4. Accomplishments

4.1 Award

1) Dr. Mohammad Shahidehpour received the IEEE Power and Energy Society Outstanding Power Engineering Educator Award (For leadership in the power engineering field and contributions to the engineering profession and engineering education) in 2012.
2) Dr. Mohammad Shahidehpour Technologist of the Year Award from the Illinois Technology Association (Presented to the individual whose talent has championed true technology innovation, either through new application of existing technology or the development of technology to achieve a truly unique product or service) in 2011
3) Dr. Mohammad Shahidehpour received the Outstanding Engineer Award, IEEE Power and Energy Society Chicago Chapter (for significant leadership and contributions towards IIT's Prefect power microgrid, the IIT's wind consortium, and the IIT's Smart Grid Education and Workforce Development) in 2011
4) In the 27th Annual Conference of the ECEDHA (Electrical and Computer Engineering Department Heads Association) on March 14, 2011, IIT's Center for Electricity Innovation, the principal unit performing this DOE project, won the Innovation Award from ECEDHA (single award) for establishing the Illinois Institute of Technology as a global leader in microgrids, smart grid technology, and sustainable energy. Below is a copy of the citation.
5) Dr. Mohammad Shahidehpour received IIT's First Research Leadership Award (in Recognition of Outstanding Accomplishments in Developing Strong Research Collaborations and Large Scale Research Projects) in 2010
6) Dr. Mohammad Shahidehpour received the Distinguished Service Award, IEEE Power &Energy Society (For serving as General Chair of the 2012 IEEE Innovative Smart Grid Conference)
7) Dr. Mohammad Shahidehpour received the Distinguished Service Award, IEEE Power & Energy Society (For serving as VP of Publications) in 2011

ECEDHA

Electrical and Computer Engineering Department Heads Association

2010 Innovative Program Award

presented to

Mohammad Shahidehpour
Illinois Institute of Technology

for the Center for Electricity Innovation
Establishing the Illinois Institute of Technology as a global leader in microgrids,
smart grid technology, and sustainable energy

Presented at the 27th Annual Conference of the ECEDHA

Ed Schlesinger
ECEDHA President
2010-2011

Phoenix, Arizona
March 14, 2011

4.2 List of Presentations

4.2.1 Presentations at the First Consortium Conference

September 30, 2010, Illinois Institute of Technology

1) A World-class University-Industry Consortium for Wind Energy Research, Education, and Workforce Development, Mohammad Shahidehpour, Illinois Institute of Technology
2) Acciona and Its Support for Consortium, Frank Bristol, Acciona
3) SmartSignal and Its Collaboration with the IIT Wind Energy Consortium, Jim Gagnard, SmartSignal
4) Acoustics of Wind Turbine, Alan Cain, Innovation Technology Applications
5) Acoustic Measurements using Phased Arrays, Ganesh Raman, Illinois Institute of Technology
6) Wind Management Tool for the IIT Wind Project, Greg Rouse, Intelligent Power Solutions

7) IPRO 311 – Integration of Plug-in Hybrid Electric Vehicles and Renewable Energy Systems, Alireza Khaligh, Illinois Institute of Technology

8) Next Generation Lightweight Electric Drive Systems, Richard Gowen, Dakota Power

9) Wind Energy Class Offering at the Illinois Institute of Technology, Zuyi Li, Illinois Institute of Technology

10) Impact of Wind Forecasting Precision on Unit Commitment and Network Control, John Birge, University of Chicago

11) DOE Educational Program Wind University Consortia, Brian Connor – U.S. Department of Energy

12) Smart Transmission Making a Smart Grid Smarter, Paul McCoy, Trans-Elect Development Company

4.2.2 Presentations at the Second Wind Consortium Conference

July 20, 2011, Illinois Institute of Technology

13) Overview of the Center for Renewable Energy, David G. Loomis, Illinois State University

14) A Big Step Toward Energy Independence, Paul McCoy, Atlantic Wind Connection

15) Integrating Midwest Wind Energy into Southeast Electricity Markets, Aidan Tuohy, Electric Power Research Institute

16) Advanced Wind Integration Study, Zuyi Li, Illinois Institute of Technology

17) Viryd Technologies Overview & Installation, Alan Hays, Viryd Technologies

18) Perfect Power @ IIT and Local Area Measurement System, Alex Flueck, Illinois Institute of Technology

19) Microgrid Master Controller & Wind Management Tool, Greg Rouse, Intelligent Power Solutions

20) DP Switched Reluctance Technology, Richard Gowen, Dakota Power

21) Impacts of Wind Power on Grid Operations, Jay Giri, Alstom Grid

22) Wind Energy & Perfect Power, David Chiesa, S&C Electric Company

23) CFD Simulation of a Horizontal Axis Wind Turbine, Hamid Arastoopour, Illinois Institute of Technology

24) Acoustic Phased Array Measurements of Wind Turbines, Ganesh Raman, Illinois Institute of Technology

25) Development of a Comprehensive Tutorial on Wind Energy Technology, Interconnection & Integration, Bob Zavadil, EnerNex

26) IPRO 323: Modeling of Building-Integrated Wind Turbine Modules, Dietmar Rempfer, Illinois Institute of Technology

27) Advancing Wind Power in Illinois-Emerging Technologies, Dave Parta, GE Intelligent Platforms

28) GE Energy 1.5 MW Wind Turbine, IIT Grand Ridge Discussion, Steve Moffitt, GE

29) Vindicator® Laser Wind Turbine Control System, Bill Fetzer, Catch the Wind

4.2.3 Other Presentations

30) Market Clearing under Uncertainty, Antonio J. Conejo, University of Castilla – La Mancha, Spain, January 2011, at Illinois Institute of Technology

31) Integrating Non-dispatchable Producers (Wind) in Electricity Markets, Antonio J. Conejo, University of Castilla – La Mancha, Spain, January 2011, at Illinois Institute of Technology

32) Improving Efficiency and Reliability of Drivetrain Components by Smart Surface and Lubrication Engineering, Ali Erdemir, Argonne National Laboratory, February 2011

33) Vindicator® Laser Wind Sensor, The Future of Wind Sensing Technology, Scripted Tech Brief, Catch the Wind, 2011

34) Energy: The Road Ahead, Richard Gowen, Keynote address at the Energy Summit held at West Point Military Academy, April 2011

35) Large-Scale Simulation of Electric Power Systems for Wind Integration, PhD Final Defense, Wei Tian, Illinois Institute of Technology, August 2011

36) A World-class University-Industry Consortium for Wind Energy Research, Education, and Workforce Development , Mohammad Shahidehpour, IEEE Power and Energy Society General Meeting 2010, held in Minneapolis, Minnesota, July 2011

4.3 List of Videos

1) IIT Wind Turbine Ribbon Cutting Ceremony, Illinois Institute of Technology

2) Viryd Test-stand at IIT Laboratory, Illinois Institute of Technology, Viryd Technologies

3) IIT Wind Turbine (1.5MW GE) at Grand Ridge, Illinois Institute of Technology

4) IIT Wind Turbine (8kW Viryd) at Soccer Field, Illinois Institute of Technology

5) Switch Reluctance DC Machine (SRDCM) Exploded Animation, Dakota Power

4.4 List of Theses

4.4.1 Ph.D. Dissertations

1) Mohammad Khodayar, Coordination of Storage with Renewable Energy Resources in Power Systems, Illinois Institute of Technology, July 2012

Abstract: The ever-increasing penetration of variable wind energy in power systems affects the hourly dispatch of thermal power generation in electricity markets. The coordination of wind power generation units with pumped-storage hydro (PS) generation could relieve the variability of wind energy and increase its hourly dispatchability. Chapter 2 proposes a coordination methodology for wind and pumped-storage hydro (PS) units in the day-ahead operation planning of power systems. With coordination, the PS unit can offset intrahour wind energy imbalances (i.e., deviations from hourly schedules) and minimize wind energy curtailments. The variability of wind energy, which makes it non-dispatchable and difficult to control, could bring significant challenges to power system operators. In Chapter 3, the wind-PS coordination is based on the application of stochastic security-constrained unit commitment (Stochastic SCUC). In this study, the hourly bus- level coordinated scheduling of wind energy and PS is compared with the system-level coordinated operation strategies in the day-ahead scheduling of power systems.

From GENCO point of view volatility of wind generation can reduce the profit in day-ahead market by imposing potential imbalance charges. In Chapter 4 day-ahead price-based scheduling strategy for the coordination of wind and storage units in a generating company (GENCO) is proposed. The proposed strategy is based on the stochastic price-based unit commitment (PBUC) which considers volatilities in day-ahead intra-hour market prices and wind power generation when scheduling wind and storage units. The proposed approach firms up the hourly sum of wind and storage unit generation, and mitigate potential wind energy imbalance charges for GENCOs in electricity markets. Although the proposed approach applies to any kind of storage, we consider the pumped-storage hydro (PS) unit in this study.

The increased utilization of PEVs, which consume electricity rather than fossil fuel for driving, offers unique economic and environmental opportunities, and brings out new challenges to electric power system operation and planning. The storage capability of PEVs could help power systems mitigate the variability of renewable energy sources and reduce grid operation costs. Vehicle-to-grid (V2G) enables PEVs to have bi-directional power flows once they are connected to the grid, i.e., they can either inject power to, and draw power from, the grid which adds further complexity to power system operations. PEVs signify customers' random behavior when considering their driving patterns, locational energy

requirements, topological grid interconnections, and other constraints imposed by the consumers. The proposed approach in Chapter 5 evaluates the effect of integrating a large number of electric vehicles (EVs) on power grid operation and control. The EV fleets could serve as electricity load when drawing energy from the grid and as energy storage (vehicle-to-grid) when delivering energy to the grid. Two operating modes for EV fleets were considered which are consumer-controlled and grid-controlled. The power grid generation mix represents a multitude of units including thermal, hydro, and wind. In this chapter, the impact of EV battery utilization on offsetting the hourly intermittency of wind generation units in transmission-constrained power grids is evaluated. Moreover, the effect of charging/discharging schedule of EV batteries and consumer driving requirements on the optimal hourly transmission-constrained commitment and dispatch of generation units in the day-ahead scheduling is investigated. The hourly solution of the proposed method will minimize the cost of supplying the hourly load while satisfying the temporal constraints of individual components in power grids.

In Chapter 6 the coordinated integration of aggregated plug-in electric vehicle (PEV) fleets and renewable energy sources (wind energy) in power systems is studied by stochastic security-constrained unit commitment (Stochastic SCUC) model, which minimizes the expected grid operation cost while considering the random behavior of the many PEVs. PEVs are mobile and distributed devices with deferrable options for the supply/utilization of energy at various times and locations. Numerical tests demonstrate the effectiveness of the proposed approach for analyzing the impact of PEVs on the grid operation cost and hourly wind energy dispatch.

Microgrid is composed of distributed energy resources (DER) including distributed generation (DG), controllable loads, and storage. Microgrids could satisfy hourly demands economically according to power quality and reliability (PQR) requirements. Other objectives in a microgrid could include the reduction in distribution system losses and increase in the efficiency of the combined heat and power (CHP) supply. In Chapter 7, the role of high reliability distribution system (HRDS) in microgrid operations is evaluated. HRDS, which offers a higher operation reliability and fewer outages in microgrids, is applied to looped networks in distribution systems. The storage system would enhance the microgrid reliability while offering hourly ancillary services and demand response for reducing operation costs. The HRDS implemented at Illinois Institute of Technology (IIT) is used as a case study along with the local DER to increase the load point reliability and decrease the operation cost of the microgrid. The outage frequency and duration indices are measured at the microgrid level and the customer level, and the potential system enhancements are discussed at the IIT microgrid.

2) Kaveh Aflaki, Large Scale Integration of Sustainable Energy and Congestion Management in the Western Interconnection, Illinois Institute of Technology, July 2012

Abstract: Sustainable energy is the maintainable type of energy that meets the needs of the present for generating electricity without compromising the ability of future generations to meet their needs. In electricity generation, implementing sustainable energy sources for generating electricity is one of the critical and the most inevitable challenging topics. Sustainable energy resources for generating electricity which is some cases called renewable energy are wind, solar, hydro, and geothermal energy. Furthermore, sustainable energy is a term which is use for techniques to improve energy efficiency as

well in some of the researches. Wind and solar energy are the fastest growing sustainable energy sources that can be used as alternatives to the pollution generated from other electricity production in the United States. When the Department of Energy, (DOE), announced its vision for a 20% wind and a 5% solar energy contribution to electricity generation by the year 2030 in the United States, most of the research centers, national laboratories, and universities shifted their priorities to do research on different aspects of wind and solar energy. Furthermore, greenhouse gas reduction led to Carbon Tax policies for pollution generating units, which boosted the combined efforts at wind and solar energy research as well as their implementation. The DOE, as well as different recovery acts enacted at the state level, emphasize the expectation of an increased level of wind, solar, and other renewable energy sources so that together they will provide 30% of the total U.S. electricity consumed nationwide by 2030. The utilization of sustainable energy sources like wind and solar energy will offer great socioeconomic benefits reductions in power plant emissions and the supply of zero cost electricity.

Large scale wind and solar energy integration to the bulk grid could introduce inevitable challenges to regional transmission and generation systems. The most important challenges for transmission system are the congestion analysis of the grid and planning for transmission expansion to transfer the zero cost generated electricity to different electricity markets. The other big challenge is competition of current generation units in the electricity market. Current generators in the grid based on where they are located want to compete and participate in the electricity markets. However, generators like coal units are generating tons of carbon dioxide. Coming policies regarding carbon tax and adding high level of sustainable sources to the bulk grid force them to retire. This thesis addresses the congestion identification and management, optimization, simulation and analysis of large scale electric power systems in different scenarios for high level of wind and solar energy integration and related transmission expansion issues.

This thesis brings a new method used to study transmission congestions in Western Interconnection of the United States. The process involved Security-Constrained Unit Commitment (SCUC) formulation applying its results for analysis of transmission congestion. The proposed SCUC tool for these analyses is referred to as Power Market Simulator, POMS, which is being developed in the Electrical and Computer Engineering Department of Illinois Institute of Technology. With the help of POMS, all congested branches are shown on a Geographical Information System, GIS, synchronized map. In next step all congested branches are compared with two results; the National Electric Transmission Congestion Study, NETCS published by the U.S. Department of Energy in December 2009; and the annual 2009 report of Transmission Expansion Planning Policy committee, TEPPC, of Western Electricity Coordinating Council, WECC. Moreover, POMS allowed calculation of LMP for the entire WECC which was not considered in the report of NETCS.

This thesis presents results and findings in simulation of the system operation in the Western Interconnection of the United States with the inclusion of large-scale wind and solar power penetration into the grid for year 2030. For this study, a simulator is developed and implemented as a Wind Integration Simulator, WINS, in the Galvin Center for Electricity Innovation at the Illinois Institute of Technology (IIT). In WINS high level wind and solar energy with the forecasted wind and solar time series profiles were added to the bulk grid of WECC. Their impact on different existing types of generation

plants is studied. WINS utilize Security-Constrained Unit Commitment (SCUC) to simulate the wind and solar energy penetration. The bulk system of western interconnection which is coordinated and promoted by WECC and is the second largest bulk grid in the three interconnections of the North America primarily used as a case study for this thesis. High transmission capacities assumed accessible to all generation resources that mean the transmission constraints are relaxed. Moreover, none of the current bilateral contracts for WECC are considered. WINS uses hourly forecasted profiles of the wind and solar energy for an economic dispatch of the units. The production costs, wind and solar power contributions in peak load hours and off-peak load hours are also calculated and studied for this thesis. The sensitivity of the fuel prices, wind turbine power output, load volatility and demand side management as well as carbon tax are analyzed in different possible scenarios.

In order to incorporate large scale of wind and solar energy into a bulk electricity grid footprint, planned transmission expansion showed need to take place. Transmission expansion reduces grid congestion and balances Locational Marginal Prices (LMP). This thesis explores the advancements in high-performance computing and visual analytics of economic-based transmission expansion in the Western Electricity Coordinating Council (WECC). This expansion is based on 2018 and 2029 forecasted data. An advanced congestion analysis is proposed using WINS for optimization, simulation and visualization of the results. It identifies transmission congestions and different area average bus LMP, and expands the transmission system while accommodating large scale wind and solar energy to achieve the Department of Energy's (DOE) renewable energy vision for year 2030. In wind and solar integration studies, WINS applies annual wind energy forecast data as individual generation profile curves for each defined wind and solar farm units in the Security-Constrained Unit Commitment (SCUC) problem. WINS applies the SCUC engine to solve optimization issues caused by network constraints. Results are visualized on the Geographical Information System (GIS) format map. An iterative transmission expansion analysis, based on the average marginal prices for each area, is used to identify the minimum WECC transmission lines required. By using WINS, the transmission congestion and transmission expansion analysis results are visualized on a map of North America.

