Final Report

Project Title: Kansas Wind Energy Consortium

Covering Period: July 1, 2010 – September 30, 2015
Date of Report: December 31, 2015

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Award Number: DE-EE0000555

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Project Objective: This project addresses both fundamental and applied research problems that will help with problems defined by the DOE "20% Wind by 2030 Report". In particular, this work focuses on increasing the capacity of small or community wind generation capabilities that would be operated in a distributed generation approach.

Background: A consortium (KWEC – Kansas Wind Energy Consortium) of researchers from Kansas State University and Wichita State University aims to dramatically increase the penetration of wind energy via distributed wind power generation. We believe distributed generation through wind power will play a critical role in the ability to reach and extend the renewable energy production targets set by the Department of Energy. KWEC aims to find technical and economic solutions to enable widespread implementation of distributed renewable energy resources that would apply to wind.

Status: All tasks have been completed and under budget.

Task 1.0 Non-contact instrumentation for vibration measurement and damping

The initial effort was to develop a non-contact vision-based measurement system to characterize the cyclic torque fluctuations which fatigue turbine blades, bearings, gearboxes and towers and reduce the long term economic viability of wind generators. When coupled with traditional strain gauges, the data captured from this instrumentation will validate vibration models and provide feedback for novel control schemes that mitigate the deleterious effects of cyclic stresses on system reliability. Cyclic stresses in wind turbines arise from many factors including turbulence, wind-speed gradient with height, tower shadow, grid connection fluctuations, and the harmonics of the generator itself. Non-contact instrumentation technology permits analysis of various wind generators both large and small as they are developed without requiring extensive modifications to retrofit sensors.

The key tasks of this effort were:

a. Investigate the robustness of the vibration absorber to uncertainty in rotor torsion measurements.
b. Develop a permanent magnet synchronous generator model for use in in the NREL FAST model with the 5 MW turbine. Add this generator model to the FAST model.
c. Examine the torsional vibration absorber for the cases of steady wind, time varying wind, and turbulent wind using the FAST software.
d. Conduct experimentation of determining the influence of using blade pitch to quiet the bending moment vibrations in the rotor.

Below is a summary of the results for this task.

Permanent Magnet Generator Model and Controller for 5 MW Turbine

The generator model used in this work is a PMSG. The generator can be modeled using phase related quantities, however, a more efficient representation is to use direct and quadrature reference frame theory. The three phase permanent magnet synchronous generator is transformed into a direct – quadrature (DQ) model because the balanced three phase quantities can be simplified into two variables pertaining to the direct and quadrature axes. The inputs to the generator model are the direct and quadrature voltages in volts, namely v_d and v_q, respectively together with the rotor angular velocity, ω_r in radians per sec. The outputs of the system are the direct and quadrature currents, i_d and i_q, respectively in amps. The mathematical model of the generator is a standard set of differential equations where it has been stipulated that L_d and L_q are the same. The Simulink diagram of Figure 1 shows the model where L_s represents the direct and quadrature axis inductance.

