UNIVERSITY OF MINNESOTA

Twin Cities Campus

Saint Anthony Falls Laboratory
Engineering, Environmental, Biological and Geophysical Fluid Dynamics

College of Science and Engineering

Mississippi River at 3rd Avenue S. E.
Minneapolis, MN 55414

Dept. Main Office: 612-624-4363
Fax: 612-624-4398

Project Title: Virtual Wind Simulator with Advanced Control & Aeroelastic Model for Improving the Operation of Wind Farms

Contract Number: RD4-13 **Milestone Number:** 1 **Report Date:** 3/2/2016

Principal Investigator: Fotis Sotiropoulos (612) 624-2022

Contract Contact: Bridget Foss (612) 624-5571

Congressional District: (Corporate office) Minnesota 5th

Congressional District: (Project location) Minnesota 5th

MILESTONE REPORT

Executive Summary: The goal for this project is to develop, demonstrate and transfer into practice an industry-leading numerical simulation model for optimization of performance, financial decision making, and operational planning of existing and newly planned wind energy plants. This project will leverage the previously completed Cycle 3 RDF project through which the first version of the Virtual Wind Simulator software (VWS) was developed and validated. We will extend the capabilities of this first generation modeling tool to include the ability to simulate aeroelastic loading of the blades and incorporate current industry standards and advanced turbine control methods and technologies and we will demonstrate these capabilities via comparisons with data from utility-scale wind turbines and farms. The resulting VWiS+ modeling tool will thus be able to be used in practice to improve wind farm performance and reduce operational costs.

As planned, during this reporting period (monthly) activities have been carried out to address the following objectives:

(a) Preliminary design and validation of the individual blade pitch control design.
(b) Implementation of the generator torque control in the VWiS.
(c) Validation and application of the VWiS with generator torque control using Clipper turbine data

Project funding provided by customers of Xcel Energy through a grant from the Renewable Development Fund.

Technical Progress:

Task 1.2: Design of advanced blade pitch / generator torque control algorithm for improved power capture and load reduction.

In this report the preliminary design and validation of the individual blade pitch control design for the UMN's 2.5 MW Clipper Liberty wind turbine is described. Using NREL's Fatigue, Aerodynamics, Structures and Turbulence (FAST) simulator open and closed loop simulation are used to discuss the influence of the developed control loops. The control design approach makes use of a classical so called "1 periodic" (1P) multi blade coordinate transformation together with two decoupled integral control loops to reduce the blade loading. Further an additional "2 periodic" (2P) loop, referred to as higher harmonic control in literature, is designed. This feedback loop also features two decoupled controllers in order to reduce the loading on the fixed frame parts of the turbine, i.e., the shaft and nacelle.

The Clipper model has been implemented in FAST and augmented with the standard torque and collective pitch control laws. In this section we present simulations results of the Clipper turbine in the operational region 3. To allow a validation in realistic conditions, a wind data input file with a mean wind speed of 12m/s and 7% turbulence has been generated with the NREL's Turbsim software.

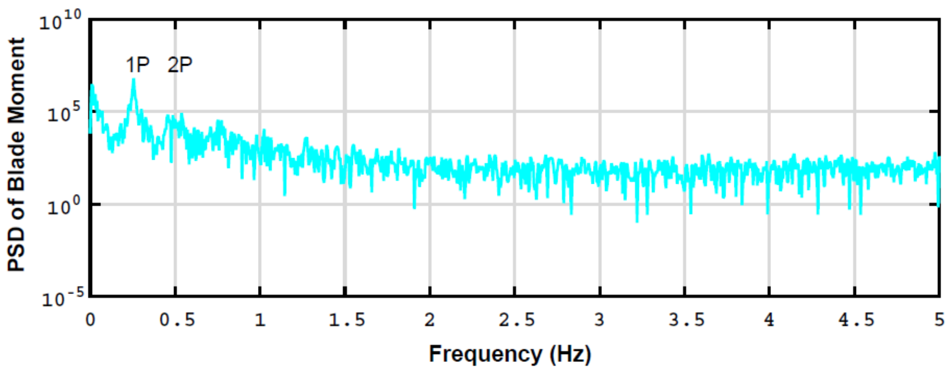


Figure 1: PSD of the blade out-of-plane moment.