3) Xiaodong Shi, Survivable Operation of Three Phase AC Drives in Wind Generator Systems, Illinois Institute of Technology, May 2012

Abstract: Recent years have seen significant popularity in the use of wind generators owing to the depletion of natural resources and growing concerns about our environment. However, this development has raised issues concerning reliability of the wind turbine components. Among these faults, failure of current sensors is one of most common fault that can bring the wind generator to a standstill and lead to reduction in power yielded. In addition, unscheduled maintenance often results in longer downtime and causes reduction of wind plant availability especially for those wind turbines located offshore or in remote areas.

This dissertation proposes a survivable drive method to continue to operate the wind turbine in spite of current sensor failure. One of the common control strategies for the optimal of three-phase AC generators is vector control. Therefore, vector control method is implemented in this dissertation for both induction machine and Brushless PMSM. In order to achieve survivability when current sensor fault

happens, a simple and effective method which doesn't rely on current feedbacks is required as a backup control strategy. For this purpose, a state transition control strategy is proposed for an induction machine and a Brushless Permanent Magnet Machine. In addition, a current sensor failure detection method is designed to trigger the transition. Simulation and experimental results have been presented to prove feasibility and demonstrate the effectiveness of the proposed strategy.

4) Yao Da, Novel Fault Diagnostic Technique And Universal Sensor For Permanent Magnet Electric Machines Using Search Coils, Illinois Institute of Technology, May 2012

Abstract: Over the past decade, permanent magnet synchronous machines (PMSMs) have gained significant popularity in industry, such as wind turbines and electric vehicles, owing to their high efficiency, high output power to volume ratio, and high torque to current ratio. In these mission critical applications, an unexpected fault or failure of the machine could lead to very high repair or replacement cost, or even catastrophic system failure. Therefore a robust and reliable health monitoring and fault diagnostic approach is desired, which could help in scheduling preventive maintenance to lengthen their lifespan and avoid machine failure. This dissertation presents a novel multi-faults diagnostic approach using search coils. These search coils are wound around armature teeth, so they typically need to be installed during manufacturing. But its immunity to high frequency harmonics makes it suitable for inverter/rectifier fed motors or generators, such as wind turbines and automotive systems. In addition, this method does not require the knowledge of proprietary constructional details of the machine. Since the electromagnetic flux is directly measured in this method, it provides much more information than any other scheme: the direction of eccentricity and the location of shorted windings. Furthermore, this method is also capable of evaluating the severity of each fault, which is of significant importance in mission critical applications such as automotive, aerospace and military applications. In addition to these uses, the search coils can be used as a universal sensor to estimate phase current or rotor position, which are critical information in a PMSM close-loop control, which allow it to work as a backup sensor for fault tolerant operation. The proposed fault detection scheme and universal sensor concept have been tested under several scenarios with Finite Element Analysis and experimentally validated.

5) Jie Li, Optimal Behavior Modeling and Analysis of Electricity Market Participants, Illinois Institute of Technology, May 2012

Abstract: In restructured electricity power markets, competition among market participants is a key issue of concern for both the ISO (Independent System Operator) and the market participants themselves. This dissertation analyzes the market behavior of both the generation side and demand side participants, and provides solution guidelines for devising effective competition strategies for market players' profit maximization objectives.

Generation side is the most competitive part in the electricity market with the unbundling of generation, transmission and distribution. Acting as self-interested entities, GENCOs (Generation Companies) are seeking effective and computationally efficient methodology for generation resource scheduling, while keeping its financial risks at acceptable levels when constituting bidding strategies. To help GENCOs

achieve such goal, this dissertation propose a game theory based supply function like bidding model to construct the optimal bidding strategies in both energy and ancillary service markets.

On the demand side, demand participation in the electricity market has already been advocated for a long time for its benefit to the entire market and the society as a whole. This dissertation focuses on a specific large electricity consumer type – Internet Data Center (IDC). By analyzing the unique energy consumption pattern for different IDC applications, this dissertation devises effective electric demand management solution, and quantifies the demand response effect of IDC on the electricity market.

6) Yanling Yuan, Load Redistribution Attacks and Protection Strategy in Electric Power Systems, Illinois Institute of Technology, May 2012

Abstract: Electric power systems have evolved over the past century to the largest and the most complex cyber-physical systems. With the development of Smart Grid, cyber security has becoming an area of growing concern. The well functioning of state estimation, which provides faithful estimation of the real-time physical system information based on a large number of distributed meter measurements, is of paramount importance for maintain stable and secure system operation. False data injection attack, which is against state estimation through SCADA network, has recently attracted wide research interest. This paper further develops the concept of load redistribution attack, a special type of false data injection attack. The physical and market impact of load redistribution (LR) attacks are quantitatively analyzed in this thesis.

Since LR attacks can successfully bypass bad data detection and manipulate the state estimation outcome, Security constrained economic dispatch (SCED) based on the false estimated state would lead the system into a false secure and optimal operating state. The physical damaging effects of LR attacks are analyzed thoroughly in this thesis. Based on the damaging effect analysis, two different attacking goals are differentiated from the adversary's perspective, i.e., immediate attacking goal and delayed attacking goal. For the immediate attacking goal, a max-min attacker-defender model is proposed to identify the most damaging immediate LR attack. Different algorithms are used to solve this bi-level optimization problem. For the delayed attacking goal, a tri-level model is proposed and solved to identity the most damaging delayed LR attack. This paper is a first attempt to formalize the physic impact of false data injection attacks on the system operation and control.

Recent research examined the possible economic impact of false data injection attacks against state estimation in electric power market operations. False data injection attacks, by manipulating the state estimation, can manipulate the nodal price of ex-post real-time market. In conjunction with virtual bidding, these integrity attacks can lead to consistent financial profit for the attacker. This thesis further this study by quantifying the economic impact of LR attacks to the market operation of power systems. A convex model is developed under the mechanism of virtual bidding to compute the optimal injection of LR attack and the optimal selection of nodal pairs for virtual power, which gains the most profit from the attackers' perspective.

This thesis investigates the construction of LR attacks against AC state estimation. A practical procedure is proposed to construct an effective LR attack that can bypass the bad data detection (BBD) in AC state estimation, while having great damaging effect to the physical and market operation of power systems.

The quantitative impact analysis of LR attacks provides an in-depth insight on effective attack prevention with limited protection resource budget. This thesis also proposes the theory and criterion of protecting the system from the damage of a specific LR attack, considering the existence of stochastic measurement error. Effective protection strategies can then be designed to defeat the attacker's attempt.

7) Wei Tian, Large-scale Simulation of Electric Power Systems for Wind Integration, Illinois Institute of Technology, July 2011

Abstract: The utilization of wind energy will pose great socioeconomic benefits with reductions in power plant emissions and the supply of zero cost energy; however, large-scale wind energy integration could introduce inevitable challenges to regional transmission systems and hourly system operations. This thesis addresses the congestion identification, simulation and analysis of large-scale electric power systems in different scenarios, large-scale wind energy integration and related transmission expansion issues.

A methodology based on the security-constrained unit commitment (SCUC) is applied to analyze the transmission congestions in the Eastern Interconnection of the United States. The identified congestions are visualized along with the Geographical Information System (GIS) data and compared with the results in National Electric Transmission Congestion Study (NETCS) published by the Department of Energy of the United States in 2006. The study also provides the locational marginal price (LMP) information in the Eastern Interconnection, which is not available in the NETCS report.

This thesis implements a comprehensive simulation and scenario analysis of the Illinois electric power system for the year 2011. Possible scenarios representing electrical load sensitivities to economic growth, fuel price variations, and the impact of carbon cost, are studied.

This thesis presents the hourly simulation results for the large-scale wind energy integration in the Eastern Interconnection of the United States. An hourly unit commitment is applied for the simulation of the economics of wind energy integration in the year 2030. The energy portfolio for supplying the hourly load in 2030 is developed based on wind integration levels. The sensitivities of fuel price, wind energy quantity, load forecast, carbon cost, and load management to the proposed 2030 wind integration are studied.

This thesis identifies transmission congestions and expands the existing transmission system in the Eastern Interconnection of the United States for accommodating a large-scale integration of wind energy. Violated transmission flows which would cause the infeasibility of hourly SCUC are identified. An iterative transmission expansion analysis is implemented to identify the minimum required additions to the Eastern Interconnection for mitigating hourly transmission congestions.

8) Bruno Monnier, Three Dimensional Flow Structures and Turbulence Distribution in an Urban Environment, Illinois Institute of Technology, December 2010

Abstract: Understanding and controlling the dispersion of pollutants and contaminants in urban areas has become a major focus recently. Field measurements, numerical studies, and wind tunnel experiments have increased in number. Specifically, there is a growing need for a spatio-temporal description of such complex flow fields under well-controlled conditions, typically obtained in wind tunnel experiments. The reduced scale model of interest is a 4 by 3 array of cuboid blocks in an experimentally modeled, neutrally stratified, atmospheric boundary-layer. The use of Stereoscopic Particle Image Velocimetry (SPIV) allows for a three-dimensional description of this urban flow. A large amount of SPIV data is collected upstream and in each middle street of the urban environment allowing for a study of the flow evolution from street to street. Valuable information about the flow structures are presented along with the mechanisms responsible for contaminant transport and dispersion. The effects of small incidence angles of the incoming flow with respect to the urban array and the effects of streamwise spacing between streets on the flow characteristics are investigated. A major observation from this work is that a strong channeling effect is observed for incidence angles as small as 4.5◦ and is found to be comparable in strength to that observed in other investigations for much larger angles. A coupling between this channeling effect and the structures responsible for contaminant transport is revealed.

An innovative method using sparse measurements to estimate the continuous temporal evolution of the dominant structures in the flow is investigated. Proper Orthogonal Decomposition is used to obtain a reduced-order representation (ROR) of the flow field. Sparse velocity measurements within the domain serve as input to measurement models that provide an estimation of the ROR of the velocity field. This ROR of the flow field could be regarded as the first that provides a temporal evolution of a spatially well-resolved flow field in a complex geometry. Finally, a linear state-space model is used to describe the continuous temporal evolution of the ROR of the velocity field which is of primary importance with respect to contaminant tracking at the urban scale.

9) Mark E. Carlos, An Analysis of Wind Power Plant Site Prospecting in the Central United States, Southern Illinois University, December 2010

Abstract: Rapid deployment of terrestrial wind power plants (WPPs) is a function of accurate identification of areas suitable for WPPs. Efficient WPP site prospecting not only decreases installation lead time, but also reduces site selection expenses and provides faster reductions of greenhouse gas emissions. Combining conventional predictor variables, such as wind strength and proximity to transmission lines, with nonconventional socioeconomic and demographic predictor variables, will result in improved identification of suitable counties for WPPs and therefore accelerate the site prospecting phase of wind power plant deployment. Existing and under-construction American terrestrial WPPs located in the top 12 windiest states (230 as of June 2009) plus 178 potential countylevel predictor variables are introduced to logistic regression with stepwise selection and a random sampling validation methodology to identify influential predictor variables. In addition to the wind resource and proximity to electricity transmission lines, existence of a Renewable Portfolio Standard, the population density within

a 200 mile radius of the county center, median home values, and farm land area in the county are the four strongest nonconventional predictors (Hosmer and Lemeshowχ 2 = 9.1250, N = 1009, df = 8, p = 0.3319, -2LogLikelihood = 619.521). Evaluation of the final model using multiple statistics, including the Heidke skill score (0.2647), confirms overall model predictive skill. The model identifies the existence of 238 suitable counties in the twelve state region that do not possess WPPs (~73% validated overall accuracy) and eliminates 654 counties that are not classified as suitable for WPPs. The 238 counties identified by the model represent ideal counties for further exploration of WPP development and possible transmission line construction. The results of this study will therefore allow faster integration of renewable energy sources and limit climate change impacts from increasing atmospheric greenhouse gas concentrations.

10) Amin Khodaei, Optimal Transmission Switching in Power System Operation and Planning, Illinois Institute of Technology, December 2010

Abstract: Transmission networks are traditionally considered as fixed assets where market-based changes in transmission states are not considered by power system operators. However, system operators consider changes in transmission states by adjusting the network topology for security purposes. The adjustment in transmission state, known as transmission switching (TS), could mitigate transmission flow violations, manage congestion, enhance power system security and adjust bus voltage levels. TS, as a market tool, could potentially affect power generation dispatch and commitment and improve power system economics.

This dissertation presents the formulations and the methodologies for combining the security as well as the economic features of TS. The TS applications are incorporated into the DC model of security-constrained unit commitment (SCUC) for the day-ahead power system scheduling. The dissertation will also consider the AC solution of SCUC for TS applications. The TS application to the AC network solution will enhance the reactive power flow for mitigating any bus voltage violations. The power system operation results are compared based on the AC and the DC power network solutions and the results are discussed. TS applications are also considered in the security-constrained power system planning in which various network planning options are considered for improving the short-term TS solutions. The TS solutions will improve the real power flow and provide security and the economic feedbacks to the planning module on how the long-term planning alternatives can be improved. The results are discussed and additional recommendations are made for future TS studies in power systems.

11) Shaghayegh Bahramirad, Design and Implementation of Hydrokinetic Run-of-River Turbines, Illinois Institute of Technology, December 2010

Abstract: The restructured electric power system considers load as a constant value and that the forecasted load value should be satisfied under any circumstances. Therefore, the competition was among generators that submit strategic bids to the ISO (independent system operator) to supply the forecasted load. The market clearing price is set by the marginal price of the last accepted generator to satisfy the fixed load. Thus the demand-side has no role in the market clearing and price setting process. Furthermore, price spikes might occur when the demand-side has no role in setting electricity prices, so

generators have no incentive to bid close to their marginal cost which would lead to bids that are much higher than actual generation costs. This behavior would lead to volatile market prices that are far from the perfectly competitive prices. The demand-side participation may reduce the system load during peak periods, which is a more economical way to respond to generation capacity shortages. Using demand-side also mitigates the potential to exercise market power, which is caused by price manipulations of generation companies. The price manipulations mainly occur when the generation schedule is obtained through the minimization of total operating cost, i.e. no load-side participation is considered. An increase in demand-side participation would have benefits for individual consumers and the entire electricity market. Demand-side participation would include distributed generation, on-site storage, and demand response. This dissertation discusses two aspects of demand side participation; distributed generation and demand response. Hydrokinetic energy as an example of distributed generation has been studied. A hydrokinetic turbine has been designed and a sensitivity analysis has been performed with an optimal placement of turbines in a hydrokinetic farm. In addition, demand response in a day ahead market clearing process has been investigated.

12) Cong Liu, Interdependency of Gas and Electricity in Restructured Power Systems, Illinois Institute of Technology, July 2010

Abstract: The electric power generation relies increasingly on the natural gas supply system as additional natural gas-fired power plants are installed in restructured power systems. In this context, the economics and the reliability of electric power and natural gas systems will impact one another. This dissertation addresses the interdependency of electricity and natural gas systems and proposes an integrated approach for the operation and the scheduling of the coupled energy systems.

The dissertation considers combined-cycle gas turbine units (CCGTs) as key elements for linking electric power and natural gas systems and proposes mode and component models for representing CCGTs. The component and mode models are used in scheduling of CCGTs by mixed-integer programming (MIP).

The dissertation proposes two integrated short-term scheduling models. The first one is from the viewpoint of the ISO (Independent System Operator) which proposes a security-based methodology for the unit commitment solution when considering the natural gas transmission system and contracts. The proposed solution applies a Benders decomposition method to incorporate the natural gas transmission feasibility check subproblem in the security-constrained unit commitment (SCUC) solution. The second integrated model considers a joint-operator for the coordinated scheduling of the interdependent electric power and natural gas systems. The integrated operator utilizes an augmented Lagrangian relaxation (LR) based model for the coordinated least-cost allocation of natural gas resources to individual gas loads and generating power plants.

The natural gas flow exhibits remarkable differences with the electric power flow because of the slow response of the former system and storage nature of pipelines. The dissertation also proposes an integrated short-term scheduling model with the transient state natural gas flow formulations which is represented by a group of partial differential equations and nonlinear algebraic equations. In this

dissertation, the implicit finite difference method is adopted to approximate partial differential equations into algebraic difference equations.

