility data. Developed methods to monitor area overall stress from synchrophasor measurements at the border of an area.

Results: Software that utilities and regulators could use to process standard data reported to NERC to quantify annual cascading performance of large areas in terms of number of transmission line outages. Subject to further testing, the system stress metric might provide real-time monitoring of severe line outages with an understandable and easily computed combination of synchrophasor measurements. Better situation awareness will facilitate integration of variable generation sources such as wind.

Real-Time PMU-Based Tools for Monitoring Operational Reliability *(task 5.4)*
Alejandro Dominguez-Garcia, Univ. of Illinois at Urbana-Champaign)

Accomplishments: Estimated linear sensitivity distribution factors (DFs) by exploiting measurements obtained from phasor measurement units (PMUs) in near real-time without the use of a power flow model. The DFs are used by operators in contingency analysis, congestion relief, and remedial action schemes.

Results: A power system monitoring tool that is adaptive to operating point and system network changes using parameters estimated with online measurements. Provides improved situation awareness that can be important in reliably integrating variable generation sources.

II. Controlling and Protecting the System with Diverse Generation, Load, and Energy Storage Resources

Communication Architecture for Wide-Area Control and Protection of the Smart Grid (task 2.1)

Anjan Bose, Washington State Univ.

Accomplishments: Developed a method to design, simulate and test the IT infrastructure for a given power grid to accommodate phasor measurement data at substations and new smart grid applications, including those applications for wide-area protection and control. Method tested on several power systems, including the Poland Grid (2,383 buses). Simulations showed that in properly designed, high-bandwidth communications networks, expected communications delays (or latencies) can be within a range that supports hierarchically-coordinated control and protection of a smart grid.

Results: Simulations demonstrated that the proposed IT infrastructure and communications network design would meet performance requirements. The simulations also showed the communications bandwidth requirements throughout the network. This methodology could be used to test designs for grids with high penetrations of variable generation.

Improved Grid Resiliency Through Interactive System Control *(task 6.3)*

Vijay Vittal, Arizona State Univ.

Accomplishments: To increase grid resiliency, used a hierarchical set of wide area synchronized measurements with a fault-tolerant control framework to effectively deploy corrective control with a static VAr compensator (SVC). Controller adjusts to performance issues in the associated underlying communication networks.

Results: A control design that uses new sources of wide area measurements to enhance grid stability while providing control robustness in the event of communications errors. Advances resiliency of the cyber-physical system with high penetrations of uncertain variable generation.

Wide Area Control Systems *(task 1.4)*

Mani Venkatasubramanian, Washington State Univ.

Accomplishments: Taking advantage of new synchrophasor technologies, developed a new wide-area hierarchical voltage controller, and a new wide-area transient stability controller. The voltage controller addresses reliability concerns due to power electronic interfaces, such as with wind and solar technologies, while providing grid-wide coordination of substation voltage controllers. To stabilize the system after large contingencies, the transient stability controller uses a formulation that predicts the evolution of the system and makes control decisions accordingly.

Results: Algorithms have been tested through simulations. Need to start working with industry on actual designs and implementations. The controllers address stability issues that could pose concerns with high penetrations of uncertain variable generation.

Hierarchical Coordinated Protection of the Smart Grid with High Penetration of Renewable Resources *(task 2.3)*

Mladen Kezunovic, Texas A&M

Accomplishments: Developed the "Hierarchical Coordinated Protection" concept which is based on (1) predicting protection needs in real-time, (2) adapting protection actions to the power system's prevailing conditions, and (3) executing corrective actions when the condition is verified with power system data from intelligent electronic devices (such as PMU's) as well as non-power system data (such as meteorological, lightning strike, and geographic information). Protection under this concept is better suited for integrating renewable generation, avoids unnecessary tripping of overloaded lines, improves anti-islanding controls, and mitigates cascading events, among other system conditions in the future grid.

Results: Testing shows that the new approach, when implemented with the legacy protection system, has superior performance when compared to existing protection approaches alone. The predictive, adaptive, and corrective features of this protection allow the system to be more flexible as output from renewable generation varies.

Resiliency for High-Impact, Low-Frequency (HILF) Events *(task 6.1)*

Tom Overbye, Univ. of Illinois at Urbana-Champaign

Accomplishments: Developed a modeling methodology to integrate the calculation of geomagnetic disturbance (GMD) impacts from solar storms into power flow and transient stability applications, allowing for estimations of the likelihood that GMD impacts could result in power system voltage instability.