In Figure 1 the power spectral density (PSD) of the loads on the first blade is depicted. For the generation of the PSDs the software package M-Crunch has been used for post-processing the simulation data. Clearly visible is a dominant constant peak, which is due to the thrust acting on the turbine. However, relevant for the fatigue loads of the blades is the peak at a frequency of 1P, where P refers to the rotational frequency of the turbine. In case of the Clipper the maximum rotational frequency, which is set by the standard control law in region 3, is 15.5 rounds per minute. This corresponds to around 0.25Hz. At this frequency a peak in the load spectrum is clearly visible.

Figure 2 shows the PSD of the yaw-bearing yaw moment, thus the moment which tries to yaw the nacelle. The three blade loads in the rotating coordinate frame are transformed in the non-rotating frame of the turbine. As explained by Bossanyi (2003) the 1P components on the blades are experienced as constant yaw and pitch moments on the nacelle. While it can be shown that the 3P component on the blades is canceled out in the yaw and pitch moments on the nacelle (i.e. they are transformed into a symmetric load leading to tower fore-aft bending), the 2P and 4P blade loads are transferred into this 3P component on the nacelle yaw and pitch loads. The same is valid for higher frequencies, which appear in the 3n harmonics for n=0,1,2, … This explains the peaks in Figure 2 at around 0.75Hz (3P) and 1.5Hz (6P). With this knowledge available, a classical IPC control law is designed in the next section.

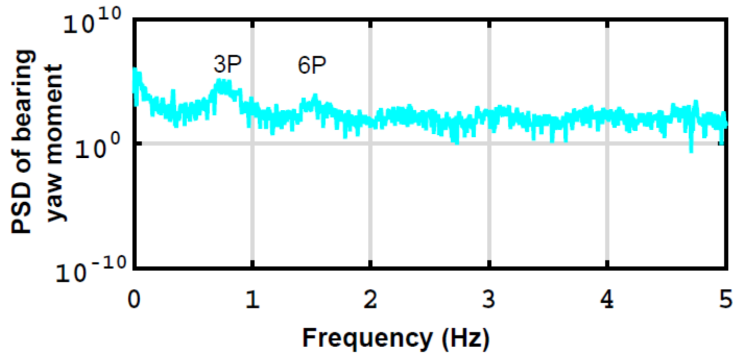


Figure 2: PSD of the yaw-bearing yaw moment.

A preliminary Control design is presented in this part. The first part of the developed controller uses a 1 periodic (1P) transformation of the measured blade loads together with two single-input single-output (SISO) integral controllers to suppress the generated static load. For the second part, the blade loads are 2 periodic (2P) coordinates transformed which enables the suppressing of the 2P loads on the blades, again using linear integral control. To generate the 1P and 2P coordinates transformations the so called multi blade coordinates (MBC) transformation (Bir 2008, Seiler 2013) is used and described below.

Multi-blade coordinates transformation employed is first described. The loads measured on the turbine are the blade loads and thus, are in the rotating frame. The design of a controller using these measurements directly would involve periodic control techniques, as the underlying system is time variant with the rotational frequency. The MBC transformation projects the time variant loads onto the non-rotating frame. In this non-rotating frame the turbine dynamics can be approximated sufficiently exact by linear time-invariant models, allowing the design of a linear controller in this coordinate frame.

As a linear controller shall be designed, the measured loads signals are projected onto the non-rotating frame by the MBC transformation

$$\begin{bmatrix} M_{\cos} \\ M_{\sin} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\phi) & \cos(\phi + \frac{2}{3}\pi) & \cos(\phi + \frac{4}{3}\pi) \\ \sin(\phi) & \sin(\phi + \frac{2}{3}\pi) & \sin(\phi + \frac{4}{3}\pi) \end{bmatrix} \begin{bmatrix} M_{by,1} \\ M_{by,2} \\ M_{by,3} \end{bmatrix}, \tag{1}$$

where M_{cos} and M_{sin} are the transformed loads, ϕ is the rotational angle of the first blade and $M_{by,1}$, $M_{by,2}$ and $M_{by,3}$ are the measured out of blade loads. This transformation transforms the 1P loads on the blades to a constant load which can be mitigated with a controller showing low bandwidth. The inverse coordinates transformation is given by

$$\begin{bmatrix} \beta_{\mathrm{IPC},1} \\ \beta_{\mathrm{IPC},2} \\ \beta_{\mathrm{IPC},3} \end{bmatrix} = \begin{bmatrix} \cos(\phi) & \sin(2\phi) \\ \cos(\phi + \frac{2}{3}\pi) & \sin(\phi + \frac{2}{3}\pi) \\ \cos(\phi + \frac{4}{3}\pi) & \sin(\phi + \frac{4}{3}\pi) \end{bmatrix} \begin{bmatrix} \beta_{\cos} \\ \beta_{\sin} \end{bmatrix} \tag{2}$$

and is used to transform the two generated pitch angles β_{cos} and β_{sin} by the controller to mitigate the pitch and yaw moment back to physical pitch deflections on the three blades.