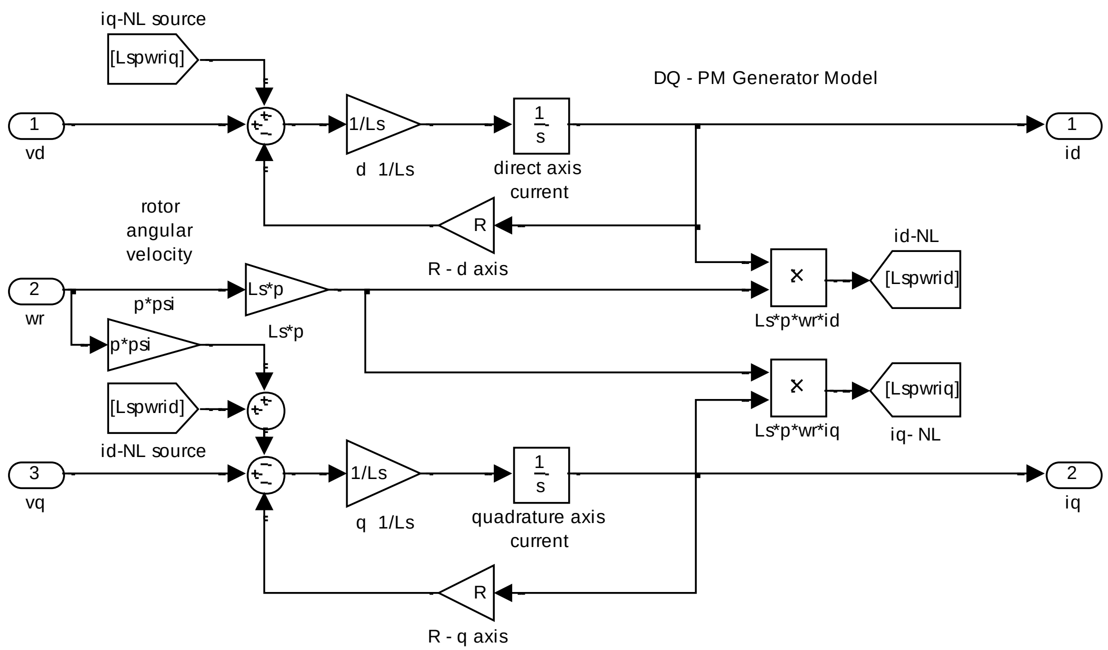


Figure 1: Generator Simulink Model

The control strategy for the generator system is to linearize and decoupled the model through feedback linearization. The vibration isolation scheme described in the previous report requires the ability to control the generator torque. The feedback linerazation and torque controller is shown in Figure 2. In the box marked “Generator” resides the generator model of Figure 1. The generator model and controller of Figure 2 have been incorporated into the FAST model of the 5 MW turbine. Because of the feedback linearization, the overall transfer function between the desired input torque and output torque is a linear, first order system.

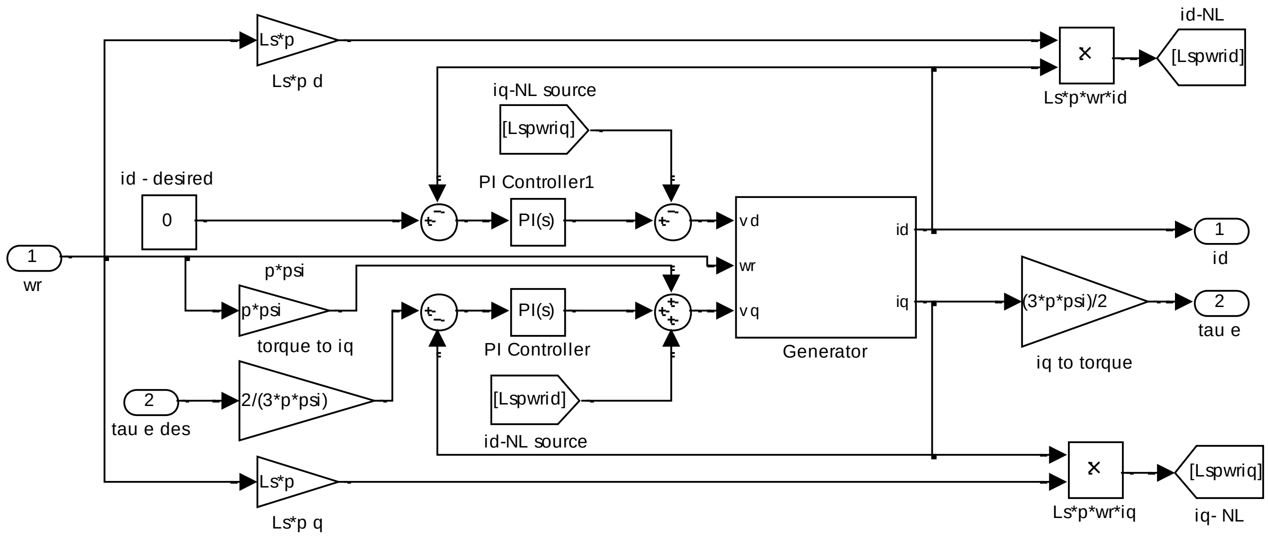


Figure 2: Generator Torque Controller

Optical Torsion Sensor

It has been demonstrated that the fiber Bragg grating (FBG), an optical sensor, can measure shaft torsion on a rotating shaft. Figure 3 shows how that can be done. In order to provide the light source and receive the returned signal, the optical fiber is channeled to the shaft center and delivered to the shaft end. The light signal is coupled with off-shaft instruments by graded index (GRIN) lenses where the light passes from the rotating lens through air to a stationary lens. Connected to the stationary lens are the optical light source and an optical spectrum analyzer. There is an optical circulator which routes source light to the gratings and the return light to the spectrum analyzer. The mass of the rotor mounted instruments is slight. It is through this means that shaft torsion can be directly measured.