13) Saeed Kamalini, Security Constrained Expansion Planning of Fast-Response Units for Wind Integration, Illinois Institute of Technology, July 2010

Abstract: The increasing socio-environmental concerns have persuaded decision makers to support large integrations of WG (Wind Generation) in power systems. Renewable generation is fuel-free and clean which would reduce the cost of electricity production and delivery. On the other hand, WG is volatile and intermittent. WG uncertainties could decrease the expected payoff of a GENCO (Generation Company) and possibly reduce the investors' interest in the WG capacity planning. Chapters 2 and 3 in this study have developed sophisticated mechanisms for proper WG expansions. Chapter 4 discusses that proper long-term and mid-term operations planning which would include the simulation of power system uncertainties could provide a wider range of global options for managing the reliability and economics in power systems operations. From a power system's viewpoint, WG fluctuations could lead to additional system reserve requirements and the adoption of fast-response units for reliability purposes which would result in higher operation costs. Indeed, such conflicts between reliability and economics are inevitable in competitive environments. The optimal capacity expansion of renewable generation and fast-response capacity is the main theme of this dissertation. Chapter 5 discusses that the large integration of WG would also affect other generation resources including fossil fuel based and hydro units. A proper long-term or mid-term operation planning study is required to investigate the coordination of various generation resources.

This dissertation offers algorithms for managing tradeoffs between profitability and reliability. The dissertation discusses assumptions, functions, and methodologies for the large integration of WG that would maximize profits of self-interested GENCOs and enhance the power system operation reliability at the presence of uncertainties.

4.4.2 M.S. Theses

1) Ming Cai, Modeling and Numerical Simulation of Wind Turbine Performance in Rainy Conditions Using a Multiphase Flow Approach, Illinois Institute of Technology, May 2012

Abstract: Wind energy is becoming one of the key renewable sources of energy in the United States and the world due to its environmental and economic advantages and absence of water requirements. The performance of a wind turbine is largely affected by surrounding environments and the total power output of a wind farm is closely related to meteorological phenomena such as rain and icing. Investigating the effects of these phenomena is necessary to improve the design and performance of the wind turbines. In this research, we focused on the study of wind turbine performance in rainy conditions as the stepping stone to the future study of icing. We applied Computational Fluid Dynamics (CFD) technology to investigate the impact of rain on wind turbines. A novel model coupling the Lagrangian

method with the Eulerian method was developed. The rain droplet was tracked in the Lagrangian frame due to its discrete nature, and the film formed on the wind turbine was simulated with the Eulerian Volume of Fluid Model (VOF). The performance loss and impact on the flow field were also studied. Numerical studies have been conducted on 2-Dimensional S809 airfoils and 3- Dimensional Horizontal Axial Wind Turbines (HAWT). The performance loss under heavy rain conditions was observed and the flow field was analyzed. The impact of air moisture content on wind turbine performance was also studied using our 3-D model. Due to the lack of experimental data on wind turbine performance under heavy rain conditions, our coupled two phase flow model was applied to a NACA 64-210 airfoil to compare with the experimental data in rainy conditions. Simulation results using our model showed good agreement with the experimental data.

2) Hirenkumar Patel, Analysis of Mechanical Noise Generation in Wind Turbine Drive Train, Illinois Institute of Technology, May 2012

Abstract: The research work presented here is a part of a project, funded by U.S. Department of Energy to study mechanical noise generated by a wind turbine drive train. In our study a Viryd 8 kW wind turbine drive train test bed located at the Illinois Institute of Technology was used. Various wind speeds and turbulence levels could be simulated using a computer program that is used to control the test bed. Acoustic measurements were carried out using a single microphone and a microphone array. The microphone array was used to localize noise sources on the drive train. Various beamforming algorithms such as FDBF, DAMAS2, CLSC, DAS and TIDY were used to study the noise sources. Qualification experiments using synthetic sources showed that \Clean based on spatial coherence" beamforming algorithm localizes noise sources very accurately for narrowband frequency analysis and TIDY was found to work best for broadband analysis. The resolution of the beamform maps improved for higher frequencies of interest (>700 Hz). The continuous variable planetary (CVP) gearbox, which is a proprietary gearbox by Viryd was used in the drive train to optimize the generator rotational speed. An interesting trend was observed in active power generated for the wind speeds greater than 10 m/s, where the power does not increase significantly as it is regulated at 6000 Watts. CVP speed ratio, ratio of input rotational speed to output rotational speed of CVP, was also found to be having similar effect after wind speed reaches a value of 10 m/s. Vibrations of the drive train test bed were studied using accelerometers. It was observed that the test bed was vibrating at a fundamental frequency of 120 Hz, with harmonics of decreasing amplitude at 240 and 360 Hz. Vibrations in all degrees of motion were found to be occurring at similar frequencies. Acoustic beamforming using a microphone array showed that the test bed was a dominant noise source at the same frequencies. Initially the entire test bed was covered by a Plexi-glass casing for safety reasons. It was found that the glass casing affected the microphone array measurements as the noise produced by the components had no direct path to the array. Almost all the measured noise was refracted through the gaps between the glass casing and the stretcher holding it, that led to spurious microphone array results. As a result of this, the experiments were conducted without the glass casing. It was discovered after the experiments that the glass casing not only affects the path of sound but the amplitude is also affected. The components of the drive train namely gearbox, brake, CVP and generator, were found to be emitting sound at various discrete frequencies ranging from 165 to 3885 Hz. They were also found to be emitting broadband noise, where

gearbox and generator were found to be most dominant noise sources. We were able to separate each noise source on a complex wind turbine drive train that contributed to the mechanical noise generation from a wind turbine.

3) Jing Guo, Control Of Doubly-Fed Induction Generator For Wind Application, Illinois Institute of Technology, May 2012

Abstract: With growing concerns over environmental pollution and globe warming, renewable energy has received considerable attention as an alternative energy resource of electricity production. Because of the immense potential of wind energy on the earth, wind power generation has gained significant popularity over recent years. From this research, it has been concluded that there is a constant need to reduce the size and rating of power electronic converters, improve efficiency of the electromechanical system and make the system more reliable by eliminating the gearbox. This thesis analyzes a doubly fed induction generator (DFIG) drive system for distributed wind generation systems. The structure of a doubly fed induction generator is similar to that of an induction generator. To illustrate the operation principle and control strategy of a DFIG clearly, the fundamentals and control principle of an induction generator have been discussed. For DFIG control, two closed control loops are designed-active power control loop and rotor speed control loop; and they can be switched between each other. By utilizing active power control loop, the output power of the system can be regulated to meet different customer requirements and their dependence on grid electricity can be eliminated, therefore the cost and the power loss on transmission lines can be reduced. On the other hand, by switching to the speed control loop, the system can extract maximum power at different wind speeds, and any extra power can either be stored or sold to the utility for profit. To validate the proposed concept, Finite Element Analysis (FEA) models of a doubly fed induction generator and an induction generator have been built and simulated using the software Magnet®; furthermore, the control systems of these two generators are implemented and simulated in a Matlab/Simulink environment. Finally, a Magnet and Matlab/Simulink co-simulation has been performed for the DFIG. By analyzing the simulation results, the differences between the doubly-fed induction generator and an induction generator have been demonstrated.

4) Udit Goyal, Computational Techniques for Wind Turbine Power Prediction, Illinois Institute of Technology, December 2011

Abstract: Wind energy is expected to play an important role in meeting the ever- increasing energy requirements and reducing our dependence on conventional sources of energy. Wind turbines are broadly classified as horizontal-axis and vertical-axis depending upon the orientation of the rotor shaft relative to the wind direction. Considerable research has been carried out on horizontal-axis wind turbines, which today are sophisticated and efficient electro-mechanical systems. Continuous research and development in areas of electronics, controls and instrumentation aids in the advancements of this technology. From an aerodynamic point of view the Betz limit is known to impose theoretical limit on the power extraction of propellers. The momentum balance equations show that the maximum of 59.3 percent of free-stream energy can be extracted by propellers. This limit, however is not well de fined, particularly when considering diff user and nozzle-augmented wind turbines with local flow accelerations. In this study the actuator disk approach is used to model the momentum loss across a

wind turbine rotor and simulate the Betz limit using Fluent software. This approach is subsequently applied to study the coefficient of performance expected from different user and nozzle-augmented wind turbines. Vertical-axis wind turbines, on the other hand, are still not completely understood in terms of blade aerodynamics and are the focus of various research studies. Large variations in angle of attack and wake evolution downstream of the blade have a time-dependent effect on the blade forces, instantaneous torque and hence the coefficient of power of the turbine. Since Navier-Stokes solutions for vertical- axis wind turbines are expensive and complicated, various low-cost models have been developed based on momentum balance such as single, double and double multiple-streamtube formulations. These models, however, use static lift and drag data for the airfoils as inputs, neglecting the unsteady effects on aerodynamic coefficients. In the present study, an alternative approach based on the panel method is explored further for developing a low-cost computational method for simulating the aerodynamics of vertical-axis wind turbines. At each time step an airfoil is represented as a combination of source and vortex distributions which induce a potential in the flow field. A time-stepping mechanism is implemented satisfying the Kutta and the Kelvin Helmholtz condition for the wake evolution behind the rotating blades. The effect of this vortex evolution on the aerodynamic forces on the airfoil is studied, focusing on the coefficient of performance (Cp) of the blade. Results show a decrease in Cp values till the wake attains a quasi-steady state. A comparison study is performed with other computational models, showing the importance of the wake evolution in time. An optimization of the blade pitch angle is also performed by defining a composite variable pitch function in order to improve the torque and hence the instantaneous power from the blades.

5) Chandrahas Aserkar, Induction Motor Modeling For Electromechanical Dynamic Simulation and Electromagnetic Transient Simulation, Illinois Institute of Technology, December 2011

Abstract: The initial part of this research work focuses on distribution power flow for agent based distribution systems. Power flow analysis is an essential tool for power system planning and operation. Traditionally, most distribution systems are radial or weakly meshed types. Faced with the power markets of today, increasing requirements for reliability and ongoing distributed generation have meant that the structure of the distribution systems has become more complex. Also, with the advent of smart-grid technology, distribution automation and micro-grids, the distribution systems are focusing towards distributed control with the use of smart switches via agents. Thus the need for power flow analysis in such systems becomes more important than before. The forward-backward sweep method is a very popular method for distribution power-flow analysis. But, the traditional forward-backward sweep method focuses on the load flow solution based on the bus-injection to branch-current (BIBC) matrix, which is calculated considering the network topology. For distribution systems focusing on distributed control, the complete distribution network topology is unknown to any one agent and hence the complete BIBC matrix is not formed. Rather, the property of these agents to communicate with each other is exploited to obtain the power flow solution. Here, we focus on altering the network topology based algorithm for forward-backward sweep method so as to make it suitable for agent based distribution systems. The later part of this research work focuses on development of induction motor load models for transient dynamic stability simulators (TS) and electromagnetic transient simulators (EMT), to study the voltage stability of power systems. A Transient Stability simulator runs at a larger

time step and is used to study relatively slower dynamics in the system. On the other hand, an Electromagnetic Transient simulator uses a smaller time step to capture the fast dynamics in the system. A combined TS-EMT simulator attempts to model the bulk of the system as a slowly varying dynamic system and a small portion of the system for which the fast dynamics are to be studied, with an electromagnetic transient model. Load modeling is a very important aspect for studying power system stability. Power system stability is the property of a power system that insures the system remains in electromechanical equilibrium throughout any normal and abnormal operating conditions. It is thus defined as the ability of designated synchronous machines in the system to remain in synchronism with one another following disturbance at various locations in the system. It also indicates the ability of induction motors in the system to maintain electrical torque to carry the load following these disturbances. This research work provides a detailed modeling of the induction motor for electromechanical as well as electromagnetic transient simulations and uses them to study the effects of composite load models on power system voltage stability.

6) Joan Camprubi, Sustainable Stadium: Qatar 2022, Illinois Institute of Technology, July 2011

Abstract: This thesis tries to evaluate in general terms which are the energy needs and concerns for a sustainable soccer field planned to be built for the next 2022 Qatar World Cup. To face the issue about the high temperatures and to reduce the electricity waste and greenhouse effect, several renewable energies such as solar, wind, heat pumps or piezoelectric energies would be taken into account. Some economic concerns and other approximations have been done in order to achieve a general overview of the impact of solar and wind energy to feed the stadiums grid and also make some profits at the same time that geothermal heat pumps can help to decrease air conditioning costs and piezoelectric energy can be tested and included as a future prospective to look after. Moreover is an opportunity to show to the entire world that a sustainable stadium with 8.6MW of solar and 1.6MW of wind power is feasible and Qatar could decrease their oil dependence.

7) Naglaa Elashry, Modeling and Simulation of Wind Power Generation Using Kites, Southern Illinois University, May 2011

Abstract: This thesis presents the modeling and simulation of wind energy generators, denoted as KiteGen, which employ power kites to capture high altitude wind power. A simple kite model is used to describe the system's dynamics. A simple structure for KiteGen is investigated through simulation. The Simscape and SimMechanics toolboxes (under Matlab) are used to develop the simulation model of the system. Linearized model of the system as well as its reduced order models are found using Matlab/Simulink and control toolbox to determine the stability, controllability and observability of the system for the purpose of control design.

8) Emad Elhaji, Impact of Wind Turbine on Power System Voltage Stability, Southern Illinois University, May 2011

Abstract: This thesis discusses the impact of WTGUs on the IEEE 26-bus power system voltage stability. The effect of WTGUs is studied by increasing the real generated power and real and reactive load power by factor (1+delta_lambda), where delta_lambda is incremental in the loading factor until reaching the

voltages on the buses to the point of collapse. The lowest voltage bus in the system is a critical bus that WTGUs will be connected on it. The WTGUs are Farm of wind turbines that are connected to the system. Two types of WTGUs are discussed in this thesis. The first type of WTGU that discus is the fixed speed wind turbine. There are two types of fixed speed wind turbines: pitch angle regulated, and stall regulated. The pitch angle regulated fixed speed wind turbine is focused in this study. The second type of WTGU is the semi-variable speed wind turbine.

The models of WTGUs for both types (pitch angle regulated, and semivariable speed) are used to calculate the reactive power that will be added to the system, but real power is known from manufacture. The real and reactive powers for both WTGUs are dependent on the wind speed, wind turbine characteristic, parameters for induction generator and terminal voltage.

One of the most important parts in this thesis is the sensitivity analysis. The main concept of the sensitivity is the slope of the voltage profile at specific loading factor lambda. In this part, the study is focused on the effect of increasing the real generated power and real and reactive loaded power on the critical bus.

9) Erik Ela, "Advanced Interaction between Day-Ahead Markets and Unit Commitment Methods with High Wind Power Penetrations," ECE Department, Illinois Institute of Technology, May 2010.

Abstract: Recent trends in the power and electrical energy industry have seen tremendous growth in the amount of installed wind power plants for use in power generation. Concerns of climate change and the availability of fossil fuels have stimulated interest in providing increasing amounts of renewable energy. Many countries see wind power as a major contributor to the total renewable energy mix. Wind power plants have a collection of wind turbine generators that convert the power of the wind into electrical energy. The plants can cover vast areas and can have wind speeds that are variable both geographically and temporally. This variability in wind speed that leads to variability in wind power production makes wind power generation a unique source of power generation.

The power system is very complex in nature. When restructuring of the industry began, innovative ways of administering a market had to be thought of so that the laws of economics do not clash with the laws of physics. When the first energy markets were being designed, wind power held a very small fraction of the participants in the market and its unique characteristics were not anticipated. Since wind power has grown in recent years, wind power forecasting has become an essential tool to assist in its integration. This research attempts to step back to see if the current process of integrating wind power and wind power forecasts into the unit commitment and day-ahead markets is efficient. It then evaluates novel ideas from prior research to improve this process and how these new methods could be integrated into the current market structures.

4.5 List of Papers and Reports

4.5.1 Journal Publications

1) Wei Tian, Mohammad Shahidehpour, Zuyi Li, Analysis of 2030 Large-Scale Wind Energy Integration in the Eastern Interconnection Using WINS, The Electricity Journal, Volume 24, Issue 8, October 2011, Pages 71-87

Abstract: A simulation of the 2030 load forecast in the Eastern Interconnection suggests that large-scale wind energy integration will have a major impact on the hourly commitment and dispatch of gas and coal units, especially at off-peak load hours. While fuel price alterations will have major impacts on the system production cost, load variation will have a larger impact and potential carbon costs will have the greatest impact.