The main damage equivalent load contribution on the nacelle is caused by the out of plane bending moment at a frequency of 3P (see figure 2) and comes from the 2P load contribution on the blades. One possible approach to mitigate these loads is to transform the 2P blade loads to a constant load by an adapted MBC transformation. This so-called 2P MBC transformation, also referred to as higher harmonics control in literature, can be stated by

$$\begin{bmatrix} M_{\cos} \\ M_{\sin} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\phi) & \cos(2\phi + \frac{4}{3}\pi) & \cos(2\phi + \frac{2}{3}\pi) \\ \sin(\phi) & \sin(2\phi + \frac{4}{3}\pi) & \sin(2\phi + \frac{2}{3}\pi) \end{bmatrix} \begin{bmatrix} M_{by,1} \\ M_{by,2} \\ M_{by,3} \end{bmatrix}. \quad (3)$$

Equation (3) transforms the 2P loads on the blades to a constant loads while shifting all other harmonics to 3P or higher. This allows the design of a low bandwidth controller to mitigate the 2P blade loads. These two controllers are described in the next section. Note, that the 1P MBC transformation is physically happening on the real turbine, as the nacelle and the shaft encounter exactly these 1P transformed loads as a constant yaw and pitch load. When applying the 1P MBC transformation the 2P blade loads are transformed into a 3P load component on the nacelle. This is confirmed in the nonlinear simulations, as the measured load on the nacelle shows a clear peak at the 3P frequency. The transformed loads are depicted in Figure 2. In contrast to that, the 2P transformation is used to transform the 2P loads to a constant load, not having a direct physical equivalent.

The first control design uses the 1P MBC transformation of the blade loads to transform the 1P blade loads to constant pitch and yaw loads on the turbine's nacelle. Assuming, that the pitch and yaw moment can be controlled independently, two SISO controllers are designed. The two controllers are simple integral controllers of the form K_i/s. The control gain K_i is used to set the crossover frequency, i.e. the frequency when the open loop transfer function crosses the 0dB line in the bode diagram. Note, that by designing two integral SISO controller we are assuming that there is no or low cross coupling in the controlled frequency range. This has been confirmed by detailed analyses of the linear models. As the load which shall be mitigated is constant a rather low crossover frequency of 0.25rad/s is selected for both loops.

In Figure 3 a block diagram of the wind turbine together with the standard region 3 pitch proportional-integral (PI) control law is depict. Additionally the 1P control loop using the 1P MBC transformation is closed to mitigate the 1P blade loads showing up as constant load on the nacelle.

For the mitigation of the 2P loads on the blades an additional loop using the 2P MBC transformation is used as depicted in Figure 4 The two loops work at different frequencies and thus do not interact with each other. The 1P and 2P controllers can be seen as two pass band controller acting only at the 1P and 2P frequency on the blades.

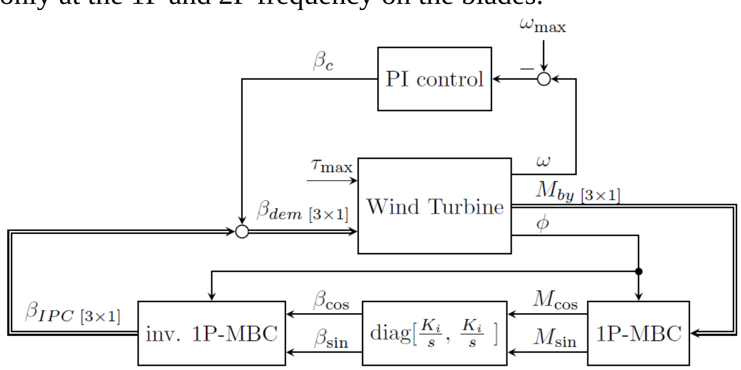


Figure 3: Wind turbine augmented with standard region 3 collective pitch and 1P IPC load mitigation control law.