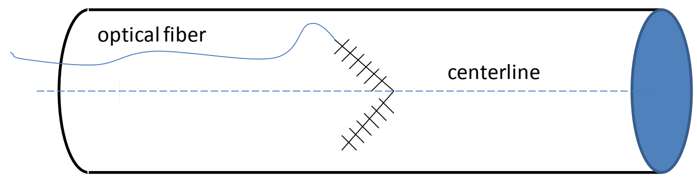


Figure 3: Mounting of Gratings

Vibration Absorber Case Studies

The generator model and controller were included in the FAST model of the 5 MW turbine. A band pass filter was created out of a PI controller and the low pass, first order model of the controlled generator. The band pass filter identifies the torsion harmonics that need to be removed from the rotor stresses. By a generator applying a torque in opposition to these torsion harmonics, the torsion harmonics are removed from the rotor. Three tests were conducted with the vibration absorber. The tests consisted of steady wind, time varying wind, and turbulent wind. The vibration absorber is shown in Figure 4. The sub-system in Figure 4 consists of the controlled generator model in Figure 2. The different wind simulation results are shown in Figures 5 – 10 where the quantity N in the figures is the transmission gear ratio.

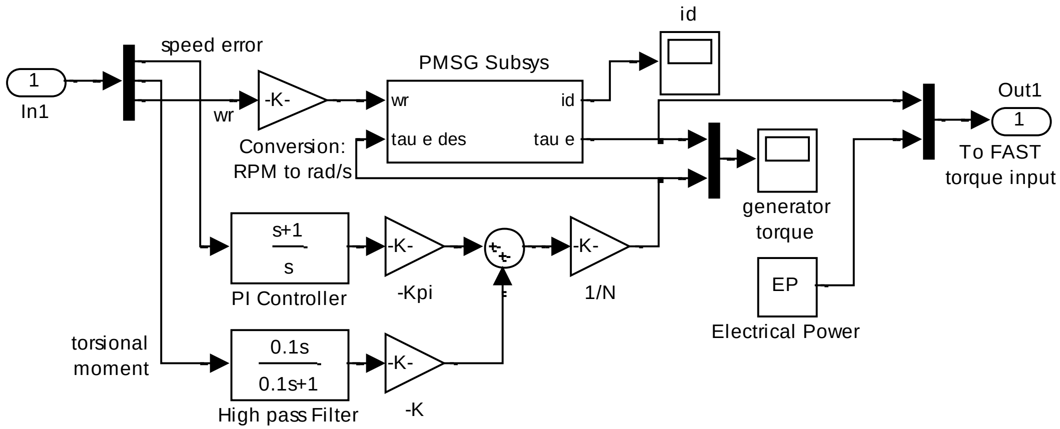