Results: Matlab code was developed for assessing the sensitivities of the geomagnetically-induced currents on particular transformers to the geomagnetically-induced electric fields on individual transmission lines. This will lead to better assessments of system vulnerability to solar storms. This work provides an example of how new tools can help quantify vulnerabilities to the grid.

III. Designing, Planning, and Investing in the Power System to Support Sustainable Energy Systems

A National Transmission Overlay *(task 1.2)*

Jim McCalley, Iowa State Univ.

Collaborator: Dionysios Aliprantis, Iowa State Univ.

Accomplishments: Designed a U.S. interregional transmission overlay to facilitate the growth of wind, solar, nuclear, geothermal, and clean-coal generation over the next 40 years. Developed an associated design process and necessary tools. The design process co-optimizes generation and transmission, identifying a minimum cost transmission network and corresponding generation expansion plan in terms of location, capacity, and technology. Also, conducted "reachability" analysis of power system dynamics to capture uncertainties in (1) model parameters, (2) operating condition (e.g., load levels, generation dispatch, and voltage levels), and (3) disturbances to the system state (such as equipment/line outages).

Results: Planning analyses quantified the value of the development of a national transmission overlay. Related benefits to the overlay include (a) decreased cost per unit reduction of CO_2; (b) increased resilience to large-scale disturbances; and (c) increased flexibility with lowered cost in adapting to future unfolding scenarios. A national transmission HVAC overlay improves "connectivity" among areas and the dynamic frequency response of areas with high renewable penetration. A high-capacity HVDC overlay improves frequency response and can be used to "transmit variability."

Computational Issues of Optimization for Planning *(task 5.2)*

Sarah Ryan, Iowa State Univ.

Accomplishments: Developed improved computational methods for long-term resource and transmission planning under uncertainty in demand and fuel prices. Customized and tested a method to efficiently reduce the number of scenarios that must be considered, thereby reducing the computation time. Expanded optimization problem to a tri-level model of transmission and generation expansion in a centrally coordinated wholesale market, thereby capturing both technology choices and market influences. The top level represents a centralized transmission planner. The second level depicts the expansion planning decisions of multiple generation companies. The third level is an equilibrium model of operational decisions by the generation companies and the system operator to meet demands of load-serving entities in a wholesale electricity market.

Results: The lower computational burden of planning under uncertainty will allow more operational details and planning choices in analyses. The tri-level solution algorithm quickly identifies combinations of transmission projects that promise higher net benefits. Better transmission plans will expand the use of renewable resources, equalize locational prices, and prevent undue market influences, resulting in lower prices for consumers and viable profits for producers.

Integrating Transmission and Distribution Engineering Eventualities *(task 1.1)*
Gerald T. Heydt, Arizona State Univ.

Accomplishments: Analyzed advantages and disadvantages of selected innovative transmission technologies such as six-phase AC (and other high phase order), multi-terminal and meshed network HVDC, and high temperature, low sag transmission.

Results: By identifying technological and cost issues associated with alternative transmission conductors and transmission voltages, informed discussions can occur on transmission expansion planning to support renewable generation technologies.

Hierarchical Probabilistic Coordination and Optimization of Distributed Energy Resources and Smart Appliances *(task 5.3)*
Sakis Meliopoulos, Georgia Tech

Accomplishments: Defined the requirements of an infrastructure that enables optimal use of distributed resources (both utility and customer-owned) through real-time, hierarchical monitoring and control. Created a stochastic optimization algorithm that coordinates the operation of non-dispatchable resources (e.g., renewables) and other resources including storage, smart appliances, and PHEVs. This centralized approach relies on a sophisticated infrastructure of metering, communications, analytics and controls as well as on participation (i.e., consent) of customers.

Results: Based on comprehensive studies of application on utility-scale systems, a business case analysis justifies the investment in the proposed optimization scheme. The analysis includes an economic assessment based on anticipated benefits on system operation, economics and reliability versus the anticipated costs. This integrated approach to power system operations maximizes the value from the use of renewable generation technologies.