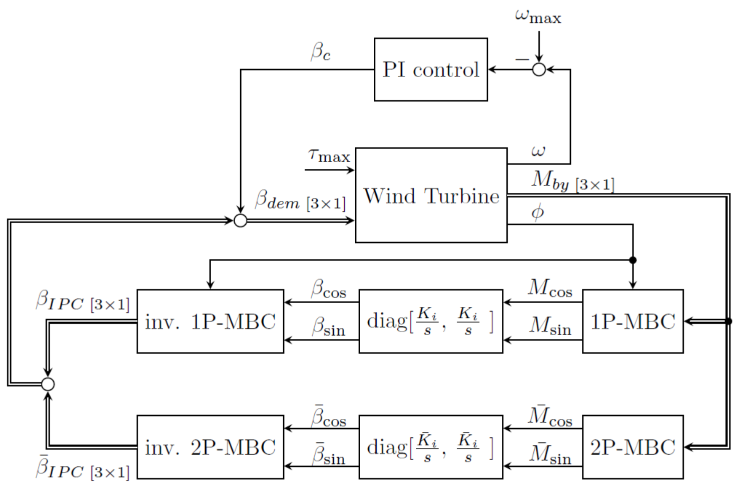


Figure 4: Wind turbine additionally augmented with 2P IPC load mitigation control loop.

Both controller structures have been tested using the FAST simulator. The tested point in regions 3 was chosen at 12m/s wind speed with a turbulence of 7\% in all three axes, thus involving wind shear and yaw turbulence. The added 1P control loop mainly leads to a reduction of the blade damage equivalent loads (DELs), which were computed using the M-Crunsh post-processor with a S-N slope of 10 at the blade for composite materials. This is depicted in Figure 5. Without IPC a dominant peak at 1P is present, which gets mitigated by both IPC controllers. The damage equivalent loads could be reduced by around 25\% compared to the simulation without individual blade pitch control (IPC).

A PSD of the nacelle yaw loads are depicted in Figure 6. While the constant load is reduced by the 1P IPC controller, the 3P load is not changing using this control strategy. This is due to the low bandwidth of integral controllers, only mitigating the constant loads on the fixed frame. Thus, also DELs on the nacelle and shaft are not reduced, as constant loads only have a minor contribution to them. This clearly shows the necessity of a controller acting at the nacelle's 3P frequency (the blade 2P frequency) which can be achieved using the 2P control approach presented above. A DEL reduction of around 20\% on the nacelle and shaft has been achieved by this additional 2P control loop. As depicted in Figures 6 the 2P controller significantly reduces the 3P components on the non-rotating parts of the turbine. For the analysis an S-N slope of 4, typical used for steal, has been used. Note that the peak at around 0.3Hz is associated with the tower side to side mode which can hardly be influenced by IPC.

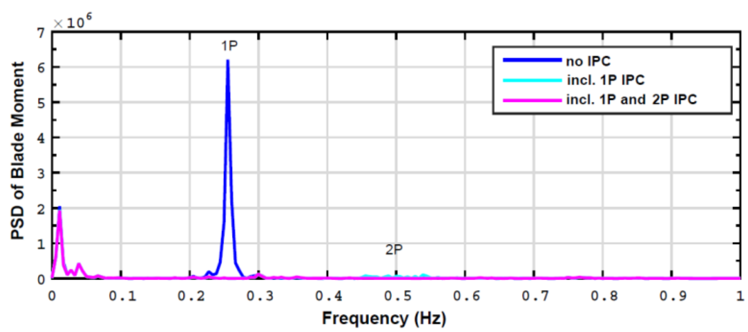


Figure 5: PSD of the blade out-of-plane moment with and without IPC.

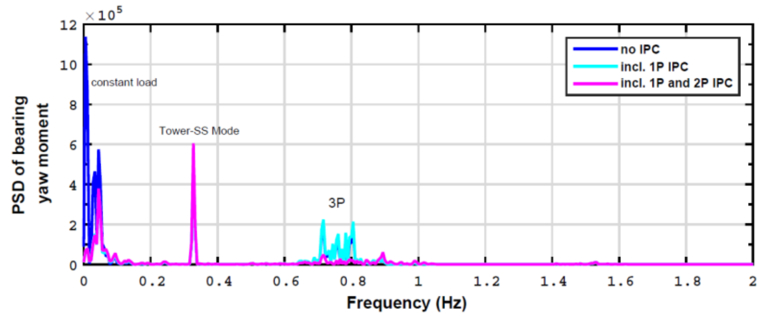


Figure 6: PSD of the yaw-bearing yaw moment with and without IPC.

Having the first, based on an industrial well established IPC control design, available, the following work will focus on the investigation on other control design techniques to further reduce the loads. Another relevant aspect is the robustness analysis of the controllers for different wind speeds, thus in the whole region 3 of the operational range.