2) S. Kamalinia, M. Shahidehpour, and A. Khodaei, "Security-constrained expansion planning of fast-response units for wind integration," Electric Power Systems Research, vol.81, no.1, pp.107-116, January 2011

Abstract: This paper proposes a stochastic expansion planning of fast-response thermal units for the large-scale integration of wind generation (WG). The paper assumes that the wind integration level is given and considers the short-term thermal constraints and the volatility of wind units in the planning of fast-response thermal units. Random outages of generating units and transmission lines as well as hourly load and wind speed forecast errors are modeled in Monte Carlo scenarios. The Monte Carlo simplification methods are introduced to handle large-scale stochastic expansion planning as a tradeoff between the solution accuracy and the calculation time. The proposed security-constrained approach can be used by an ISO or a regulatory body to secure the optimal planning of power systems while the WG integration is increasing. The effectiveness of the proposed approach is demonstrated through numerical simulations.

3) S. Kamalinia and M. Shahidehpour, "Generation expansion planning in wind-thermal power systems," IET Generation, Transmission & Distribution, vol.4, no.8, pp.940-951, August 2010

Abstract: The intermittency and volatility of wind generation (WG) would require additional upward and downward reserves, as well as enhanced ramping capabilities in power systems. This paper investigates the optimal expansion planning of fast-response generating capacity (e.g., gas-fired units) to accommodate the uncertainty of WG. The study utilizes a MIP-based security-constrained unit commitment (SCUC) for analyzing operational and reliability issues related to the proposed optimization problem. Numerical experiments signify the effectiveness of the proposed method.

4) M. Khodayar, M. Barati, and M. Shahidehpour, "Integration of High Reliability Distribution System in Microgrid Operation," IEEE Transactions on Smart Grid, Vol. 3, 2012

Abstract: In this paper, the application of high reliability distribution system (HRDS) in the economic operation of a microgrid is studied. HRDS, which offers higher operation reliability and fewer outages in

microgrids, is applied to looped networks in distribution systems. The microgrid model in this study is composed of distributed energy resources (DER) including distributed generation (DG), controllable loads, and storage. The microgrid would utilize the local DER as well as the main grid for supplying its hourly load economically which is subject to power quality and reliability requirements. The HRDS implemented at Illinois Institute of Technology (IIT) is used as a case study along with the local DER to increase the load point reliability and decrease the operation cost of the IIT microgrid. The availability of distribution lines, main grid supply, and microgrid generation is considered using the Markov chain Monte Carlo simulation in the microgrid scenarios. The reliability indices based on frequency and duration of outages are measured at the microgrid level and the load point level, and the potential system enhancements are discussed for improving the economic operation of the IIT microgrid.

5) A. Khodaei, M. Shahidehpour, "Microgrid-based Co-optimization of Generation and Transmission Planning in Power Systems," IEEE Transactions on Power Systems, Vol. 27, 2012

Abstract: This paper presents an algorithm for the microgrid planning as an alternative to the co-optimization of generation and transmission expansion planning in electric power systems. The integration of microgrids in distribution systems will offer a decentralized control of local resources for satisfying the network reliability and the power quality required by local loads. The objective in this paper is to minimize the total system planning cost comprising investment and operation costs of local microgrids, the co-optimized planning of large generating units and transmission lines, and the expected cost of unserved energy. The cost of unserved energy reflects the cost of load shedding which is added to the objective function for reliability considerations. The microgrid-based co-optimization planning problem is decomposed into a planning problem and annual reliability subproblem. The optimal integer planning decisions calculated in the planning problem will be examined against the system reliability limits in the subproblem and the planning decisions will be revised using proper feasibility cuts if the annual reliability limits are violated. Numerical simulations demonstrate the effectiveness of the proposed microgrid-based co-optimization planning in power systems and explore the economic and reliability merits of microgrid planning as compared to grid-based generation and transmission upgrades.

6) M. Khodayar and M. Shahidehpour, "Stochastic Price-based Coordination of Intra-hour Wind Energy and Storage in a Generation Company," IEEE Transactions on Sustainable Energy, 2012

Abstract: This paper develops a day-ahead price-based scheduling strategy for the coordination of wind and storage units in a generating company (GENCO). The proposed strategy is based on the stochastic price-based unit commitment (PBUC) which considers volatilities in day-ahead intra-hour market prices and wind power generation when scheduling wind and storage units. The proposed approach firms up the hourly sum of wind and storage unit generation, and mitigate potential wind energy imbalance charges for GENCOs in electricity markets. Although the proposed approach applies to any kind of storage, we consider the pumped-storage hydro (PS) unit in this study. Numerical examples illustrate a GENCO's day-ahead coordinated scheduling results for wind and PS units.

7) H. Wu, M. Shahidehpour, and A. Al-Abdulwahab, “Hourly Demand Response in Day-ahead Scheduling for Managing the Variability of Renewable Energy,” IET Journal on Generation, Transmission & Distribution, 2012

Abstract: This paper proposes a stochastic optimization model for the day-ahead scheduling in power systems, which incorporates the hourly demand response (DR) for managing the variability of renewable energy sources (RES). DR considers physical and operating constraints of the hourly demand for economic and reliability responses. The proposed stochastic day-ahead scheduling algorithm considers random outages of system components and forecast errors for hourly loads and RES. The Monte Carlo simulation (MCS) is applied to create stochastic security-constrained unit commitment (SCUC) scenarios for the day-ahead scheduling. A general purpose MILP software is employed to solve the stochastic SCUC problem. Numerical results in the paper demonstrate the benefits of applying DR to the proposed day-ahead scheduling with variable renewable energy sources.

8) A. Khodaei, M. Shahidehpour, L. Wu, and Z. Li, “Coordination of Short-Term Operation Constraints in Multi-Area Expansion Planning,” IEEE Transactions on Power Systems, Vol. 27, 2012

Abstract: This paper presents a comprehensive expansion planning algorithm of generation and transmission components in multi-area power systems. The objective is to minimize the total system cost in the planning horizon, comprising investment and operation costs and salvage values subject to long-term system reliability and short-term operation constraints. The multi-area expansion planning problem is decomposed into a planning problem and annual reliability subproblems. The planning decisions calculated in the planning problem would also satisfy the short-term operation constraints. A detailed model of thermal and hydro units is considered using the mixed-integer programming (MIP) formulation. In addition, a multi-state representation for the expansion planning of renewable energy units is explored. The proposed approach considers customers’ demand response as an option for reducing the short-term operation costs. The planning problem solution is applied to the annual reliability indices subproblems which examine system reliability indices as a post-processor. If the reliability limit is not satisfied, additional reliability constraints will be introduced which are based on the sensitivity of system reliability index to investment decisions. The new reliability constraints are added to the next iterations of the planning problem to govern the revised plan for the optimal expansion. Numerical simulations indicate the effectiveness of the proposed approach for solving the operation-constrained multi-area expansion planning problem of practical power systems.

9) C. Sahin, M. Shahidehpour, I. Erkmen, “Allocation of Hourly Reserve versus Demand Response for Security-Constrained Scheduling of Stochastic Wind Energy,” IEEE Transactions on Sustainable Energy, 2012

Abstract: This paper presents a stochastic method for the hourly scheduling of optimal reserves when the hourly forecast errors of wind energy and load are considered. The approach utilizes the stochastic security-constrained unit commitment (SCUC) model and a two-stage stochastic programming for the day-ahead scheduling of wind energy and conventional units with N-1 contingencies. The effect of

aggregated hourly demand (DR) response is considered as a means of mitigating transmission violations when uncertainties are considered. The proposed mixed-integer programming (MIP) model applies the Monte Carlo method for representing the hourly wind energy and system load forecast errors. A 6-bus, 118-bus, and the Northwest region of Turkish electric power network are considered to demonstrate the effectiveness of the proposed day-ahead stochastic scheduling method in power systems.

10) M. Khodayar, L. Wu, and M. Shahidehpour, "Hourly Coordination of Electric Vehicle Operation and Volatile Wind Power Generation in SCUC," IEEE Transactions on Smart Grid, Vol. 3, No. 3, pp. 1271-1279, Sept. 2012

Abstract: In this paper, the coordinated integration of aggregated plug-in electric vehicle (PEV) fleets and renewable energy sources (wind energy) in power systems is studied by stochastic security-constrained unit commitment (Stochastic SCUC) model, which minimizes the expected grid operation cost while considering the random behavior of the many PEVs. PEVs are mobile and distributed devices with deferrable options for the supply/utilization of energy at various times and locations. The increased utilization of PEVs, which consume electricity rather than fossil fuel for driving, offers unique economic and environmental opportunities, and brings out new challenges to electric power system operation and planning. The storage capability of PEVs could help power systems mitigate the variability of renewable energy sources and reduce grid operation costs. Vehicle-to-grid (V2G) enables PEVs to have bi-directional power flows once they are connected to the grid, i.e., they can either inject power to, and draw power from, the grid which adds further complexity to power system operations. PEVs signify customers' random behavior when considering their driving patterns, locational energy requirements, topological grid interconnections, and other constraints imposed by the consumers. Numerical tests demonstrate the effectiveness of the proposed approach for analyzing the impact of PEVs on the grid operation cost and hourly wind energy dispatch.

11) A. Lotfjou, Y. Fu, and M. Shahidehpour, "Hybrid AC/DC Transmission Expansion Planning," IEEE Transactions on Power Delivery, Vol. 27, No. 3, pp. 1620-1628, July 2012

Abstract: This paper proposes a hybrid algorithm for the AC/DC transmission expansion planning (TEP). The stochastic simulation method would consider random outages of generating units and AC/DC transmission lines as well as load forecast errors. The mixed-integer linear programming problem is decomposed into a master planning problem with integer investment decision variables and subproblems which examine the feasibility of master planning solution and calculate the optimal operation schedule over the planning horizon. The independent system operator (ISO) would utilize the proposed method to select the optimal set of AC/DC transmission lines for satisfying TEP criteria: supplying load forecasts, minimizing investment costs, and optimizing market operations. The proposed set of DC transmission system may use either current source converters (CSCs) or voltages source converters (VSCs). Numerical examples illustrate the effectiveness of the proposed TEP model.

12) L. Abreu, M. Khodayar, M. Shahidehpour, L. Wu, "Risk-Constrained Coordination of Cascaded Hydro Units with Volatile Wind Power Generation" IEEE Transactions on Sustainable Energy, Vol. 3, No. 3, pp. 359-368, July 2012

Abstract: This paper presents a stochastic hourly coordination strategy for wind units and cascaded hydro generation as storage to firm up the hourly dispatch in a generating company (GENCO). The proposed strategy is based on the stochastic price-based unit commitment (Stochastic PBUC) formulation which includes wind energy imbalance charges. The forecast errors of electricity market price and wind speed are simulated with the Monte Carlo method via a scenario approach. The risk-aversion constraints are considered for limiting a GENCO's financial risks when considering uncertain wind power generation. The proposed optimization model is solved by mixed- integer linear programming (MIP) and illustrative examples examine the effectiveness of the proposed risk-based coordination model for optimizing a GENCO's payoff.

13) C. Sahin, M. Shahidehpour, and I. Erkmen "Generation Risk Assessment in Volatile Conditions with Wind, Hydro, and Natural Gas Units" Applied Energy, Vol. 96, pp. 4-11, Aug. 2012

Abstract: This paper studies a generating company (GENCO)'s midterm (a few months to a year) scheduling payoffs and risks in volatile operating conditions. The proposed algorithm considers the integration of intermittent wind units into a GENCO's generation assets and coordinates the GENCO's hourly wind generation schedule with that of natural gas (NG) units (with volatile gas prices) and hydro units (with water inflow forecast) for maximizing the GENCO's payoff. The proposed midterm GENCO model applies market price forecasts to the risk-constrained stochastic price-based unit commitment (PBUC) for calculating the GENCO's risk in energy and ancillary services markets. The proposed PBUC minimizes the cost of a) NG contracts, storage, startup and shutdown, b) startup and shutdown of cascaded hydro units, and c) penalty for defaulting on the scheduled power delivery. Simulation results show that the diversification of generating assets including bilateral contracts (BCs) could enhance the GENCO's midterm planning by increasing the expected payoff and decreasing the financial risk.

14) L. Wu, M. Shahidehpour, and Z. Li, "Comparison of Scenario-Based and Interval Optimization Approaches to Stochastic SCUC," IEEE Transactions on Power Systems, Vol. 27, No. 2, pp. 913-921, May 2012

Abstract: This paper compares applications of scenario-based and interval optimization approaches to stochastic security- constrained unit commitment (Stochastic SCUC). The uncertainty of wind power generation is considered in this study to compare the two approaches, while other types of uncertainty can be addressed similarly. For the simulation of uncertainty, the scenario-based approach considers the Monte Carlo (MC) method, while lower and upper bounds are adopted in the interval optimization. The Stochastic SCUC problem is formulated as a mixed-integer linear programming (MIP) problem and solved using the two approaches. The scenario-based solutions are insensitive to the number of scenarios, but present additional computation burdens. The interval optimization solution requires less computation and automatically generates lower and upper bounds for the operation cost and generation dispatch, but its optimal solution is very sensitive to the uncertainty interval. The numerical results on a 6-bus system and the modified IEEE 118-bus system show the attributes of the two approaches for solving the Stochastic SCUC problem. Several convergence acceleration options are also discussed for overcoming the computation obstacles in the scenario-based approach.

15) A. Khodaei and M. Shahidehpour, “Security-Constrained Transmission Switching with Voltage Constraints,” International Journal of Electrical Power and Energy Systems, Vol. 35, No. 1, pp. 74-82, Feb. 2012

Abstract: Transmission switching (TS) would play a vital role in the security and economics of electric power systems. The application of TS to the AC model of security-constrained unit commitment (SCUC) for the day-ahead scheduling is presented in this paper. The proposed AC model of SCUC with TS would include real and reactive power flow constraints which increase the controllability of base case and contingency solutions with voltage constraints. A general FACTS model is introduced for the reactive power management in SCUC which is based on the power injection model (PIM). A modified Newton-Raphson power flow model is introduced in the proposed SCUC with TS in which line flows are considered as variables. The proposed AC network model is compared with the DC network model (without voltage constraints) for enhancing the power network controllability and minimizing the operation cost. The case studies exhibit the effectiveness of the TS application to SCUC with AC network constraints.

16) A. Khodaei, M. Shahidehpour, and S. Bahramirad, “SCUC With Hourly Demand Response Considering Intertemporal Load Characteristics,” IEEE Transactions on Smart Grid, Vol. 2, No. 3, pp. 564-571, Sept. 2011

Abstract: In this paper, the hourly demand response (DR) is incorporated into security-constrained unit commitment (SCUC) for economic and security purposes. SCUC considers fixed and responsive loads. Unlike fixed hourly loads, responsive loads are modeled with their inter-temporal characteristics. The responsive loads linked to hourly market prices can be curtailed or shifted to other operating hours. The study results show that DR could shave the peak load, reduce the system operating cost, reduce fuel consumptions and carbon footprints, and reduce the transmission congestion by reshaping the hourly load profile. Numerical simulations in this paper exhibit the effectiveness of the proposed approach.

17) L. Wu and M. Shahidehpour, “Optimal Coordination of Stochastic Hydro and Natural Gas Supplies in Midterm Operation of Power Systems,” IET Journal on Generation, Transmission & Distribution, Vol. 5, No. 5, pp. 577-587, May 2011

Abstract: This paper presents a stochastic security-constrained unit commitment (SCUC) model for the optimization of coordinated midterm water and natural gas supplies. The stochastic model considers random outages of system components, load forecast errors, and water inflow uncertainty, which are modeled as scenarios in the Monte Carlo (MC) simulation. Water resources may be used in winter to cover gas unit outages caused by an insufficient gas supply. However, those hydro units may not then be available for peak load shaving in the following summer if the summer happens to be a dry season. Thus, water reservoirs would have to be utilized efficiently throughout the year to provide substantial cost reductions while maintaining the power system reliability. The proposed model also considers the impact of midterm scheduling of water and gas on the power system reliability. Reliability indices are incorporated in the hourly unit commitment problem. The stochastic problem is formulated as a two-stage optimization where the first stage optimizes the short-term water and gas usages and the second

stage considers the midterm schedule. Numerical simulations indicate the effectiveness of the proposed stochastic approach for the optimal scheduling of midterm water and gas usages.