IV. Using Markets to Help Integrate Renewables

Decision-Making Framework for the Future Grid *(task 5.1)*
Santiago Grijalva, Georgia Tech.)

Accomplishments: Developed a scheduling algorithm to allow residential “prosumers” (i.e., cyber-physical entities that can consume, produce, store and/or transport electricity) to optimally schedule their energy use in a dynamic pricing environment, for a given time horizon. Also, developed a method to optimally design electricity price signals for retail markets so that when residential consumers maximize their benefit individually, they adopt an energy schedule that also maximizes the electricity provider's benefit.

Results: In addition to their prescriptive potentials (provide concrete guidance on how decision makers should act), scheduling algorithms also have descriptive potentials (illustrate through simulations why decision makers could be better off if new technology or policy are implemented) and normative potentials (demonstrate how decisions should be made so that these changes are effectively realized). Research could suggest new business models and foster collaboration on future grid research.

Direct and Telemetric Coupling of Renewable Energy Resources with Flexible Loads *(task 3.1)*

Shmuel Oren, Univ. of California, Berkeley

Accomplishments: Developed a short-term two-stage stochastic unit commitment model representing the operation of day-ahead and real-time electricity markets to analyze coupling contracts that coordinate the consumption schedules of deferrable loads with renewable resources.

Results: This work will show the value of contracted renewable resources, supplemented by spot electricity purchased from the grid, to serve such flexible loads. Business models will be explored for serving such loads or for aggregating load flexibility to provide wholesale balancing energy and reserves. Using the stochastic unit commitment model, daily cost savings of 2-3% were demonstrated against a time series model of renewable power production calibrated against one year of NREL wind power production data for a reduced system of the California ISO.

Mitigating Renewables Intermittency through Non-Disruptive Distributed Load Control *(task 3.2)*

Duncan Callaway, Univ. of California, Berkeley

Accomplishments: Developed new methods to model and control aggregations of thermostatically-controlled loads that reduce communications and power measurement requirements, and minimize temperature deviations for users. Evaluated how different real time communications abilities affect ability to accurately estimate local temperature and ON/OFF state of loads, and controllability of loads. Finally, analyze thermo-statically controlled load resource potential, costs, and revenue potential associated with TCL control in California

Results: Renewables integration requires power system flexibility (e.g., managing frequency response and energy imbalances) that can be provided by demand response. Results lay groundwork for a demonstration.

Planning and Market Design for Using Dispatchable Loads to Meet Renewable Portfolio Standards and Emissions Reduction Targets *(task 3.3)*

Timothy Mount, Cornell Univ.

Collaborators: K. Max Zhang and Robert J. Thomas, Cornell Univ.

Accomplishments: Developed an integrated multi-scale physical and economic framework for modeling deferrable demand to evaluate the effects of stochastic renewable sources and deferrable demand on total system costs and emissions from generating units.

Results: Initial analyses for a test network in the Northeast demonstrated how deferrable demand can:

- Flatten the daily dispatch pattern of conventional generators,
- Mitigate the variability of wind generation,
- Reduce ramping costs and maintain reliability,
- Lower costs to customers,
- Improve environmental quality (to be completed).

Probabilistic Simulation Methodology for Evaluation of Renewable Resource Intermittency and Variability Impacts in Power System Operations and Planning *(task 3.4)*

George Gross, Univ. of Illinois at Urbana-Champaign
Collaborator: Alejandro Dominguez-Garcia, Univ. of Illinois at Urbana-Champaign

Accomplishments: Developed a comprehensive, stochastic simulation approach for power systems with renewable and storage resources operating in a competitive market environment. The approach has explicit representation of (1) uncertainty in conventional, variable energy resources, and loads; (2) time-varying loads and renewable and energy storage resources; and (3) time-dependent transmission usage. The approach is particularly suitable for longer-term studies of power system operations, planning, economics, investment, and policy analysis/formulation.

Results: The following results were obtained through extensive testing using numerous sensitivity cases on a modified IEEE 118-bus system, making use of scaled ISO load and offer data, and historical wind data in the ISO geographic footprint:

- energy storage and wind resources tend to complement each other and the symbiotic effects reduce wholesale costs and improve system reliability;
- emission impacts with energy storage depend on the resource mix characteristics and the location of energy storage; and,
- storage seems to attenuate the "diminishing returns" associated with increased penetration of wind generation.