Task 1.3: Implementation of advanced control algorithm in the VWiS

The actuator line model is employed for turbine parametrization. The actuator line model accounts for the blades as separate rotating lines. The forces distributed on each line (blade) are calculated based on a blade element approach, in which the blade is divided into elements in the radial direction, and tabulated as 2D airfoil data. A 4-point width discrete delta function proposed is employed for force distribution from the actuator line grid nodes to the background grid nodes.

Utility-scale turbines have several inputs that can be controlled to increase the captured power and reduce structural loads. These inputs include generator torque, τ_g, and blade pitch, β, at varying wind speeds, u, which can control the rotor speed of the turbine, ω (Figure 1)

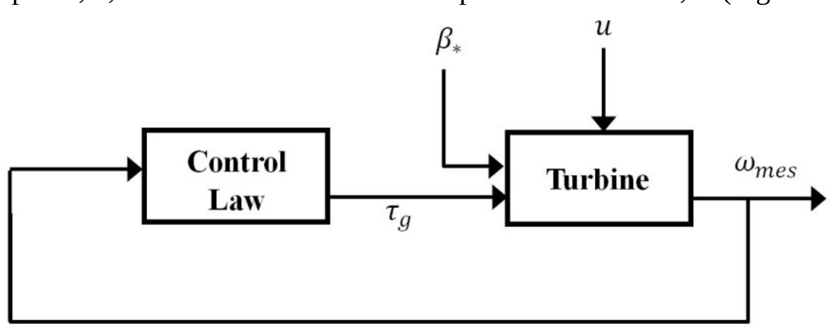


Figure 7: Block Diagram of a Standard Turbine Controller in Low Wind Speeds (Region 2).

In general, the generator torque is varied at low wind speeds (commonly referred to as Region 2) to maximize power captured. At high wind speed (commonly called Region 3), the blade pitch angle is used to mitigate mechanical and electrical loads.

In the standard generator torque controller, which is used at low wind speeds, the dynamics of the turbine are modelled as a single degree-of-freedom rotational system:

$$\frac{d\omega}{dt} = \frac{1}{J}(\tau_{aero} - \tau_g) \tag{4}$$

where J is the rotational inertial of the rotor, τ_{aero} is the aerodynamic torque given by the actuator line model, and τ_g is the generator torque, which can be computed using the standard control law:

$$\tau_g = K_g \omega^2 \tag{5}$$

where $K_g = \frac{1}{2}\rho A R^3 \frac{C_{P*}}{\lambda_*^3 N}$ and N is the gearbox ratio. If K_g is chosen properly, the power from the turbine will converge to the optimal C_P in steady winds. In turbulent winds, the turbine will cycle around the optimal tip speed ratio.

We apply the developed method to simulate a Clipper Liberty 2.5MW wind turbine, the centrepiece of the EOLOS wind energy research field station, which is installed at UMore Park in Rosemount, MN (about 20 miles southeast of the Twin Cities campus). The rotor diameter of the turbine is 96 meters at a hub height of 80 meters. A 130-meter-tall meteorological tower is located at 160 meters south of the turbine. Instruments are installed at 10 different heights on the tower spanning the entire swept area of the turbine blades, in which four with sonic anemometers measuring wind speed and turbulence at a very rapid sampling rate, and six with temperature, barometric pressure and humidity sensors as well as cup and vane anemometers. The turbine's Supervisory Control and Data Acquisition (SCADA) system is employed to record the operational and performance data from the turbine.

The lengths of the computational domain are 1500 meters, 800 meters and 1000 meters in the streamwise (x), spanwise (y) and vertical (z) directions, respectively. The mesh near the turbine and in turbine near-wake is uniform with a grid spacing of 5 meters. The numbers of grid nodes are 201, 121 and 121 in x, y and z directions, respectively. The time step is 0.044 s. For the actuator line grid, 51 points are employed along each line (blade). For the turbulent inflow cases, a fully developed turbulent boundary layer flow, which is from a precursor simulation, is fed at the inlet. Wall model is employed at the ground. Free slip boundary condition is used for the top boundary. Periodic boundary condition is employed in the spanwise direction. The VWiS code is used to carry out simulations for three cases: fixed ω, fixed TSR, and generator torque control. For the fixed TSR case, the inflow velocity for calculating ω is taken at hub height 1.67D upstream of the turbine. The distance 1.67D is chosen as this is the upstream distance of the met tower from the turbine at the EOLOS field station. The computations were first carried out until the total kinetic energy of the computational domain reached a quasi-steady state, and subsequently the flow fields were averaged for approximately 20 minutes.