18) C. Liu, M. Shahidehpour, J. Wang, “Coordinated Scheduling of Electricity and Natural Gas Infrastructures with a Transient Model for Natural Gas Flow,” Chaos (American Institute of Physics), Vol. 21, pp. 025102-1 through 025102-12 , May 2011

Abstract: This paper focuses on transient characteristics of natural gas flow in the coordinated scheduling of security-constrained electricity and natural gas infrastructures. The paper takes into account the slow transient process in the natural gas transmission systems. Considering their transient characteristics, natural gas transmission systems are modeled as a set of partial differential equations (PDEs) and algebraic equations. An implicit finite difference method is applied to approximate PDEs by difference equations. The coordinated scheduling of electricity and natural gas systems is described as a bi-level programming formulation from the independent system operator’s viewpoint. The objective of the upper-level problem is to minimize the operating cost of electric power systems while the natural gas scheduling optimization problem is nested within the lower-level problem. Numerical examples are presented to verify the effectiveness of the proposed solution and to compare the solutions for steady-state and transient models of natural gas transmission systems.

19) C. Sahin, Z. Li, M. Shahidehpour, and I. Erkmen, "Impact of Natural Gas System on Risk-Constrained Midterm Hydrothermal Scheduling,” IEEE Transactions on Power Systems, Vol. 26, No. 2, pp. 520-531, May 2011

Abstract: This paper studies the impact of natural gas (NG) contracts and constraints on a GENCO’s midterm risk-constrained hydrothermal scheduling problem. The NG contracts and constraints are modeled as a set of linear equations. The proposed model utilizes the stochastic price-based unit commitment (PBUC). The PBUC hourly solution considers uncertainties of market prices for energy and ancillary services, uncertainties of natural water inflows, and random NG infrastructure interruptions in Monte-Carlo scenarios. Illustrative examples analyze the GENCO’s risk levels when considering midterm schedules for generating units, target payoffs, and usages of water inflow, NG and other thermal resources. Simulation results show that a GENCO’s midterm schedules and financial risks could be impacted significantly with the consideration of NG contracts and constraints.

20) A. Lotfjou, M. Shahidehpour, and Y. Fu, “Hourly Scheduling of DC Transmission Lines in SCUC With Voltage Source Converters,” IEEE Transactions on Power Delivery, Vol. 26, No. 2, pp. 650-660, April 2011

Abstract: This paper presents the modeling of high voltage direct current (DC) transmission systems with voltage source converters (VSCs) in security-constrained unit commitment (SCUC). The impact of VSC-DC transmission system on the economics and the security of integrated AC/DC transmission systems is discussed. The nonlinear AC/DC equations are linearized and the Newton-Raphson method is utilized to solve the linearized network in the base case and contingencies. The SCUC solution will determine the optimal hourly schedule of controllable VSC-DC transmission systems in electricity markets. Numerical examples show the efficiency of the proposed model.

21) C. Liu, M. Shahidehpour, and J. Wang, "Application of Augmented Lagrangian Relaxation to Coordinated Scheduling of Interdependent Hydrothermal Power and Natural Gas Systems," IET Journal on Generation, Transmission & Distribution, Vol. 4, No. 12, pp. 1314–1325 Dec. 2010

Abstract: This paper proposes an optimization model for the coordinated scheduling of interdependent electric power and natural gas transmission systems from a joint operator's viewpoint. The objective is to minimize the coordinated social cost while satisfying network and temporal constraints of the two interdependent systems. The joint operator will coordinate hourly schedules to supply natural gas to loads or generate electric power. We consider the application of LR or augmented LR to relax the coupling constraints of the two systems. The Lagrangian dual is decomposed into the security-constrained unit commitment subproblem with the hydro coordination (SCUC) and the natural gas allocation subproblem. The application of LR for solving the coordinated problem could cause oscillations in the dual solution which is due to the nonconvex characteristics of the coordinated problem represented by integer variables and network constraints. Moreover, with slight changes in multiplier values, the linear cost function of the natural gas well may result in a cycling behavior of the gas well output between its max and min limits. To avoid numerical oscillations and improve the solution quality, the augmented LR with a piecewise linear approximation of quadratic penalty terms and the block descent coordination (BDC) technique are proposed. We consider the 6-bus with 7-node and the 118-bus with 14-node systems to verify that the applicability of the proposed method to the coordinated scheduling of electric power and natural gas transmission systems.

22) A. Khodaei and M. Shahidehpour, Y. Fu, "Transmission Switching in Security-Constrained Unit Commitment," IEEE Transactions on Power Systems, Vol. 25, No. 4, pp. 1937-1945, Nov. 2010

Abstract: Transmission switching (TS) is introduced in security-constrained unit commitment (SCUC) for alleviating transmission violations and reducing operating costs. The SCUC problem is decomposed into the unit commitment (UC) master problem and the TS subproblem. The UC master problem finds the optimal hourly schedule of generating units. The TS subproblem uses this solution for transmission switching to find the optimal dispatch of units when considering network constraints. The TS subproblem also examines contingencies and identifies required changes to the UC master problem solution when contingencies cannot be mitigated in the TS subproblem. To propose a practical TS model, the standing phase angle difference limit is considered and relevant constraints are added to the TS subproblem. The case studies exhibit the effectiveness of the proposed approach.

23) L. Wu and M. Shahidehpour, Y. Fu, "Security-Constrained Generation and Transmission Outage Scheduling with Uncertainties," IEEE Transactions on Power Systems, Vol. 25, No. 3, pp. 1674-1685, Aug. 2010

Abstract: This study presents a stochastic model for the Independent System Operator's (ISO's) optimal coordinated long-term maintenance scheduling of generation units and transmission lines with short-term security-constrained unit commitment (SCUC). Random disturbances of power systems including forced outages of generation units and transmission lines, load forecast errors, and fuel price fluctuations are modeled as scenario trees using the Monte Carlo simulation. Lagrangian relaxation (LR)

is applied to separate the coordinated optimization problem into long-term equipment maintenance (LTEM) and stochastic long-term SCUC (LTSCUC) subproblems. For the stochastic LTSCUC subproblem, scenario bundle constraints are relaxed via LR and the optimization problem is decomposed into deterministic LTSCUC problems. LR is applied to each deterministic LTSCUC to relax long-term fuel and emission limits and decompose the problem into short-term SCUC subproblems. The decomposition is further applied to short-term SCUC subproblems for separating hourly unit commitment and transmission network constraints. The unit commitment is formulated as a mixed-integer programming (MIP) problem and solved by the branch-and-cut method using CPLEX. The outcome of this study includes the hourly scheduling of outages of generation units and transmission lines, which corresponds to the optimal generation unit commitment and dispatch, and transmission flows. The hourly schedules minimize the total cost of operation and maintenance and satisfy long-term and short-term constraints of generation units and transmission network with the inclusion of power system uncertainty. A modified IEEE-118 bus system is used to exhibit the effectiveness of the proposed scheduling approach.

24) A. Khodaei and M. Shahidehpour, S. Kamalinia, "Transmission Switching in Expansion Planning," IEEE Transactions on Power Systems, Vol. 25, No. 3, pp. 1722-1733, Aug. 2010

Abstract: Transmission switching (TS) is introduced to add flexibility to the transmission and generation capacity expansion planning problem. TS could improve the performance of the capacity expansion planning model and reduce the total planning cost. The capacity expansion planning problem is decomposed into a master problem and two subproblems. The master problem utilizes the candidate set for additional generating unit and transmission capacity investments to find the optimal plan throughout the planning horizon. The subproblems use the optimal plan, apply transmission switching to relieve any transmission flow violations, and calculate the optimal dispatch of generating units. The transmission network contingencies are also considered in the subproblems. The case studies exhibit the effectiveness of the proposed expansion planning approach.

25) O. Tor, A. Guven, and M. Shahidehpour, "Promoting the Investment on IPPs for Optimal Grid Planning," IEEE Transactions on Power Systems, Vol. 25, No. 3, pp. 1743-1750, Aug. 2010

Abstract: This paper presents a transmission expansion planning (TEP) model which coordinates investment decisions in monopolistic transmission and decentralized generator sectors. The proposed planning approach gauges transmission congestion and security constraints with respect to transmission investments while promoting investments on independent power produces (IPPs) through incentive payments. The paper includes discussions on incentive mechanisms and prioritization among qualified IPPs for several planning scenarios. Such incentives might be necessary to trigger investments on IPPs earlier than those projected by the decentralized generation system, when the power system security is threatened. The proposed planning approach would optimize the sum of transmission investments, incentive payments to IPPs, and congestion costs along the planning horizon. The case studies illustrate how the proposed planning algorithm could be utilized in order to determine incentive payments to candidate generators when necessary, and prioritize such incentives among multiple IPP candidates.

26) L. Wu and M. Shahidehpour, “A Hybrid Model for Price Forecasting,” IEEE Transactions on Power Systems, Vol. 25, No. 3, pp. 1519-1530, Aug. 2010

Abstract: This paper presents a hybrid time-series and adaptive wavelet neural network (AWNN) model for the day-ahead electricity market clearing price forecast. Instead of using price series, one-period continuously compounded return series is used to achieve more attractive statistical properties. The autoregressive moving average with exogenous variables (ARMAX) model is used to catch the linear relationship between price return series and explanatory variable load series, the generalized autoregressive conditional heteroscedastic (GARCH) model is used to unveil the heteroscedastic character of residuals, and AWNN is used to present the non-linear, non-stationary impact of load series on electricity prices. The Monte Carlo method is adopted to generate more evenly distributed random numbers used for time series and AWNN models to accelerate the convergence. Several criteria such as average mean absolute percentage error (AMAPE) and the variance of forecast errors are used to assess the model and measure the forecasting accuracy. Illustrative price forecasting examples of the PJM market are presented to show the efficiency of the proposed method.

27) L. Wu and M. Shahidehpour, Y. Fu, “Accelerating the Benders Decomposition for Network-Constrained Unit Commitment Problems,” Energy Systems, Vol. 1, pp. 339-376, July 2010

Abstract: This study presents an optimization method by generating multiple strong Benders cuts for accelerating the convergence of Benders Decomposition (BD) when solving the network-constrained generation unit commitment (NCUC) problem. In NCUC, dc transmission network evaluation subproblems are highly degenerate, which would lead to many dual optimal solutions. Furthermore, the classical BD cuts are often low-density which involve only a limited number of decision variables in the master problem. Therefore, the dual optimal solutions and the corresponding Benders cuts are of crucial importance for improving the efficiency of the BD algorithm. The proposed method would generate multiple strong Benders cuts, which are pareto optimal, among candidates from multiple dual optimal solutions. Such cuts would be high-density in comparison with low-density cuts produced by the classical BD. The proposed multiple strong Benders cuts are efficient in terms of reducing the total iteration number and the overall computing time. The high-density cuts may restrict the feasible region of the master unit commitment (UC) problem in each iteration as they incorporate more decision variables in each Benders cut. The multiple strong Benders cuts would accordingly reduce the iteration number and overall computing time. Numerical tests demonstrate the efficiency of the proposed multiple strong Benders cuts method in comparison with the classical BD algorithm and the linear sensitivity factors (LSF) method. The proposed method can be extended to other applications of BD for solving the large-scale optimization problems in power systems operation, maintenance, and planning.

28) C. Liu, M. Shahidehpour, and L. Wu, “Extended Benders Decomposition for Two-Stage SCUC, IEEE Transactions on Power Systems, Vol. 25, No. 2, pp. 1192-1194, May 2010

Abstract: This paper presents the solution of a two-stage security-constrained unit commitment (SCUC) problem. The proposed SCUC model could include integer variables at the second stage. A framework of extended Benders decomposition with linear feasibility and optimality cuts is proposed for the solution

of mixed-integer programming (MIP) problems at both stages. Test results show the effectiveness of the proposed methodology.

29) S. Kamalinia and M. Shahidehpour, "Capacity Adequacy Calculation by Considering Locational Capacity Prices," IET Journal on Generation, Transmission & Distribution, Vol. 4, No. 3, pp. 376-385, Feb. 2010

Abstract: A proper investment mechanism is required in restructured power systems to secure the adequacy of installed capacity by encouraging investments on generation and transmission expansions. In this paper, we propose a locational capacity price (LCP) model along with multi-level load bidding curves, which reflect the effectiveness of the market-based capacity payment and at the same time, prohibits the capacity withholding and the exercising of market power. The purpose of capacity expansion decision is analyzed and compared with three other market design options, i.e., energy only, capacity payment, and installed capacity. The case studies show that the proposed LCP method provides proper investment signals in capacity-constrained locations. The proposed LCP method also provides signals to system operators to alleviate transmission congestions economically using proper operation strategies in power systems.

30) A. Lotfjou and M. Shahidehpour, "Security-Constrained Unit Commitment with AC/DC Transmission Systems," IEEE Transactions on Power Systems, Vol. 25, No. 1, pp. 531-543, Feb. 2010

Abstract: This paper presents the solution of security- constraint unit commitment (SCUC) problem with a detailed representation of high voltage direct current (DC) transmission system with current source converter (CSC). We find an economic operation and control strategy for AC and CSC-DC transmission systems by solving the SCUC problem with AC/DC transmission constraints. The presented model is decomposed into a master problem for the solution of hourly unit commitment (UC) problem and subproblems that examine the security (branch flows and bus voltages) of integrated AC/DC transmission systems. The solution of transmission security check subproblem is based on linear programming (LP) which minimizes AC bus mismatches subjected to AC/DC transmission security constraints. The iterative SCUC solution coordinates the power transfer on the DC transmission system for enhancing the economics and the security of AC transmission system. The numerical tests illustrated the efficiency of the proposed model.

4.5.2 Conference Publications

1) Wei Tian, Zuyi Li, Mohammad Shahidehpour, "Transmission Congestion Analysis in the Eastern Interconnection using POMS," IEEE Power and Energy Society General Meeting, July 2010, Minneapolis, Minnesota.

Abstract: A methodology based on the security-constrained unit commitment (SCUC) is applied to analyze the transmission congestion in the Eastern Interconnection of the United States for 2008 and 2018. The proposed SCUC tool for this study is referred to as the POwer Market Simulator (POMS). The

identified congestions are visualized along with the Geographical Information System (GIS) data and compared with the results published by the U.S. Department of Energy's National Electric Transmission Congestion Study (NETCS) in 2006. The POMS study also provides the locational marginal price (LMP) information in the Eastern Interconnection, which is not available in the NETCS report. The POMS simulation results for representing congested branches and LMPs could be applied to the future transmission expansion planning studies.

2) Ganesh Raman, Mahesh Krishnamurthy, Rakesh C Ramachandran, Clement Pereira, Xiaodong Shi, Yong Jiang, Martin Price, and Matthew Arnold, Test bed for acoustic assessment of small wind turbine drive-trains, Fourth International Meeting on Wind Turbine Noise, Rome, Italy, 12-14 April 2011

Abstract: This paper describes a test facility for acoustic assessment of small wind turbine drive trains. The wind turbine drive train chosen for our facility was that of a 8 kW horizontal axis wind turbine (Viryd 8000). The facility has a drive side and a turbine side. On the drive side, a drive motor is connected through a gearbox to a flywheel that compensates for the absence of the blades. The turbine side includes the entire driveline of the wind turbine. The system can simulate inflow wind speed and turbulence. The system also includes accelerometers and torque sensors. For the acoustic assessment both single microphones and an array of 24 microphones were used. Various beamforming algorithms were used for source localization. These include classical beamforming (FDBF), deconvolution approaches for mapping acoustic sources (DAMAS2), CLEAN based on source coherence (CLSC) and TIDY. The array was calibrated and validated for both coherent and incoherent sources. Acoustic measurements from the fully functional drive train test facility are presented for a few operating conditions. Further tests in the facility will be conducted to assess wind turbine drive train acoustics and vibration for various wind velocities and turbulence levels. The facility will also be used to develop techniques for the minimization of sound and vibration from small wind turbine drive trains.

3) Xiaodong Shi; Serradilla, J.P.; Krishnamurthy, M.; , "A back EMF-based rotor position prediction in Permanent Magnet machines for survivable wind generator systems," IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society , vol., no., pp.778-783, 7-10 Nov. 2010

Abstract: In wind power generators, position information is often required for tracking maximum power point as well as implementing control strategies for the Permanent Magnet (PM) generator. For such a system, failure of position sensor could potentially lead to major fault or require the system to be shut down. This could cause significant economic losses and also require unscheduled maintenance. This paper proposes a new sensorless position estimation approach to track position of the PM machine using the back EMF if the position sensor fails. This technique can also be used to provide initial rotor position for the proper implementation of a fall-back strategy. This technique can also be extended to detect position information at low speeds. Simulation and experimental results have been presented showing the effectiveness the proposed scheme and validate the claims presented.