Robust and Dynamic Reserve Requirements *(task 1.3)*

Kory Hedman, Arizona State Univ.

Accomplishments: Developed systematic ways to determine dynamic reserve requirements (zones and levels) with reserve rules for renewable resources and N-1 contingencies to improve reserve location/deliverability. The algorithms account for the specific operational conditions (e.g., transfer capability, congestion, etc.) to determine the appropriate reserve levels and locations to improve reserve deliverability while also improving economic efficiency.

Results: Using IEEE test systems, demonstrated that robust and dynamic reserves will improve reserve deliverability, reduce costs to integrate renewables, and reduce out of market corrections (e.g., 2% cost savings were obtained).

V. Educating the Engineering Workforce through Courses, Professional Training, and Online Tools

Comprehensive Educational Tools for Reliability Modeling and Evaluation of the Emerging Smart Grid (task 4.1)
Chanan Singh, Texas A&M

Accomplishments: Developed educational material for teaching reliability modeling and evaluation of the emerging power grid with high penetration of renewables, and massive deployment of computer and communication technologies. The audience is university-level instructors, graduate students, and industry professionals.

Results: Two courses are being developed: a semester graduate course and a short course than can be offered in about six hours. The graduate course has been offered twice. It has nine main modules with some sub-modules. The materials for the short course are being organized into seven modules with PowerPoint slides enhanced with videos that present the material. The materials should be accessible on-line by late summer 2013.

Critical Infrastructure Security: The Smart Grid (task 4.6)
Anurag Srivastava, Washington State Univ.)
Collaborators: Carl Hauser, Washington State Univ.; David Bakken, Washington State Univ.; M.S. Kim, Washington State Univ.

Accomplishments: Developed a university course with multi-disciplinary content in data communication, distributed computing, control, cyber-security, and power systems. The course provides background on smart grid technologies (e.g., principles, components and operations) and the related infrastructure needed for secure sensing, communication, computation, and control in a power system. The audience for the course and materials is undergraduate and graduate students in engineering and computer science as well as university-level instructors.

Results: This course titled, "Critical Infrastructure Security: The Emerging Smart Grid "was offered in the Spring of 2012 and 2013. It was team taught and offered to online distance engineering students and engineers from industry as well as in the conventional classroom setting. Course materials will be first available in the summer of 2013 with updates occurring as the course is repeated.

Energy Economics and Policy: Courses and Training *(task 4.5)*
James Bushnell, University of California, Davis

Accomplishments: Developed a Masters, Ph.D. and professional development courses in energy economics and policy. Designed for both non-economists (with backgrounds in energy technology and engineering) and economists interested in applications to energy. Also, for online interactive learning, implemented The Electricity Strategy Game at https://esg.haas.berkeley.edu.

Results: Masters-level course aimed at graduate students in economics, engineering, sciences and public policy offered through Haas School of Business at Univ. of California, Berkeley. Research-level (PhD) material offered through Department of Economics at Univ. of California, Davis. Practitioner-level material offered through short courses at ISOs and Univ. of Cal. campuses. Course materials are available upon request by instructors at accredited universities. Access to The Electricity Strategy Game site is available upon request.

Energy Processing for Smart Grids (task 4.4)

James Momoh, Howard Univ.
Collaborator: Peter Bofah, Howard Univ.

Accomplishments: Developing a university course, with materials, on energy processing for the smart grid. Educational material is needed for teaching renewable energy, storage facility, energy processing, measurement techniques, and smart grid technologies/systems. This university course is for undergraduates and first year graduate students in power engineering.

Results: While the materials for the comprehensive course on Energy Process for the Smart Grid are being developed, a subset of the material is now being used to teach the introductory course "Fundamentals of Energy Systems" for juniors in engineering. Lecture notes will be collated into a book that will be published and available for purchase. An online e-book version will also be available upon request along with the completed course material syllabus.

PSERC Academy: A Virtual Library of Short Videos (task 4.2)

Raja Ayyanar, Arizona State

Accomplishments: Creating an online library of short (i.e., 15-20 minute) videos on various topics of sustainable energy systems, smart grid and power engineering, and on important background topics required to understand these concepts.