Simulations with uniform inflow were carried out first at different fixed TSR and with different values of K_g in the generator torque control. In Figure 8, we compare the computed C_P of these simulations with those predicted from blade element momentum theory, which should work well for uniform inflow. Good agreement is obtained between the theory and the results of the simulations with fixed TSR and generator torque control.

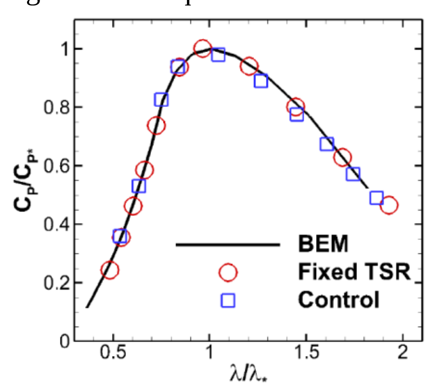
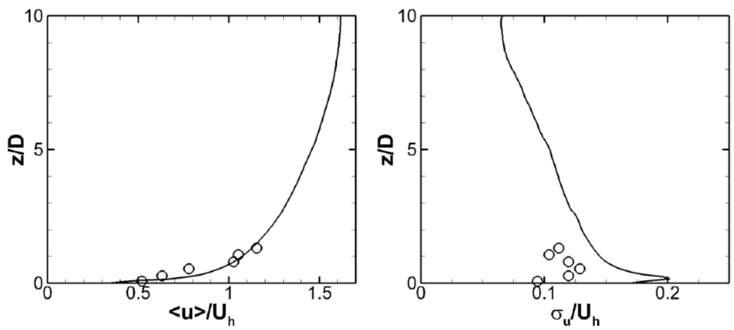


Figure 8: Power coefficients calculated for uniform flow. Solid black line: Blade element momentum theory; Red circles: Simulated with VWiS for different fixed TSR; Blue squares: Simulated with VWiS with generator torque control with different K_g.

For the turbulent inflow cases, the selected time period for comparison is from 11:20 am to 12:20 pm on May 19, 2012, in which the wind is from the south (where the meteorological tower is installed) and the atmospheric stability is neutral. The time-averaged wind speed from the upstream meteorological tower is 8.4 m/s at the turbine hub height. The comparison of the vertical profiles is shown in Figure~\ref{fig:Inflow}. Good agreement with the measurements is obtained for the mean streamwise velocity. However, the turbulence intensity σ_u is over predicted.



(a) <u> (b) σ_u

Figure 9: Vertical profiles of the streamwise velocity (a) and turbulence intensity σ_u (b) at the inlet for the turbulent inflow cases. Solid lines: Simulated with VWiS; Symbols: Measurements from the meteorological tower.

The computed results from the three cases with turbulent inflow are summarized in Table 1. As seen, the time-averaged power and aerodynamic torque from the VWiS simulations agree well with the measurements for all the three cases. However the rms (root-mean-square) of the power and aerodynamic torque fluctuations from the computations are larger than that from measurements. This is probably because the turbulence intensity of the inflow is higher for the simulation (Figure 9(b)). It is also observed that the rms of the aerodynamic torque fluctuations from the case with fixed ω is significantly higher than that from the other two cases. The reason for this observation, however, is still not clear and more work in underway to explain the physical reasons for this finding.

	ω (rad/s)	TSR	P (MW)	P_{rms}	τ_{aero} $(Nm \times 10^6)$	τ_{aero}^{rms} $(Nm \times 10^6)$
Fixed ω	1.43	8.43	1.21	0.45	0.81	0.31
Fixed TSR	1.50	8.65	1.20	0.43	0.76	0.19
Torque control	1.46	8.49	1.22	0.41	0.79	0.20
Measurements	1.51	8.37	1.21	0.19	0.79*	0.09*

*The aerodynamic torque is calculated by P/ω, where P and ω are the measured values.

Table 1: Summary of the computed results from the three cases: fixed ω, fixed TSR and generator torque control.

The field view of the EOLOS turbine and the instantaneous flow field at one time instant is shown in Figure 10. The time-averaged flow fields from the generator torque control are shown in Figure 11. The flow fields from the three cases are nearly the same (not shown).