4) Xiaodong Shi; Krishnamurthy, M.; , "Concept and implementation of a simplified speed control strategy for survivable induction motor drives," Industrial Electronics (ISIE), 2011 IEEE International Symposium on , vol., no., pp.556-561, 27-30 June 2011

Abstract: Induction machine is one of the most widely used machines in residential and industrial applications. Traditional drive methods for induction machines such as vector control usually require complex control routines, fast processing unit and multiple system status feedbacks. The complexity of these methods greatly reduces the reliability of the system since the failure of the sensor or even the drift of system parameters could potentially result in system malfunction. This creates the need for a simple, cost-effective and reliable control strategy as a backup to continue operation of the system in case of failure of current and voltage feedback sensors. In this paper, an effective, yet simple and low-cost state switching control technique is proposed and implemented for a three phase squirrel cage induction machine system. This state switching control operates at two specific duty cycles of PWM which produces phase voltages with different magnitudes across the phase windings. At the same time, the frequency of phase voltages is derived from the reference speed. By switching between these two states, precise speed regulation can be achieved. This new control method makes the controller extremely simple in design and implementation for induction machine. Simulation and experimental results are included in this paper to validate our claims.

5) Yao Da; Xiaodong Shi; Krishnamurthy, M.; , "Health monitoring, fault diagnosis and failure prognosis techniques for Brushless Permanent Magnet Machines," Vehicle Power and Propulsion Conference (VPPC), 2011 IEEE , vol., no., pp.1-7, 6-9 Sept. 2011

Abstract: Over the past few years, many researchers have been attracted by the challenges of electrical machines' fault diagnosis and condition monitoring, which provide early warnings that could help schedule necessary maintenance to avoid catastrophic consequence. With advancements in the use of rare-earth magnets, Brushless Permanent Magnet Machines are widely used in industry recently, which has led to the development of numerous fault diagnosis techniques. Considerable papers have presented reviews and compared condition monitoring and fault diagnosis methods for induction machines, but none for Brushless Permanent Magnet Machines. To make a difference, this paper presents a comprehensive survey of modern research advancements and state-of-the-art in health monitoring, fault diagnosis and prognosis techniques for Brushless Permanent Magnet Machines. The symptoms of each type of fault and the principles of diagnosis process are also described and discussed.

6) Xiaodong Shi; Krishnamurthy, M.; , "A simplified state switching control strategy for survivable variable-speed induction generators," Electric Machines & Drives Conference (IEMDC), 2011 IEEE International , vol., no., pp.182-187, 15-18 May 2011

Abstract: Induction machines are one of the most widely used electric machines in wind power applications. However, the control of an induction generator is complicated if advanced control strategy is employed in order to maximize the performance. Also, the complexity of advanced control strategies and their high demand on hardware and sensors can lower the overall reliability of the generator system and potentially result in system malfunction, leading to unscheduled maintenance and power yield

reduction. In this paper, an effective, yet simple and low-cost state switching control technique is proposed and implemented as a backup control strategy in case of control or sensor failure. This state switching control system is only allowed to operate at two different duty cycles of PWM which produces phase voltages with different magnitudes. At the same time, the frequency of the phase voltages is derived from the reference speed. By switching between these two states, precise speed regulation can be achieved. Owing to its simplicity, the control strategy can be implemented on a low cost FPGA or embedded into existing controllers for use as a backup strategy. In addition since it does not require the use of current sensors, it is very suitable for survivable operation. Simulation and experimental results are included to validate our claims.

7) Nelson, C. C., Cain, A. B., Raman, G., Dougherty, R., Brentner, K. S., and Morris, P. J., “Numerical Studies of Wind Turbine Acoustics,” 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, January 9-12, 2012. DOI: 10.2514/6.2012-6

4.5.3 Manuscripts in Preparation

1) Xiaodong Shi; Krishnamurthy, M.; , "Concept and implementation of a simplified speed control strategy for survivable induction motor drives," submitted to IEEE Transactions on Industrial Electronics.

Abstract: Induction machines are one of the most widely used machines in residential and industrial applications. Traditional drive methods for induction machines, such as vector control, usually require complex control routines, fast processing unit and multiple system status feedbacks. These methods require the use of several current and position sensors for high grade operation. Failure of current sensor or even the drift of system parameters could potentially result in system malfunction. This creates the need for a simple, cost-effective and reliable control strategy as a backup control strategy to continue operation in case of failure of current and voltage sensors. In this paper, an effective, yet simple and low-cost state switching control technique is proposed for a three phase squirrel cage induction machine system. This state switching control system operates at two specific duty cycles of PWM which produces phase voltages with different magnitudes across the phase windings. At the same time, the frequency of phase voltages is derived from the reference speed. By switching between these two states, precise speed regulation can be achieved. This new control method makes the controller extremely simple in design and implementation for induction machine. Simulation and experimental results are included in this paper to validate our claims.

2) Xiaodong Shi; Krishnamurthy, M.; , "Implementation of a Simple Survivable Strategy for Three-Phase Induction Motor Drives with Smooth Control Transition," Submitted to IEEE Transactions on Power Electronics.

Abstract: Continuous operation of electric machines is required in most mission critical applications. Failure of current sensors could lead to catastrophic faults in the absence of immediate maintenance or redundancies, which in turn, could increase cost of the overall system. This paper proposes a technique for survivable operation of three-phase Induction Motor (IM) drives in the event of current sensor failure by switching from vector control to a simplified, novel state switching control with smooth transition strategy. A simple but effective current sensor failure detection mechanism keeps monitoring the conditions of current sensors and can trigger a fault flag if current sensor fails. Simulation and experimental results, including current sensor failure detection, speed and torque response, voltage vector continuity and phase current waveforms, are included to show the effectiveness of the proposed strategy.

3) Wei Tian, Mohammad Shahidehpour, Zuyi Li, Large-scale Analysis of 2018 Wind Energy Integration in the Eastern U.S. Interconnection, Submitted to The Electricity Journal

Abstract: This paper presents the hourly simulation results for the year 2018 with the large-scale wind energy integration in the Eastern Interconnection of the United States. A simulator referred to as WINS (Wind INtegration Simulator) is developed for this annual study. The wind energy integrations in the year 2018 are simulated using the hourly security-constrained unit commitment (SCUC) in WINS. The generation portfolio for supplying the hourly load in 2018 is developed with/without transmission network constraints. The sensitivities to the 2018 wind energy integration are carried out for fuel price, wind energy availability, load growth, carbon cost, and hourly load management strategies. The hourly production cost, generation credit, load payment, levelized congestion cost, LMPs, and wind energy contribution, are calculated and analyzed.

4.5.4 Unpublished Reports

1) Richard Gown, Wind Electrical Generation with a Unique High Magnetic Density Turbine Generator, Dakota Power, October 2011

Dakota Power, LLC (DP) is developing unique electric drive and power generation systems. The DP sub-contract with Illinois Institute of Technology (IIT) provides for the application of DP technology to the generation of electricity from wind power. DP technology provides a non-rare earth power dense alternative for the operation of wind turbines. DP is integrating switched reluctance technologies with other sources of magnetic energy to produce high-performance electrical machines. The DP technology has the potential to provide a lightweight, low-cost wind turbine for residential and light industrial applications.

DP is developing next-generation light weight electric drive systems for military and civilian applications through a Cooperative Agreement with the Army Research Office (ARO). This sub-contract with IIT provides for the application of DP electrical machine technology to the generation of electricity from wind. This report provides a comprehensive summary of the development of DP switched reluctance technology and the potential for its application to the generation of electricity from wind.

The process for the development of DP switched reluctance technology includes the transition of a concept for a machine through design and simulation using advanced FEA software. DP provides commercially developed Maxwell FEA simulation software to validate the potential performance of each proposed design. The optimal design, including the specific geometry, stator winding turns and current, is then fabricated to provide a prototype test machine. The performance of each prototype machine is tested and evaluated through the capabilities of the DP Dynamometer Test Facility (DTF). The resulting performance information is analyzed and incorporated into subsequent developments of the DP switched reluctance technology.

DP has evaluated the potential for switched reluctance technology to provide a non-rare earth direct drive wind turbine. This report includes the development of a switched reluctance machine to validate the performance of DP short path switched reluctance technology for application as residential wind turbines.

DP has developed a Quick Machine software program to support the introduction of switched reluctance technology in the development of wind turbines and other machine applications. The Quick Machine software provides an approximate result as compared to the detailed design produced with hours of computation with the Maxwell FEA software. The QuickMachine software facilitates the application of the principles of switched reluctance technology to the development of residential wind turbines.

This report includes a bibliography of the extensive published studies, papers, and information about the technologies, policies, laws, and regulations for the development of wind turbines. The information for this bibliography has supported the development of switched reluctance technology for the generation of electricity by wind turbines.

2) Ming Cai, Emadoddin Abbasi, and Hamid Arastoopour, “A Report on Wind Energy Research,” Illinois Institute of Technology, October 2011

The objective of this study is to develop a numerical model for assessing and analyzing the performance of a horizontal-axis wind-turbine (HAWT) in the presence of rain droplets under heavy rain conditions using computational fluid dynamics (CFD) for multiphase flow systems.

The CFD was chosen to obtain a comprehensive tool for design, scale-up, and performance evaluation of wind turbines, and also to overcome the lack of experimental data on the performance of wind turbines in rainy conditions. A set of benchmarking CFD simulations was performed, both in two and three dimensions. The simulation results were compared with the available experimental data for single phase flow in the literature to refine our CFD model. Then, the single-phase simulation results were used as a baseline to calculate the impact of rain on the performance of the wind turbine.

By capturing the shape and position of the accumulated water film, we estimated the performance loss caused by the formation of the water film. The results of this study could help designers to minimize the impact of rain on the new generation of wind turbines.

Our future work is geared toward adding the effect of splash back of droplets in our model and considering the effect of surface tension on the water film formation. In addition, we are going to apply our Lagrangian-Eulerian model in a three-dimensional case and calculate the performance of the horizontal-axis-wind-turbine in a heavy rain condition.

3) Greg Rouse, Software Integration for Small Wind Turbine into IIT's Microgrid, Intelligent Power Solutions, LLC, October 2011

In this work, Intelligent Power Solutions, LLC (IPS) assisted IIT with data gathering and software integration of an 8kW Viryd Wind Turbine installed on the main campus. The primary purpose for installing this wind turbine was to increase public awareness of renewable energy technologies and thus the primary objective of this effort was to gather data from the wind turbine and make real time data viewable on campus, something that is not typically available for Viryd Wind Turbine Installations. A secondary objective in this work was to model and predict wind turbine output and compare the predictions to actual wind turbine data. This predictive modeling will be important as wind turbine penetration increases. IIT's existing microgrid provides a unique opportunity to see how local wind turbine generation might affect the microgrid.

Under this project IPS was able to modified IIT's microgrid master control software called the Intelligent Perfect Power Supervisory Controller (IPPSC) software for displaying and reporting wind turbine data and developed graphical user interface screens for displaying this data. These screens will be accessible on campus for user to be able to login and see real time turbine performance data and trends. IPS developed and adapted artificial neural network algorithms for modeling the wind turbine performance. These models are intended to be used for predicting the wind turbine's performance in the future will be important for the operational planning required for integrating wind turbine generation resources within a microgrid.

4) Christopher C. Nelson, Alan B. Cain, Ganesh Raman, Tom Chan, Michael Saunders, Jay Noble, and Robert Engeln, Robert Dougherty, Kenneth S. Brentner, and Philip J. Morris, "Numerical Studies of Wind Turbine Acoustics," Innovative Technology Applications Company, LLC, Illinois Institute of Technology, Tecplot, Inc., OptiNav, Inc., Penn State University, October 2011

Innovative Technology Applications Company, LLC (ITAC) is currently working as part of an Illinois Institute of Technology (IIT) led team to investigate various aspects of wind power generation. ITAC's portion of this work involves the numerical simulation of the flow around wind turbines and investigating the acoustic field associated with the unsteady fluid behavior. This report discusses the progress made in this work, the analysis methods used, and the results obtained.

The current methodology combines the abilities of three different numerical tools to predict the unsteady flow around a wind turbine, the resulting acoustics, and an analysis of the noise sources. The Navier-Stokes equations are solved using the OVERFLOW solver to obtain an unsteady flow field in the vicinity of the turbine. Data from this solution is then fed into the PSU-WOPWOP Ffowcs-Williams Hawkings solver to predict the farfield acoustics. This prediction is used to record sound levels at virtual microphone locations, and this information is fed into the Beamform Interactive software package

which is used to analyze the data using a variety of beamforming methods. This methodology is referred to as the "synthetic array technique" as it uses numerical methods to perform an analysis identical to that used for experimental data from microphone arrays.

5) Ganesh Raman, Mahesh Krishnamurthy, Rakesh C. Ramachandran, Hirenkumar Patel, Localization of Wind Turbine Noise Sources On a 1.5 MW Production Scale Wind Turbine Using a Compact Microphone Array, Illinois Institute of Technology, October 2011

The primary objective of the current work was to study the behavior of various beamforming algorithms and use that understanding to locate various noise sources on a production scale 1.5 MW wind turbine located in a wind farm using a compact microphone array. The sound sources in the wind turbine include both mechanical and aerodynamic noise. The sources on the wind turbine are mostly broadband and are moving sources. The beamforming algorithms were validated in the laboratory using three speakers which could produce both coherent and incoherent noise. The spacing between the three speakers could be changed on a speaker frame. The microphone array was also tested on a moving source. The microphone array was then used to measure the wind turbine noise to locate aerodynamic and mechanical noise sources. Measurements were also made on a small wind turbine drive train simulator. This report includes a detailed discussion of all these experimental results.

6) Candace Wark and Dietmar Rempfer, Engaging Undergraduate Students in Wind Energy Research Through IIT's Interprofessional Project Course (IPRO), Illinois Institute of Technology, October 2011

One of the tasks of this DOE grant (Task 10.0) was to "Engage Undergraduate Students in Wind Energy Research". IPRO 323 was developed in response to this task and is currently in its second semester with plans for continuing on into next year. The overall goal for the students enrolled in IPRO 323 is to develop a methodology for designing and developing building-integrated wind turbine modules so that more urban environments will see wind power as a viable alternate energy source. The project plan that the students' enrolled in the course developed was to investigate designing a surface shape integrated onto the roof and/or facades of buildings to increase the power output of building mounted wind turbines. This goal of course requires the understanding of the fluid dynamics/aerodynamics of wind turbines and also the architectural, social, public, safety and environmental issues associated with integrating wind turbines into urban environments. Therefore the IPRO course will benefit from the experience and knowledge of students enrolled in various academic majors at IIT. Several undergraduate disciplines have representation on the team: Architecture, Mechanical Engineering, Aerospace Engineering, Materials Science and Engineering, Electrical Engineering and Architectural Engineering. This diverse mix of students working on one project provides a unique and interesting learning environment not typical of conventional undergraduate education.

4.6 List of Courses

4.6.1 Undergraduate Courses

A. IPRO 311 – Integration of Plug-in Hybrid Electric Vehicles and Renewable Energy Systems

Illinois Institute of Technology, Fall 2010

The purpose of the research project is to investigate the economic effects of the integration of wind power generation systems and PHEVs. For wind generations it is important to investigate factors that impact the generation of wind, like location of the wind farm, speeds of wind in the specific location, type of turbine and its characteristics. In the case of PHEVs a significant research on driving habits, type of battery and its life will be pursued. The final goal of the research is to determine the effectiveness of the method on lowering the operational cost by analyzing various cases which introduce the use of PHEVs into the power generation system. The results obtained from the research will serve targeted markets including, but not limited to, automotive industry, wind power generation industry, and utility companies. The advancement of alternative energy technology will also benefit the environment.