Figure 4: Vibration Absorber

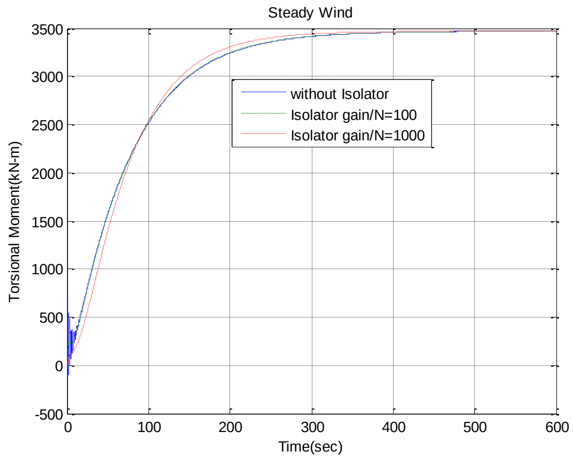


Figure 5: Steady Wind

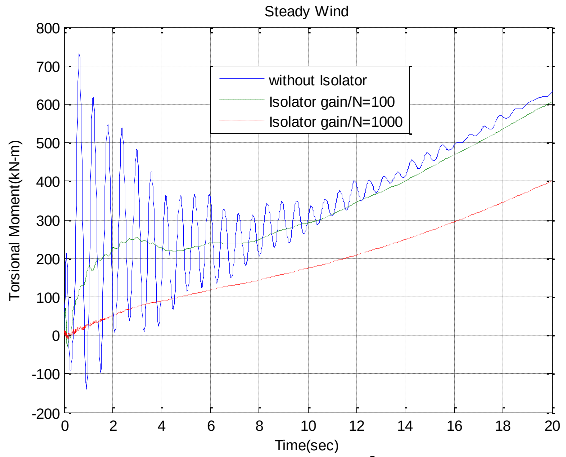


Figure 6: Portion of Figure 5

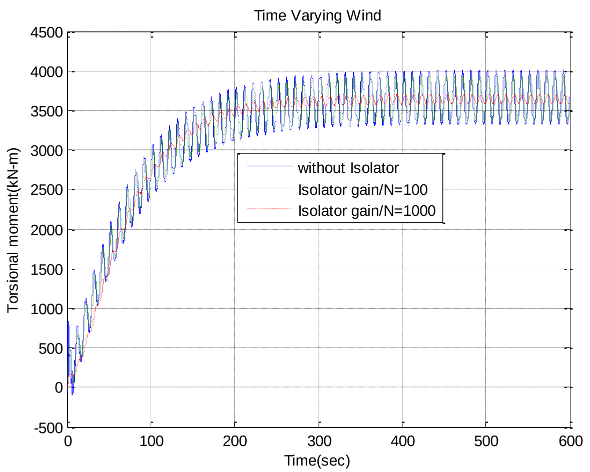


Figure 7: Time Varying Wind

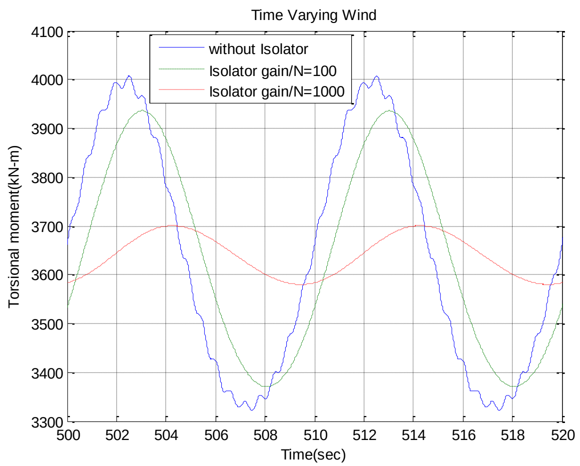


Figure 8: Portion of Figure 7

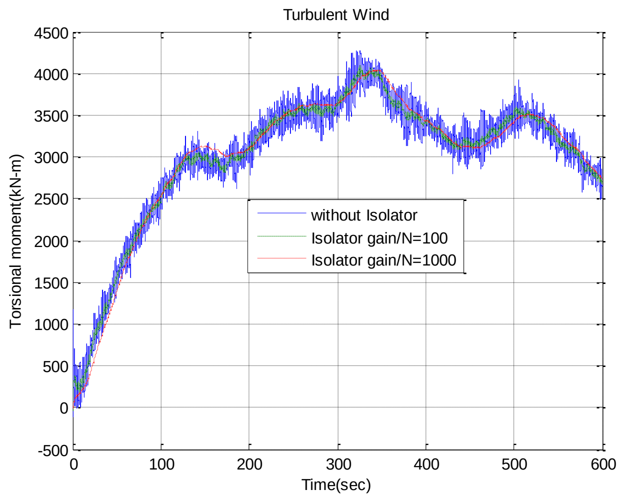


Figure 9: Turbulent Wind

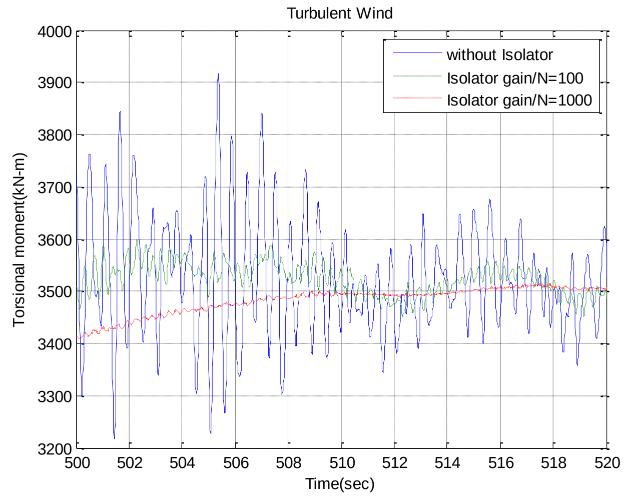


Figure 10: Portion of Figure 9

The results of this model development and the reported results are included in the invited paper "Active Control of Wind Turbine Rotor Torsional Vibration," by Warren N. White, Zhichao Yu, Ruth Douglas Miller, and David Ochs to be presented at the 2013 ASME Dynamic Systems and Control Conference to be held Oct. 21-23, 2013 in Palo Alto, CA.

Robustness of the Vibration Absorber

As a test of the robustness of the vibration absorber, two different gains were used in order to examine the difference. Some of the results are shown in Figure 1.