Results: The material for PSERC Academy will be primarily put on the website 'PsercAcademy.asu.edu'. Most of the videos will be on YouTube and the PsercAcademy.asu.edu website will provide links to these under different topic areas. The simulation files and animations will be hosted directly on the PsercAcademy.asu.edu website. PsercAcademy.asu.edu will go live in April 2013.

Smart Grid Education for Students and Professionals (task 4.3)

Mladen Kezunovic, Texas A&M

Collaborators: Sakis Meliopoulos, Georgia Institute of Technology; Alex Sprintson, Texas A&M Univ.; Vijay Vittal, Arizona State Univ.; Mani Venkatasubramanian, Washington State Univ.

Accomplishments: Building a comprehensive educational package for educators, students, practicing engineers, managers, legislators, public officials, among others, by writing a text book and preparing a set of supplemental PowerPoint presentations that may be used. The book will be for students and industry professionals. The text will be co-authored by Sakis Meliopoulos, Georgia Institute of Technology; Alex Sprintson, Texas A&M Univ.; Mani Venkatasubramanian, Washington State Univ.; and Vijay Vittal, Arizona State Univ..

Results: It is anticipated that there will be a camera-ready manuscript ready for publishing by December 31, 2013.

VI. Broad Analysis White Papers: The Information Hierarchy for the Future Grid

- **Cyber-Physical Systems Security for the Smart Grid**
  Manimaran Govindarasu, Iowa State University
  Discusses defense against cyber attacks and the need for security of information, infrastructure and applications.
- **Communication Needs and Integration Options for AMI in the Smart Grid**
  Vinod Namboodiri, Wichita State University
  Discusses communications requirements and design considerations for backhaul and home area networks.
- **Information and Computation Structures for the Smart Grid**
  Lang Tong, Cornell University
  Discusses the need for a foundational understanding of the underlying computation and information hierarchy for the future smart grid.
- **Networked Information Gathering and Fusion of PMU Measurements**
  Junshan Zhang, Arizona State University
  Discusses networked communications of synchrophasor data and how the architecture needs a robust design to avoid cascading communications failures.

VII. Broad Analysis White Papers: Grid Enablers of Sustainable Energy Systems

- **Primary and Secondary Control for High Penetration Renewables**
  Chris DeMarco, University of Wisconsin-Madison
  Argues for a new control design philosophy exploiting improved grid measurement and sensor technologies to allow renewables to more broadly contribute to grid active power and frequency control.
- **Toward Standards for Dynamics in Electric Energy Systems**
  Marija Ilic, Carnegie Mellon University
  Suggests that new paradigms (using improved grid measurement and sensor technologies) for standards for dynamics are needed to avoid emerging behavior in future electric energy systems.
- **Future Grid - The Environment**
  Ward Jewell, Wichita State University
  Discusses three environmental concerns (mitigating greenhouse gases including in transportation, adapting to changing climate, and availability of water) and makes observations about issues in addressing them.
- **Transmission Design at the National Level: Benefits, Risks and Possible Paths Forward**
  Jim McCalley, Iowa State University
  Identifies benefits to building a national transmission overlay, to lay out essential elements to facilitate continued dialogue on this topic, and to frame possible paths by which it could be realized.
- **Distributed and Centralized Generated Power System – A Comparison Approach**
  James Momoh, Howard University
  Identifies strengths and weaknesses associated with Centralized Generation (CG) and Distributed Generation (DG) infrastructure for the future electric grid system.

VIII. Links to Future Grid Initiative Web Pages

Future Grid Home Page

Thrust Area Web Pages

- Thrust Area 1: Electric Energy Challenges of the Future
- Thrust Area 2: Control and Protection Paradigms of the Future
- Thrust Area 3: Renewable Energy Integration - Technological and Market Design Challenges
- Thrust Area 4: Workforce Development
- Thrust Area 5: Computational Challenges and Analysis Under Increasingly Dynamic and Uncertain Electric Power System Conditions
- Thrust Area 6: Engineering Resilient Cyber-Physical Systems

Broad Analysis White Papers

- The Information Hierarchy for the Future Grid
- Grid Enablers of Sustainable Energy Systems

Future Grid Products to Date

Events

- Future Grid Initiative Workshop (held Dec. 7, 2011)
- Future Grid Forum: Technological Challenges in Designing the Future Grid (June 27-28, 2012)
- Future Grid Webinars (2012-2013)