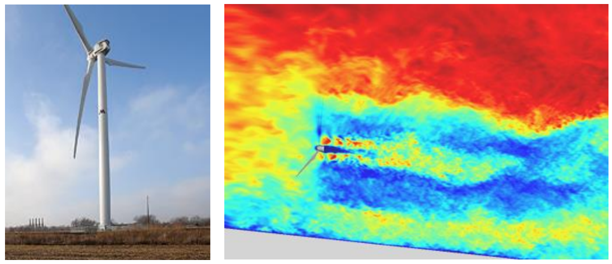


Figure 10: Left: EOLOS turbine. Right: Contours of instantaneous flow field on a streamwise-vertical plane passing through the rotor center.

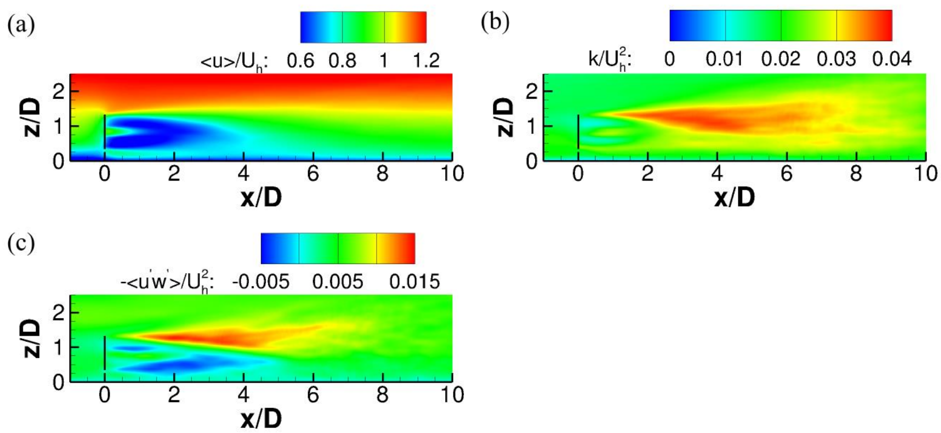


Figure 11: Time-averaged flow fields from the case with generator torque control for (a) streamwise velocity, (b) turbulence kinetic energy and (c) primary Reynolds shear stress.

Generator torque control for the University of Minnesota EOLOS wind turbine has been implemented in an actuator line model of the VWiS LES code. The computed power coefficients agree well with the ones calculated from the blade element momentum theory for uniform inflow. The model has also been applied to three cases with turbulent inflow: fixed turbine rotating speed, fixed TSR and generator torque control. The time-averaged flow fields from the three cases are nearly the same. Good agreement is obtained for the time-averaged power for all three cases. Significantly larger root-mean-square (rms) of the aerodynamic torque fluctuations is observed for the case with fixed ω. The reason for this will be investigated in the future work.

In addition to a generator torque controller, turbines typically have a blade pitch controller at or above rated wind speeds. This controller holds generator torque constant and pitches the blades to minimize structural loads. The blade pitch controller will be incorporated in future work.

Task 2.1.: Replace the turbine control unit on the EOLOS wind turbine with a programmable PLC-based controller.

A conference call between the University of Minnesota (UMN) research group and Mikhail Energy Consulting Group was conducted in 2015. In this conference call, the replacement of the Clipper controller with a PLC based programmable controller "the Bachman controller" was discussed. A decision was made to maintain the Clipper controller and not replace it with a PLC based controller.

The following is the justification provided by Mikhail Energy Consulting Group:

1. The Consultants chosen to support the IBPC addition to the Clipper Liberty turbine are experts in the Clipper turbine and the Clipper turbine control system.
2. IBPC was developed for the Clipper turbine and Clipper control system in 2012 and was proven out as a prototype system on the Liberty turbine. While UMN is developing their own IBPC system, the Consultants were involved in the Clipper IBPC development, and knowledge and lessons learned from that development will be of value informing the UMN approach especially with respect to the limits of the Clipper turbine subsystems.
3. The Clipper control system has a high fidelity control simulation capability that will be valuable in verifying the correctness of the UMN IBPC implementation before the code is run on the turbine, thus providing a measure of safety and lowering the risk of incident during turbine testing.
4. The Consultants chosen to support the IBPC addition to the Clipper Liberty turbine are not experts in the Bachmann Controller. The cost of the Bachmann control hardware and the re-development of an entirely different software control system for the Bachmann controller was unknown by the Consultants, though the cost was known by UMN personnel and factored into their decision. The cost of Bachmann controller retro-fit would have significantly eaten into the grant budget without really providing significant benefit. Clipper controller has the capability of taking the additional signals from blade sensors and incorporating individual blade pitch control commands and or take the measured fiber-bragg data and calculate the individual blade pitch commands within Clipper controller. As such, the risk and cost of using a Bachmann controller and a new control system was higher than proceeding with the known Clipper control hardware and software system.