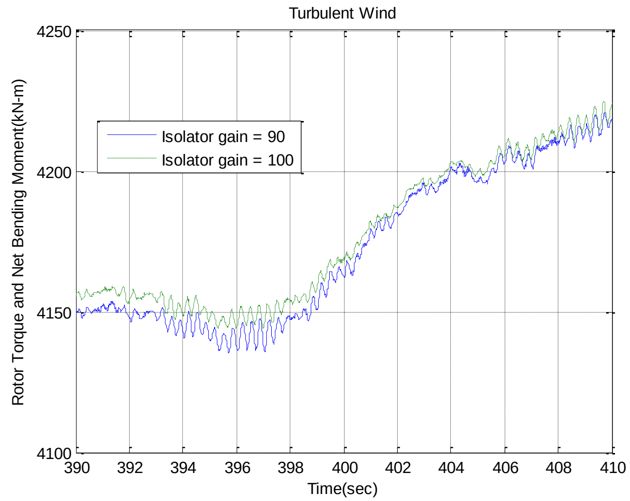


Figure 11: ROBUSTNESS TEST FOR ISOLATOR

Figure 2 shows the rotor torque and blade base in-plane bending moment sum which was used as feedback during this test. The strain at the blade base is a quantity that is usually measured in modern wind turbines. The sum of the in-plane moments at this point is different from the shaft moment. However, this calculation shows the robustness of the vibration absorber in that it is able to perform well with disturbances producing an altered feedback signal.

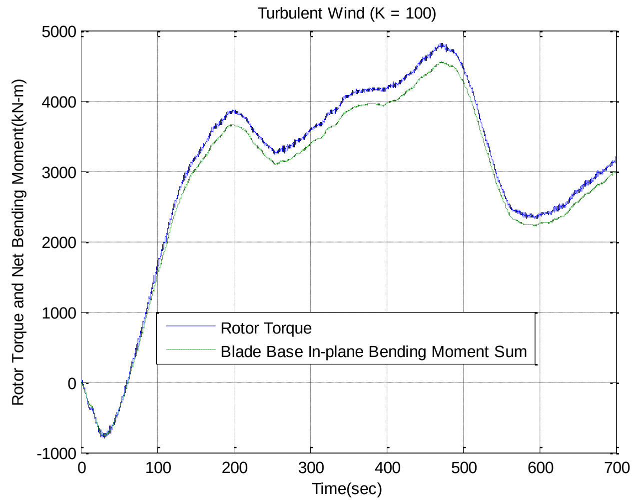


FIGURE 12: ROBUSTNESS TEST FOR ISOLATOR – IN-PLANE BLADE BASE BENDING MOMENT SUM USED FOR FEEDBACK

Task 2.0 Increasing the robustness of the power grid through distributed solar and wind generation: *a theoretical approach*

Evaluating the role of distributed wind/solar generation in the robustness of the entire grid is a critical task for a substantial future deployment of this technology. We believe that distributed generation through wind and solar technologies can increase the robustness of the power grid. First, it can reduce the dependence on foreign fuels and on massive nation-spanning power grids. Second, it can allow the containment of cascade of failures through the concept of intentional disconnection of those portions of the grid augmented by distributed sources. The entire power grid can be represented by a graph in which the nodes represent power-generation stations and transmission/distribution substations, and the links represent transmission lines. The goal of our research is to study the impact of the grid topology and capacity on the propagation of failures. We study also the effect of intentional disconnections of networked microgrid on the overall grid and on the microgrid itself to reduce and contain the cascade of failures.

This work takes a theoretical approach, which will integrate and augment the effectiveness of the results obtained by simulation so far. We will define new metrics to compute the robustness of the grid to cascading failures and determine the optimal topology with respect to those metrics. Additionally, we will define clusters as microgrids candidate for disconnection case of propagating failures, and develop efficient algorithms to detect them.

In our literature search, we found many cascading failures models; however we did not find any proposed measure to quantify the robustness of power grids against cascading failures. We presented a metric to measure the robustness of the power grid given the loads that flow on it. We defined the robustness measure with respect to cascading failures as the ability of the power grid to stop the successive failures of transmission lines, while preserving the demand loads from the generators to the distribution substations. The new measure depends on ranking each transmission line according to its effect due to removal. We applied the new metric to measure the robustness of different real and synthetic power grids. We used IEEE 300 bus test system, IEEE 118 bus test system, WSCC 179 bus equivalent system power grid topologies and synthetic power grids with the same number of power lines and number of substations to measure their robustness.

We proposed a novel optimization problem to find islands in the power grid during severe cascading failures, such that any failure is contained in small isolated part of the grid, and the delivered power in the remaining part is maximized. We constraint the problem such that there is no power flow among islands to ensure total isolation. We apply the DC power flow model in the optimization problem to ensure that the flow is based on the electric characteristics of the transmission lines, like the admittance and the voltage angle. The problem was modeled as Mixed Integer Non Linear Programming (MINLP) with quadratic constraints, and therefore, the problem is intractable.. This technique has been tested on the five IEEE test systems available at [1]. The optimal islanding technique gives the minimum load shedding in the island as well as their topological complement but is exponential in complexity. As a result, it can be applied to small or medium sized systems such as the 14 and the 30 bus.