B. IPRO 323 – Modeling of Building Integrated Wind Turbine Modules

Illinois Institute of Technology, Spring 2011

Being able to adapt cities to include onsite renewable technologies is of vital importance. IPRO 323 hopes to design a device that will reduce the reliance on fossil fuels in urban areas. This device will unite wind energy and high-rise buildings. Building-integrated wind turbine technology is not commonly used at the moment and research and development is required. The goal of IPRO 323 is to effectively integrate wind turbines and buildings with harmony as to not disturb the social and natural environments of the city, and to produce the maximum amount of power possible. This can be done by designing a surface shape to integrate onto buildings that will accelerate the velocity, and thus increase the power output of the wind turbines implemented on the shapes. In IPRO 323, it is not only important to understand the fluid dynamics of wind flow and energy to increase turbine efficiency, but to understand how it can be applied to urban environments and integrated onto current buildings to create architecturally efficient and aesthetically pleasing building-integrated wind turbine modules.

C. ECE 456 – Embedded Control and Mechatronics

Southern Illinois University

Introduction to mechatronic systems, systems modeling and simulation, sensors and actuators, real-time interfacing, DSPs and micro-controllers, analysis of sampled-data systems, z-transform, digital control design techniques, emulation method, direct method, industrial applications. This course is delivered once a year, in spring semester. It has been recently redesigned to introduce model-based control design techniques for embedded mechatronic systems using microcontrollers and Mathworks toolboxes, and has been offered twice a year so far. The course is offered to ECE senior undergraduate and graduate students. However, it is also open to students with appropriate background from other disciplines. In the redesigned course, a number of recorded webinars from Mathworks, on the subject of

modeling and control of wind turbines, have been presented in the lectures to expose the students to wind energy as an alternative energy source and to explore the techniques for modeling and control of turbines for harvesting this energy. The webinars include: (1) Modeling a Wind Turbine Using MathWorks Tools, 53:00 minutes; (2) Designing Pitch and Yaw Actuators for Wind Turbines, 36:00 minutes; (3) Determining Mechanical Loads for Wind Turbines, 34:00 minutes; (4) Designing Control Systems For Wind Turbines, 34:00 minutes. The integration of webinars in some of the class lecture has been received well by the students.

D. ECE 486 – Wind Energy Research Paper

Southern Illinois University

This course is not restricted to ECE students and has been very popular between all students from different disciplines. Upon completion of this course students are supposed to be able to: (1) Understand the energy supply and demand patterns for the United States and the world. Calculate energy consumption based on historic data, and future consumption based on past and predicted growth rates. Know the time until the reserve is depleted. (2) Understand the basic laws and the role of all clean resources of energy, such as, wind, solar, hydro, oceanic, tidal, fuel cell, waste, and clean coal technology. (3) Appreciate the social and economic issues, including public acceptance and economics of all alternative energy sources. Appreciate the role of government regulations and world events on energy utilization. (4) Research and investigate issues related to energy resources of a specific energy source.

E. ECE 495 – Capstone Senior Design Project

Southern Illinois University

This course is designed to teach senior level students about team approach to engineering projects. The students are expected to understand and analyze RFPs (Request for Proposals), identify tasks, develop team organization, and assignment of tasks. In addition as part of their work, they are required to have a work plan and time schedule. The projects must have: feasibility analysis, team approach in engineering projects, understanding and analyzing a request for proposals, identification of tasks, assignment of tasks and team organization, work plan and time scheduling, feasibility analysis and cost-benefit analysis, ethics and professionalism issues related to engineering projects in general and to the specific project assigned, team coordination and documentation of team member efforts, documentation of team communications and the team decision making processes, development, presentation and defense of the final proposal for the assigned project.

4.6.2 Graduate Courses

A. ECE 580 – Elements of Sustainable Energy

Illinois Institute of Technology, Fall 2010

This course covers cross-disciplinary subjects on sustainable energy that relate to energy generation, transmission, distribution, and delivery as well as theories, technologies, design, policies, and integration of sustainable energy. Topics include wind energy, solar energy, biomass, hydro, nuclear energy, and

ocean energy. Focus will be on the integration of sustainable energy into the electric power grid, the impact of sustainable energy on electricity market operation, and the environmental impact of sustainable energy.

B. ECE 581 – Elements of Smart Grid

Illinois Institute of Technology, Fall 2010

This course covers cross-disciplinary subjects on smart grid that relates to energy generation, transmission, distribution, and delivery as well as theories, technologies, design, policies, and implementation of smart grid. Topics include: smart sensing, communication, and control in energy systems; advanced metering infrastructure; energy management in buildings and home automation; smart grid applications to plug-in vehicles and low-carbon transportation alternatives; cyber and physical security systems; microgrids and distributed energy resources; demand response and real-time pricing; and intelligent and outage management systems.

C. ECE 581 – Wind Energy Power Systems

Southern Illinois University

The course introduces graduate students to advanced configurations of wind energy power systems with an in-depth treatment of their control and protection. Wind speed and power relations, basic design of wind energy power systems, synchronous and induction generators, power inverters, generator drives-control modes, interface with the power grid-system modeling, stability, control and protection.

4.6.3 Professional Course

A. Wind Energy Technology, Interconnection & Integration

EnerNex

This course is intended to provide the necessary background for engineers and researchers by addressing various aspects of interconnecting wind power plants into electric power systems. The study course is designed to provide knowledge on the state-of-the-art of wind-technology and wind-integration related issues. The study course will mainly discuss insights on dealing with high wind power penetration levels in North America networks. In addition, a brief summary on the European wind energy performance is also presented. This course is targeted towards power systems engineering and management personnel from utilities, RTOs, ISOs, and ITCs as well as consultants, manufacturers and developers involved with the evaluation and planning of the interconnection and operation of new wind plants. The students and professors who are working in the field of wind energy and technology will also benefit from this study course. This course is divided in 11 sessions which will be covered in 3 days. The sessions will begin at 10.00 AM each day. The duration of each session will be 45 minutes. At the end of each day attendees will be given an opportunity to raise any topics for discussion.

5. Conclusions

The consortium members have developed extensive education and research programs for educating the stakeholders on critical issues related to the wind energy research and development.

The Consortium procured one utility-grade wind unit and two small wind units. Specifically

- The Consortium procured a 1.5MW GE wind unit by working with the world leading wind energy developer, Invenergy, which is headquartered in Chicago, in September 2010. The Consortium also installed advanced instrumentation on the turbine and performed relevant turbine reliability studies. The site for the wind unit is Invenergy's Grand Ridge wind farm in Illinois. Invenergy's extensive experience in the deployment and operation of large numbers of wind turbines in the United States provided guidance to the Consortium for conducting world-class wind energy research and development. Upon the completion of the project, the Consortium has (1) installed the GE ADAPT vibrations system; (2) installed the Lube Oil System Monitoring Sensors; (3) installed associated software and hardware to acquire the data and communicate the information to IIT main campus; (4) installed associate software and hardware to receive the data at IIT main campus, capture the data in a historian, and support the Proficy SmartSignal Software; (5) created a SmartSignal Condition Monitoring model using the OEM standard available sensors plus the additional sensors; (6) installed Vindicator® laser wind sensor (LWS), which is a next generation wind sensor for utility-scale wind turbines. The Consortium commemorated the installation at the July 20, 2011 ribbon-cutting ceremony.
- The Consortium, by working with Viryd Technologies, installed an 8kW Viryd wind unit (the Lab Unit) at an engineering lab at IIT in September 2010 and an 8kW Viryd wind unit (the Field Unit) at the Stuart Field on IIT's main campus in July 2011, and performed relevant turbine reliability studies. The Lab Unit is a "bench top" wind turbine drivetrain system including all components that are in the Field Unit along with additional instrumentation. This "bench top" system is designed for use in experimentation and configured to allow several tests to be conducted and for additional tests to be added in the future. The Field Unit is very similar to the Lab Unit, which enable the Consortium members to run experiments on the Lab unit and then try to validate and correlate data on the actual turbine running in the field. The field installation provides easy access to the machine, as well as helps promote the Consortium's effort in wind and sustainable energy. The operation of the Field Unit is also monitored by the Phasor Measurement Unit (PMU) in the nearby Stuart Building. The PMU provides GPS time stamped voltage and current samples with one phasor sample per cycle (60 samples per sec) and, accordingly, detailed power measurements for the Field Unit.

Researches on turbine reliability included (1) Predictive Analytics to Improve Wind Turbine Reliability; (2) Improve Wind Turbine Power Output and Reduce Dynamic Stress Loading Through Advanced Wind Sensing Technology; (3) Use High Magnetic Density Turbine Generator as Non-rare Earth Power Dense Alternative; (4) Survivable Operation of Three Phase AC Drives in Wind Generator Systems; (5) Localization of Wind Turbine Noise Sources Using a Compact Microphone Array; (6) Wind Turbine Acoustics - Numerical Studies; and (7) Performance of Wind Turbines in Rainy Conditions. Specifically,

- The advanced instrumentation on the 1.5MW wind unit and associated software systems can be used to identify items including yaw control issues, blade pitch control issues, bearing temperature issues, power related issues such as phase imbalance and shorts, nacelle temperature issues, control box temperature issues, and turbine efficiency issues. The advanced instrumentation also provides (1) better indication of bearing health through direct measurement of vibration; (2) direct measurement of the count of metal particulate in the oil system, which is an indication of damage to the gears and is traditionally measured by climbing the tower and taking oil samples; (3) direct measurement of filter differential pressure, which provides an indication of the condition of the oil filter, and additionally, an inexpensive alternative to installing a particulate counter; (4) cooler inlet and outlet temperature, which provides an indication of the health of the cooler (plugging) and the effectiveness of the oil cooler. The SmartSignal EPI*Center software detects, diagnoses, and prioritizes developing mechanical and instrumentation turbine failures. The software analyzes in real time all the data collected in the nacelle and detects and notifies impending problems, allowing owners to focus on fixing problems early and efficiently.
- The intelligent wind sensing technology, the Vindicator® laser wind sensor (LWS) installed on top of the nacelle, determines the wind speed and direction in the undisturbed air 250 meters in front of the turbine. As a result, it can provide the control system with a predictive, three-dimensional view of actual conditions which allows the optimization of wind turbine performance. The optical control system (OCS) is designed to increase turbine performance while maintaining conservative safety requirements. When in OCS control, the system utilizes an advanced laser measurement device to drive the nacelle yaw motors to more accurately align the nacelle with the approaching wind direction. The OCS control architecture is designed to only take control when both the turbine and the OCS are operating well and without any indication of issue. In all situations where either the turbine or the OCS exhibits any cautionary signals, turbine control is returned to the legacy system until these system issues are resolved and the OCS has worked through the Initialize state. This control strategy allows the turbine to maintain all of its current functionality regarding safety monitoring.
- The Dakota Power (DP) technology provides a non-rare earth power dense alternative for the operation of wind turbines. This technology integrates switched reluctance technologies with other sources of magnetic energy to produce high-performance electrical machines. This technology has the potential to provide a lightweight, low-cost wind turbine for residential and light industrial applications. The process for the development of the DP switched reluctance technology includes the transition of a concept for a machine through design and simulation using advanced FEA software. A commercially developed Maxwell FEA simulation software is provided to validate the potential performance of each proposed design. The optimal design, including the specific geometry, stator winding turns and current, is then fabricated to provide a prototype test machine. The performance of each prototype machine is tested and evaluated through Dynamometer Test Facility (DTF). The resulting performance information is analyzed and incorporated into subsequent developments of the DP switched reluctance technology. A

Quick Machine software program has been developed to support the introduction of switched reluctance technology in the development of wind turbines and other machine applications.

- A survivable drive method is proposed to handle the current sensor failure and continue operating the wind turbine when current fault happens. Vector control is implemented and used to control the three-phase AC machine when system is healthy. When current fault happens, a current sensor failure detection mechanism is used to generator a fault signal which can trigger the transition from vector control to a simplified control method. The simplified control method, which is a state transition control, is proposed for induction machine to work as a backup control strategy. Simulation and experimental results have demonstrated the effectiveness of the proposed survivable drive method.
- A major drawback of the use of basic beamformers for localizing the noise sources on a 1.5 MW production wind turbine is that requires a large array spread over a large area serves. The propsoed idea was to use a compact microphone array along with advanced beamforming to locate the wind turbine noise sources. The results of the initial calibration of the array provided the knowledge of how various beamforming algorithms behave on exposure to different types on noise sources. From the results of actual wind turbine measurements, it was evident that the compact microphone array was effectively able to separate various noise sources, both mechanical and aerodynamic, produced by the wind turbine. The results from the GE 1.5 MW wind turbine show the potential of the microphone array by effectively separating the blade tip vortex noise, the nacelle mechanical noise, and the yaw motor noise (a narrow band source). The results from the Viryd 8kW wind turbine drive train simulator show that the use of the microphone array could separate the mechanical noise in the nacelle to its particular components such as the gearbox, cooling fan and the generator.
- Numerical simulation of the flow around wind turbines was performed for investigating the acoustic field associated with the unsteady fluid behavior. Numerical studies enable a full acoustic analysis of the flow around an operational wind turbine. The OVERFLOW code solves the unsteady Navier-Stokes equations to predict the acoustic near-field. The near-field data is used by the PSU-WOPWOP Ffowcs-Williams Hawking solver to propagate the acoustic field to the farfield. Farfield data is then recorded at locations corresponding to a microphone array, and this data is processed using the Beamform Interactive analysis software.
- A numerical model was developed for assessing and analyzing the performance of a horizontal-axis wind-turbine (HAWT) in the presence of rain droplets under heavy rain conditions using computational fluid dynamics (CFD) for multiphase flow systems. Initially a set of single-phase benchmarking CFD simulations was performed in 2-D and 3-D and the results were compared with the available experimental data in the literature to refine the CFD model. Then, the single phase simulation results were used as a baseline to calculate the impact of rain on the performance of the wind turbine. To capture the water film formation over the airfoil, a new coupled Lagrangian-Eulerian approach was employed. The performance loss caused by the formation of the water film was estimated by capturing the shape and position of the accumulated water film. The results of this study could help designers to minimize the impact of rain on the new generation of wind turbines.

Researches on wind integration included (1) Analysis of 2030 Large-Scale Wind Energy Integration in the Eastern Interconnection; (2) Large-scale Analysis of 2018 Wind Energy Integration in the Eastern U.S. Interconnection; (3) Integration of Non-dispatchable Resources in Electricity Markets; (4) Integration of Wind Unit with Microgrid. Specifically,

- A comprehensive large-scale wind energy integration analysis is considered which is based on the 2030 load forecast in the Eastern Interconnection of the United States. This study is performed using a software called WINS. In this study, transmission constraints are not considered when studying the wind energy portfolios. The wind energy integration is studied based on the capacity factors of potential wind sites. Wind energy contributions to peak/off-peak annual production costs are studied based on the WINS simulation results. The sensitivity of fuel costs, wind energy production, hourly loads, carbon costs, and load management are analyzed in the wind energy integration Scenarios. The results of the study suggest that large-scale wind energy integration will have a major impact on the hourly commitment and dispatch of gas and coal units, especially at off-peak load hours. While fuel price alterations will have major impacts on the system production cost, load variation will have a larger impact and potential carbon costs will have the greatest impact.
- A comprehensive large-scale wind energy integration analysis is implemented based on the 2018 load forecast in the Eastern Interconnection of the United States. This study is performed using a software called WINS. The wind energy integration with/without transmission constraints are studied and analyzed. The sensitivity of fuel price, wind energy production, load, carbon cost, and load shedding are implemented to study the impact of volatility of major parameters on the WINS simulation results. 19 Scenarios are studied and analyzed. The main observations based on the simulations are listed as follows: (1) Production cost is more sensitive to transmission constraints than to wind energy integration; (2) The location of wind energy integration could have an impact on the wind energy dispatch in the hourly generation portfolio; (3) The addition of wind generation units at certain locations in the Eastern Interconnection may cause additional transmission congestion; (4) In 2018, the replacement of coal units by wind energy at certain locations could mitigate transmission congestion; (5) Wind energy is often available and can replace fossil energy at off-peak load hours. During certain seasons when wind is unavailable, wind energy supply could be replaced by fossil energy; (6) In 2018, wind energy is transmitted mostly at 500kV, 345kV, and 230kV transmission levels while the 765kV transmission is utilized less by wind generation units; (7) Higher costs for gas and oil will result in additional transmission congestion as power systems try to use cheaper coal units located centrally in fewer geographical spots. Such limited utilizations of centrally located resources may also limit the available dispatch of wind generating units; (8) Higher levels of wind energy integration could result in higher levelzied congestion costs when wind generation units, located at few geographical spots, try to supply a significant level of load; (9) Carbon cost demonstrates the highest impact on the 2018 simulation results. Higher carbon costs will be instrumental in mitigating the regional transmission congestion in the Eastern Interconnection; (10) Load forecast uncertainty will have a larger impact on the 2018 simulation results as compared to fluctuations in fuel prices or possible levels of wind energy integration; (11) The levelized

congestion cost may not increase monotonically with higher levels of bus loads; (12) Peak load shaving will have a major impact on the commitment and dispatch of gas units because peak loads are mostly supplied by such units. The WINS simulation results shows that lowering the hourly volatility of load profile by introducing smart grid, additional distribution automation for the utilization of demand response, and the large-scale integration of wind energy and storage could lower the transmission congestion and improve the economics and the optimal operation of power systems in the Eastern Interconnection of the United States.