The two heuristics for islanding were implemented. These are based on a network metric called ‘modularity’ and are a variation of the Bloom and the Fast Greedy algorithms for network partitioning. These heuristics have a polynomial time complexity, with the Bloom type heuristic being faster than the Fast Greedy type heuristic. They have been properly modified to include the power flow model and provide an efficient balance between the amount of load shedding and algorithm scalability. For the small systems, the heuristics give exactly the same results as the optimal strategy. Moreover, these techniques also work very well for the larger systems available at [1], with 57, 118 and 300 buses.

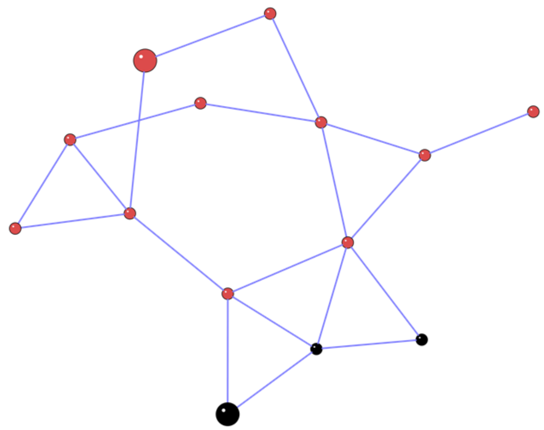
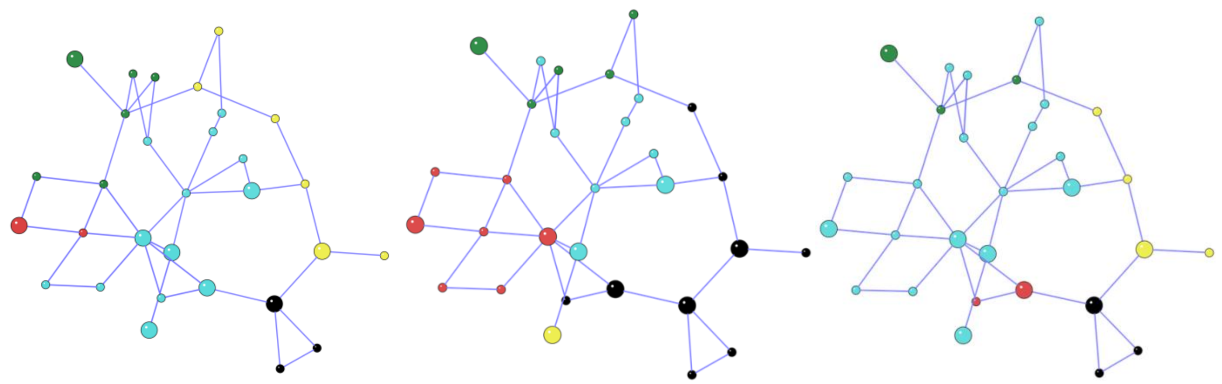


Figure 1 – Islanding using all the Three strategies in the 14-bus system

Each of the three algorithms has been designed keeping in mind that there is at least one generator in each island. At this point of the work, conventional distributed generators have been considered instead of distributed solar and wind generation.

The results are illustrated through Figures 1 and 2. Figure 1 shows islanding using all the three techniques for the 14-bus system. The circles represent the buses while the lines connecting them represent the transmission lines. The two islands are represented by the two different colors, with all the buses of the same color belonging to one island. The big circles represent the generators whereas the small circles represent the load or transit nodes. Since the island structure for each of the three techniques is the same in case of the 14-bus system, the amount of load shedding is also the same.



(a) (b) (c)

Figure 2 – Island structures for the 30-bus systems using (a) Optimal islanding, (b) Bloom type heuristic, and (c) Fast Greedy type heuristic

In Figure 2, the 30-bus system has been split into 5 islands using each of the three techniques and sub-figures (a), (b), and (c) represents the scenario using Optimal, Bloom type and Fast Greedy type techniques, respectively. Since each technique gives a different island structure, the amount of load shedding is also different.

All the above and more results have been presented in a manuscript submitted to a leading journal:

S Pahwa, M. Youssef, P. Schumm, C. Scoglio, N. Schulz, "Optimal Intentional Islanding to Suppress Cascading Failures in Power Grids", Physica A, Elsevier, Volume 392, No. 17, Pages 3741 - 3754, 2013

Task 3.0 Networked Control and Management of Distributed Wind Generation

In this effort, we will study and develop novel networked control and management strategies for variable speed wind turbine based distributed generation (DG) in both grid connected and islanded modes of operation. Specifically, we will mathematically model the dynamics involved in a microgrid mode of operation and then develop algorithms for load sharing among DGs. We will quantify the effect of the backbone communication network between DGs on both low level unit control as well as high level network control. In an overloaded situation, we will develop fair load shedding algorithms by invoking principles of fairness from social sciences arena.

In the grid connected mode, we once again will formulate a power profile allocation problem along with the study of the effect of communication network on cooperative detection of grid faults.

Large penetration of small wind generators in the distribution system can create unusually high or unusually low voltages in the distribution system, particularly in close proximity to the generators. These abnormal voltages can impact many customers or facilities connected to the network. The voltage profile of the system with these generators is very different from the one without these generators. Therefore, the current rules for switching LTC, capacitors, and regulators no longer work and thus new rules are needed. The goal of this task is to develop strategies for dynamic voltage control of distribution system while considering dynamics of wind generators, power electronics interface and the probabilistic nature of electricity production. Currently, most of the literature on voltage/var control considers only the primary side of the system and in many cases only the three-phase part of the system is considered. Since small wind generators are connected to the grid at the secondary level, suitable models to include the secondary system in analysis will be investigated. The developed models will be used to determine acceptable level of penetration of small wind generators in the system.

We started this task by focusing on learning the fundamentals of power distribution system operation and the differences between distribution and transmission system analysis. The emphasis was on learning current strategies for (1) solving power flow in distribution system; (2) state estimation in transmission and distribution systems; (3) communication network and controller design. We then focused our literature review on distributed var control over a communication network. We also conducted a literature search on models for distribution transformers for modeling the secondary side of the distribution system.

The mathematical model for the distributed var control problem in an unbalanced 3 phase grid connected system was completed, including the ptimization formulation to determine the reactive power injected from DGs in a three phase system. A convex transformed version of the var control problem was also completed. The optimal control formulation of var control across time includes stochastic variation of loads and generation. Since the system is highly nonlinear, we are using principles of non linear model predictive control to develop the solutions. Simulations were implemented to test the nonlinear model predictive control approach. We implemented an extended Kalman filter based state estimation technique to go along with the stochastic control solution, and have completed an integrated simulation of nonlinear model predictive control with state estimation and validated our approaches.

Next, an investigation of the stability and robustness of our solution was performed. We quantified the stability, optimality and robustness of the state estimation strategy while including the effects of dropped packets during the centralized estimation procedure. For tractability in mathematical analysis, we modeled packet drop as an independent Bernoulli process. We identified the relationship between generation and load variability and state estimation stability which in turn impacts the controller stability. We studied the impact of packet drops in the feedback path and its effect on stability. Initially we had assumed that the packet drops from sensors across the distribution grid were independent and followed the same Bernoulli distribution. We wanted to expand this to more general problem set up of having non identical Bernoulli distributed packet losses. As we have proposed an extended Kalman filter (KF) based state estimate for the power system, we restricted our theoretical analysis to a linear dynamical system with linear measurement equation. Even within this set up the impact of packet losses on estimation based on spatially dispersed measurements has not been quantified. We were able to analyze the stability of the state estimation process in this scenario, by deriving the conditions under which its steady state error covariance matrix is bounded. For the first time, we were able to establish bounds on critical measurement loss rates of individual sensor communication links. The analysis illustrates the tradeoff between state estimation accuracy and the quality of underlying communication network. Our analysis is critical to quantify the stability of networked control for safe and efficient operation of a power distribution grid.

Two papers have been completed for submission and resubmission based on the work in this task.

S. Deshmukh, B. Natarajan and A. Pahwa, "State estimation over a lossy network in spatially distributed cyber-physical systems," *IEEE Transactions on Signal Processing*, vol. 62, no. 15, August 2014, pp. 3911-3923.

S. Deshmukh, B. Natarajan and A. Pahwa, "State Estimation and Voltage/VAR Control in Distribution Network with Intermittent Measurements," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, January 2014, pp. 200-209.

Task 5.0 Distributed Generation Laboratory Development

Initially Task 5 was focused on a distributed generation laboratory at Wichita State University, but subsequently the project extension in 2014 repurposed funds from Task 6 to additional laboratory development at Kansas State University also as part of Task 5. Thus this part of the report is divided into two sections, one for each university.

Wichita State University

The laboratory infrastructure will be unique in that it will be distributed across Kansas while also integrating the resources associated with the National Renewable Energy Lab Wind for Schools program in Kansas. Laboratory equipment with monitor and control functionality will be integrated with a variety of sensors and renewable energy generators using existing network connections via the Internet. This will allow each university to run laboratory exercises that emulate both real-time and historical conditions that reflect dynamic power generation from renewable sources as well as the dynamic loading environment seen in a local distribution system. All aspects of a typical distributed system will be present in the laboratories, including the AC grid, distribution lines, DC generation, rotating generation, storage capabilities, and loads. Most of these components will be integrated with network control functionality, which will allow all three laboratories to appear either as one cohesive distribution system or as three separate distribution systems

The lab feeder model implemented for this task is shown in Figure 5.1.