- The electricity market structure, involving generally a pool, a futures market and a bilateral trading floor, was designed before the large integration of non-dispatchable sources, particularly wind power. There is a need to address the suitability of the current electricity market structure for producers relying on non-dispatchable energy sources. Considering the intrinsic variability and uncertainty of the production level of non-dispatchable sources, appropriate changes in the current market structure are needed to adapt such structure to an increasingly non-dispatchable generation mix. To efficiently integrate non-dispatchable production, this study presented the questions below regarding market design and organization need to be answered: (1) Which is the most appropriate time framework to clear short-term electricity markets? Is it a day-ahead horizon as today, or a shorter one? (2) Should the algorithms to clear such markets be deterministic or stochastic? How should prices be derived? (3) How much reserves should be scheduled to cope with the variable and uncertain nature of renewable non-dispatchable producers? Who should pay for such reserves? (4) How the transmission infrastructure should be expanded and operated to avoid bottlenecks that hider the integration of renewable non-dispatchable resources?
- IIT's existing microgrid provides a unique opportunity to see how local wind turbine generation might affect the microgrid. The microgrid master controller requirements for wind integration are investigated and pertain mostly when the microgrid is operating in island mode. The summarized list of microgrid master control requirements are: (1) Make short term on long term predictions of wind output and ramp rates; (2) Make adjustments to the microgrid reserve power requirements when operating in island mode; (3) Be able to curtail wind power when wind intermittency and ramp rates as required to ensure the microgrid's power reliability and safety; (4) Monitor distribution circuit power flows and curtail wind power if necessary to reduce over loading.

The education and outreach activities on wind energy included (1) Wind Energy Training Facility Development; (2) Wind Energy Course Development; (3) Wind Energy Outreach. Specifically,

- To fulfill the mission on workforce training and education, the Consortium erected a permanent facility at IIT for Workforce Training and Education on Sustainable Energy and Smart Grid. IIT secured funds from the State of Illinois to renovate the 16,000 sqft of space for establishing the facility. This project provided funds to furnish the facility with the state-of-the-art equipment to offer a world-class training and education on sustainable energy at IIT. The facility has provided and will continue to provide training on sustainable energy to various sectors including power

industry employees, union workers, high school teachers, the public, and students through instructor-led and internet-based training courses.

- Undergraduate students were engaged in the research on wind energy. The Interprofessional Project (IPRO) “Integration of Plug-in Hybrid Electric Vehicles and Renewable Energy Systems” at IIT engaged undergraduate students to investigate the economic effects of the integration of wind power generation systems and Plug-in Hybrid Electric Vehicles (PHEVs). The IPRO “Modeling of Building Integrated Wind Turbine Modules” at IIT engaged undergraduate students to develop a methodology for designing and developing building-integrated wind turbine modules so that more urban environments will see wind power as a viable alternate energy source. The Capstone Senior Design Project at Southern Illinois University (SIU) is designed to teach senior level students about team approach to engineering projects. The students were asked to create a model of a 3-phase power generation and distribution system including residential, commercial, industrial, coal-fired generation, and wind generation. The students were to understand and analyze RFPs (Request for Proposals), identify tasks, develop team organization, and assignment of tasks. A Wind Energy Research Course was also offered at SIU to introduce the concept of Clean Energy Resources. The course is not restricted to ECE students and has been very popular between all students from different disciplines.
- Graduate Courses in Wind Energy were developed and offered at both IIT and SIU. The course “Elements of Sustainable Energy” at IIT covers cross-disciplinary subjects on sustainable energy that relate to energy generation, transmission, distribution, and delivery as well as theories, technologies, design, policies, and integration of sustainable energy. Topics include wind energy, solar energy, biomass, hydro, nuclear energy, and ocean energy. Focus was on the integration of sustainable energy into the electric power grid, the impact of sustainable energy on electricity market operation, and the environmental impact of sustainable energy. The course “Elements of Smart Grid” at IIT covers cross-disciplinary subjects on smart grid that relates to energy generation, transmission, distribution, and delivery as well as theories, technologies, design, policies, and implementation of smart grid. Topics include: smart sensing, communication, and control in energy systems; advanced metering infrastructure; energy management in buildings and home automation; smart grid applications to plug-in vehicles and low-carbon transportation alternatives; cyber and physical security systems; microgrids and distributed energy resources; demand response and real-time pricing; and intelligent and outage management systems. The course “Wind Energy Power Systems” at SIU introduces graduate students to advanced configurations of wind energy power systems with an in-depth treatment of their control and protection. Topics include wind speed and power relations, basic design of wind energy power systems, synchronous and induction generators, power inverters, generator drives-control modes, interface with the power grid-system modeling, stability, control and protection.
- A Short Course on “Wind Energy Technology, Interconnection and Integration” was developed to provide an introduction to the underlying technology of wind turbine generators and wind power plants, how they are modeled for power system analysis purposes for planning and operating studies, and an introduction to using actual models in simulation programs. This course is targeted towards power systems engineering and management personnel from

utilities, RTOs, ISOs, and ITCs as well as consultants, manufacturers and developers involved with the evaluation and planning of the interconnection and operation of new wind plants. The students and professors who are working in the field of wind energy and technology will also benefit from this study course.

- IIT's Center for Electricity Innovation hosted the 2010 meeting of the Consortium members On September 30, 2010 and the 2011 meeting on July 19, 2011 on IIT's main campus in Chicago. Ribbon Cutting Events were held to commemorate the installation of the 1.5MW GE Wind Unit and the 8kW Viryd Wind Unit (the Field Unit) at the 2011 meeting.
- IIT's Center for Electricity Innovation hosted the first Great Lakes Symposium on Smart Grid and the New Energy Economy on October 18-19, 2011 and the second on September 24-26, 2012 on IIT's main campus in Chicago. The Symposium featured keynote and plenary sessions, technical presentations, and tutorials by international experts on smart grid and renewable energy applications. The Symposium is a one-of-a-kind event that breaks new ground in smart grid and renewable energy design and development and showcases smart grid and renewable energy best practices from around the country along with new technologies and ideas that are spurring innovation, growing state economies, reducing emissions and empowering consumers to conserve and save. Participants had the opportunity to engage thought leaders on key policy questions, identify investment and job creation opportunities, and learn about projects already underway.

6. Recommendations

The Consortium would like to make the following recommendations based on the research and development performed in this project.

- While current turbine designs are based on unitary blades that account for the span-wise (radially) differences of flow and moment with taper and twist, those designs are based on the assumption of a uniform flow field perfectly normal to the plane of the blade rotation. In fact, as a result of spatial and temporal wind speed and direction variations, the flow field at any point in time is not truly uniform in the radial direction. Even informed individual blade pitch control has to select a best compromise angle of attack for the entire blade length and does not have the ability to handle span-wise flow differences. With real-time spatial wind speed and direction data from a laser sensor, high response rate aerodynamic devices along the blade span could be actuated to correspond to local relative wind. This could be implemented using various flaps, jets, or tabs as developed for aircraft wings or rigid sails. Combined with the other control advances, this stage represents an optimization of active controls. Ever-increasing sophistication is projected for wind turbine sensors and controls with resultant step-wise increases in efficiency and reductions of undesirable stresses. Wind turbine control practice can begin to catch up to university research and aerospace now that forward-looking laser wind sensors can provide the needed wind accuracy, timeliness, data rates, and spatial mapping. It is time for the wind energy industry to start gaining the power performance and stress reduction advantages.
- The DP technology represents next-generation light weight electric drive systems for military and civilian applications. The same DP electrical machine technology can be applied to the generation of electricity from wind. The DP technology provides a non-rare earth power dense alternative for the operation of wind turbines by integrating switched reluctance technologies with other sources of magnetic energy to produce high-performance electrical machines. The DP technology has the potential to provide a lightweight, low-cost wind turbine for residential and light industrial applications.
- A survivable drive method can be used to handle the current sensor failure and continue operating the wind turbine when current fault happens. Vector control is implemented and used control the three-phase AC machine when system is healthy. When current fault happens, a current sensor failure detection mechanism is used to generator a fault signal which can trigger the transition from vector control to a simplified control method. A simplified control method—state transition control can work as a backup control strategy for induction machine.
- The compact microphone array can be used to separate various noise sources, both mechanical and aerodynamic, produced by the wind turbine. Various beamforming algorithms can be used to locate the noise sources on a wind turbine with a compact array. This demonstrates the potential of the microphone arrays in the future of wind turbine noise management. This tool can be further used to investigate the different types of aerodynamic noise that arise on the blade such as the blade tip noise and the trailing edge noise. This could provide valuable information on modifying the blade configuration to further reduce the aerodynamic noise. One other possible application for the microphone array is to use them as a health monitoring tool for the wind turbine.

- A full acoustic analysis of the flow around an operational wind turbine can be enabled by assembling several components. The OVERFLOW code can be used to solve the unsteady Navier-Stokes equations to predict the acoustic near-field. The near-field data can be used by the PSU-WOPWOP Ffowcs-Williams Hawking solver to propagate the acoustic field to the farfield. Farfield data can be then recorded at locations corresponding to a microphone array and processed using the Beamform Interactive analysis software.
- A coupled Lagrangian-Eulerian approach can be employed to capture the water film formation over the airfoil. The performance loss caused by the formation of the water film can be estimated by capturing the shape and position of the accumulated water film. The results could help designers to minimize the impact of rain on the new generation of wind turbines. Future work can be geared toward adding the effect of splash back of droplets in the model and considering the effect of surface tension on the water film formation. In addition, the Lagrangian-Eulerian model could be applied in a three-dimensional case and calculate the performance of the horizontal-axis-wind-turbine in a heavy rain condition.
- The WINS software can be applied to perform a comprehensive large-scale wind energy integration analysis with/without transmission constraints. The sensitivity analyses of fuel price, wind energy production, load, carbon cost, and load shedding should be implemented to study the impact of volatility of major parameters on the simulated wind integration results.
- The electricity market structure, involving generally a pool, a futures market and a bilateral trading floor, was designed before the large integration of non-dispatchable sources, particularly wind power. There is a need to address the suitability of the current electricity market structure for producers relying on non-dispatchable energy sources. Considering the intrinsic variability and uncertainty of the production level of non-dispatchable sources, appropriate changes in the current market structure are needed to adapt such structure to an increasingly non-dispatchable generation mix. To efficiently integrate non-dispatchable production, the following questions regarding market design and organization need to be answered: (1) Which is the most appropriate time framework to clear short-term electricity markets? Is it a day-ahead horizon as today, or a shorter one? (2) Should the algorithms to clear such markets be deterministic or stochastic? How should prices be derived? (3) How much reserves should be scheduled to cope with the variable and uncertain nature of renewable non-dispatchable producers? Who should pay for such reserves? (4) How the transmission infrastructure should be expanded and operated to avoid bottlenecks that hider the integration of renewable non-dispatchable resources?
- The impact of wind turbine generation on microgrid operation should be considered especially when the microgrid is operating in island mode. A list of microgrid master control requirements are: (1) Make short term on long term predictions of wind output and ramp rates; (2) Make adjustments to the microgrid reserve power requirements when operating in island mode; (3) Be able to curtail wind power when wind intermittency and ramp rates as required to ensure the microgrid's power reliability and safety; (4) Monitor distribution circuit power flows and curtail wind power if necessary to reduce over loading.

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Appendices

Appendix A: Project Summary Presentation

- Mohammad Shahidehpour, "A World-Class University-Industry Consortium for Wind Energy Research, Education, and Workforce Development," 2012.

Appendix B: Grand Ridge Wind Unit Video Clip

Appendix C: Journal and Conference Publications

1) Wei Tian, Mohammad Shahidehpour, Zuyi Li, Analysis of 2030 Large-Scale Wind Energy Integration in the Eastern Interconnection Using WINS, The Electricity Journal, Volume 24, Issue 8, October 2011, Pages 71-87
2) S. Kamalinia, M. Shahidehpour, and A. Khodaei, "Security-constrained expansion planning of fast-response units for wind integration," Electric Power Systems Research, vol.81, no.1, pp.107-116, January 2011
3) S. Kamalinia and M. Shahidehpour, "Generation expansion planning in wind-thermal power systems," IET Generation, Transmission & Distribution, vol.4, no.8, pp.940-951, August 2010
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5) A. Khodaei, M. Shahidehpour, "Microgrid-based Co-optimization of Generation and Transmission Planning in Power Systems," IEEE Transactions on Power Systems, Vol. 27, 2012
6) M. Khodayar and M. Shahidehpour, "Stochastic Price-based Coordination of Intra-hour Wind Energy and Storage in a Generation Company," IEEE Transactions on Sustainable Energy, 2012
7) H. Wu, M. Shahidehpour, and A. Al-Abdulwahab, "Hourly Demand Response in Day-ahead Scheduling for Managing the Variability of Renewable Energy," IET Journal on Generation, Transmission & Distribution, 2012
8) A. Khodaei, M. Shahidehpour, L. Wu, and Z. Li, "Coordination of Short-Term Operation Constraints in Multi-Area Expansion Planning," IEEE Transactions on Power Systems, Vol. 27, 2012
9) C. Sahin, M. Shahidehpour, I. Erkmen, "Allocation of Hourly Reserve versus Demand Response for Security-Constrained Scheduling of Stochastic Wind Energy," IEEE Transactions on Sustainable Energy, 2012
10) M. Khodayar, L. Wu, and M. Shahidehpour, "Hourly Coordination of Electric Vehicle Operation and Volatile Wind Power Generation in SCUC," IEEE Transactions on Smart Grid, Vol. 3, No. 3, pp. 1271-1279, Sept. 2012

11) A. Lotfjou, Y. Fu, and M. Shahidehpour, “Hybrid AC/DC Transmission Expansion Planning,” IEEE Transactions on Power Delivery, Vol. 27, No. 3, pp. 1620-1628, July 2012
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14) L. Wu, M. Shahidehpour, and Z. Li, “Comparison of Scenario-Based and Interval Optimization Approaches to Stochastic SCUC,” IEEE Transactions on Power Systems, Vol. 27, No. 2, pp. 913-921, May 2012
15) A. Khodaei and M. Shahidehpour, “Security-Constrained Transmission Switching with Voltage Constraints,” International Journal of Electrical Power and Energy Systems, Vol. 35, No. 1, pp. 74-82, Feb. 2012
16) A. Khodaei, M. Shahidehpour, and S. Bahramirad, “SCUC With Hourly Demand Response Considering Intertemporal Load Characteristics,” IEEE Transactions on Smart Grid, Vol. 2, No. 3, pp. 564-571, Sept. 2011
17) L. Wu and M. Shahidehpour, “Optimal Coordination of Stochastic Hydro and Natural Gas Supplies in Midterm Operation of Power Systems,” IET Journal on Generation, Transmission & Distribution, Vol. 5, No. 5, pp. 577-587, May 2011
18) C. Liu, M. Shahidehpour, J. Wang, “Coordinated Scheduling of Electricity and Natural Gas Infrastructures with a Transient Model for Natural Gas Flow,” Chaos (American Institute of Physics), Vol. 21, pp. 025102-1 through 025102-12 , May 2011
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29) S. Kamalinia and M. Shahidehpour, “Capacity Adequacy Calculation by Considering Locational Capacity Prices,” IET Journal on Generation, Transmission & Distribution, Vol. 4, No. 3, pp. 376-385, Feb. 2010
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34) Xiaodong Shi; Krishnamurthy, M.; , "Concept and implementation of a simplified speed control strategy for survivable induction motor drives," Industrial Electronics (ISIE), 2011 IEEE International Symposium on , vol., no., pp.556-561, 27-30 June 2011
35) Yao Da; Xiaodong Shi; Krishnamurthy, M.; , "Health monitoring, fault diagnosis and failure prognosis techniques for Brushless Permanent Magnet Machines," Vehicle Power and Propulsion Conference (VPPC), 2011 IEEE , vol., no., pp.1-7, 6-9 Sept. 2011
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