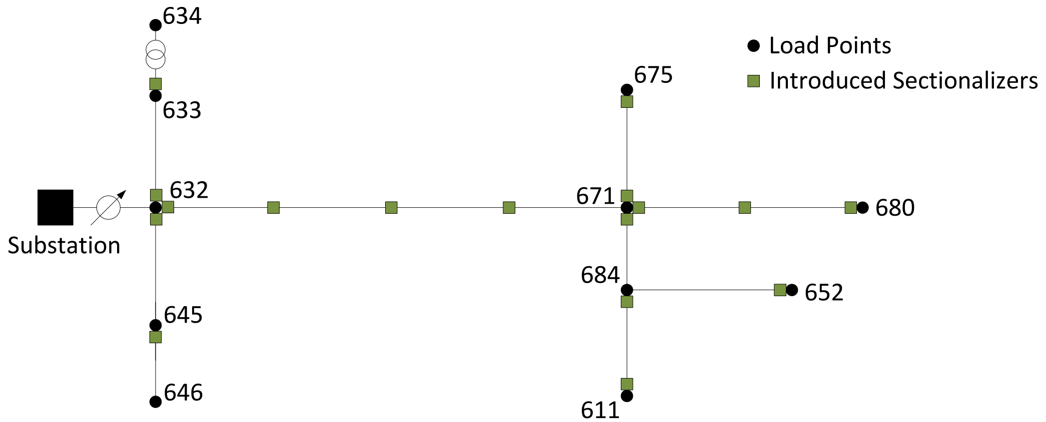


Figure 5.1. Feeder to be modeled in lab.

Initially, wireless Crossbow sensors for sensing voltage and current were planned for the resistive distribution feeder model. Investigators decided to use wired instead of wireless sensing. Wired sensing will accomplish all the goals of this project with much less time spent on programming the wireless sensors. Wireless may be added in a future project if investigators more familiar with wireless sensing are included.

Applications developed for the distribution feeder include fault location and restoration, Integrated Volt/VAR Control (IVVC), solar photovoltaic emulator with battery storage, and a doubly-fed induction generator wind turbine emulator. A new technique for emulating the wind turbine was developed. It uses programmable dc power supply to drive the dc motor. The supply is programmed in Labview software using historical wind data. A programmable dc supply was also used as a photovoltaic module emulator. The supply was installed and used in testing of the commercial inverter/battery system, using historical solar radiation data as input. The ac system was simulated using an existing ac system simulator in the lab. The inverter's response to transients on the dc and ac systems was studied.

Publications associated with this task include:

Trevor Hardy,Ward Jewell, Emulation of a 1.5MW Wind Turbine with a DC Motor, *2011 IEEE Power and Energy Society General Meeting*, Detroit, July 2011.

Perlekar Tamtam, Ward Jewell, "Steady-State Analysis of a Renewable Energy Inverter," Submitted to *2011 North American Power Symposium.*

Kansas State University

This effort was created to include more renewable energy laboratory capabilities that could significantly enhance the educational and outreach capabilities at Kansas State University. Six laboratory benches in the renewable and power power electronics area were set up to be used with the power laboratory course that all seniors take. There will be six sets of exercises designed for the proper flow of knowledge through the course. One lab exercise will introductory labs making the students accustomed to the equipment to be used throughout the course. One lab exercise will be devoted to practically explain the PWM switching and working of inverters. The other exercises will be devoted to different systems as a whole. These systems will include a direct drive wind energy system, a doubly-fed induction generator wind energy system, a PV system with the converters, and an adjustable speed drive system.

Implemented configurations:

1. Direct Drive Wind Energy System: Wind turbine emulator drive AB 2098-DSD-030X connected to the computer and operated using Ultra 3000 software. The turbine is then connected to a motor and a PM synchronous generator. – 2 setups
2. Doubly Fed Induction Generator Wind Energy System: Wind turbine emulator drive AB 2098-DSD-030X connected to the computer and operated using Ultra 3000 software. The turbine is then connected to the induction generator via a gear box. – 2 setups
3. PV setup: A PV emulator connected to a buck-boost converter and then to an inverter. – 6 setups
4. Adjustable speed drive: A voltage source inverter connected to an induction motor. V/f speed control application. – 2 setups

LIST OF EQUIPMENT ON EACH BENCH

No.	Item	Make
1	Cart	Tektronix
2	Oscilloscope	Lecroy
3	Current Probes – Qty2	Lecroy
4	Voltage Probes – Qty2	Lecroy
5	Computer	HP
6	Work Bench	Hergo
8	DC power sources	BK precision
9	FPGA Board	Altera

All equipment has been successfully installed and integrated into the laboratory as shown in the photos below.