Additional Milestones:

Project Status: This project is on schedule and within budget.

Appendix:

List of Engineers

Pete Rossmiller, Senior Air Quality Technician, Barr Engineering. Rossmiller has nearly 20 years of experience in ambient air-quality and wind resource measurement. He has managed numerous projects requiring the development of test plans and monitoring plans including (1) assisting with the selection, development, and installation of wind assessment towers, sensors, and data-collection telemetry systems for potential wind-energy developments (2) selecting and deploying SoDAR and LiDAR, three dimensional sonic and laser anemometry, data collection, and acquisition systems for use in the previous RDF funded wind energy large-eddy-simulation model research project and the University of Minnesota Eolos wind-energy research station at UMore Park.

Amir Mikhail, President, Mikhail Energy Consulting Group. Mikhail served as a Senior Vice President of Engineering for Clipper Windpower from 2001 to 2012 and was responsible for the design of Clipper's new Liberty® 2.5 MW wind turbine and was subsequently responsible for Advanced Technology development, including a 7.5/10 MW MBE (Million Barrel of Oil Equivalent) turbine which was being developed for Clipper's Britannia Project. Over 700 (>1750 MW) of the Liberty turbines are currently operational in the US. The Liberty was developed with a 10 million dollar support from the Department of Energy (DOE) and the California Energy Commission (CEC). Dr. Mikhail began his career in wind energy in 1978 as a research scientist at the School of Geophysical Science at the Georgia Institute of Technology, where he participated in wind power research sponsored by the U.S. Department of Energy. From 1980 to 1985, Dr. Mikhail was a researcher and program manager in the areas of wind technology and wind resource assessment at the National Renewable Energy Laboratory (NREL). Dr. Mikhail served as Vice President of Engineering for Zond and Enron Wind Corp. from 1989-2000. In those capacities he led the engineering design of the Z-class 550 kW to 1.5 MW wind turbines, raising over $30 million in research and development funding assistance from the DOE. He integrated evolutionary lessons learned into the further development of the EW 1.5 MW machine. Over 100 Z-550 units were installed in the US and internationally and 1000 Z-750 were installed in the US. The EW1.5 MW machine was adopted by GE when it acquired Enron Wind. Dr. Mikhail has more than thirty publications in the wind power field, 12 awarded patents. He was the recipient of the AWEA Technical Achievement Award in 1996. Dr. Mikhail received a B.S. in Aerospace Engineering and Mathematics from the University of Cairo and a M.S. and Ph.D. in Aerospace Engineering from Georgia Institute of Technology.\

Alan Danker, Principal Software Engineer, Mikhail Energy Consulting Group. Danker has over 30 years of software development experience creating robust, intelligent software, control systems, applications and products. His past responsibilities and involvements encompass the entire software life cycle at every level of responsibility and decision making from low level programming to operating a company. Danker was responsible for all aspects of the development, release and maintenance of a hard real-time, embedded Turbine Control System controlling all aspects of wind generated power production. In this project he will support the design and installation of a research grade control system on the Eolos research turbine.

Sandeep Gupta, Principal Engineer, Mikhail Energy Consulting Group. Gupta is the founder of Helios Engineering, Inc. and has 10 years of experience in wind energy. Prior to founding Helios, Dr. Gupta was at Clipper Windpower as the Loads Engineering Manager and led a team of about 10 people developing advanced controls and loads reduction techniques for the multi-megawatt turbines. While at Clipper, Dr. Gupta also led several fleet performance enhancements for improved reliability and performance improvement as well as numerous next generation product development activities including the 10MW offshore Britannia turbine. His expertise ranges from aerodynamics, aeroelasticity and controls for wind turbines as well as blade and machinery design optimization. Dr. Gupta holds a doctorate from University of Maryland at College Park and his doctoral thesis was focused on developing an improved and more accurate aerodynamics model for wind turbines. He has numerous journal and conference publications and patent applications.

Christopher Milliren, Associate Engineer, St. Anthony Falls Laboratory, University of Minnesota. Chris graduated from the University of Minnesota with a Bachelor of Science degree in civil engineering in December 2011. He began his career at the University of Minnesota St. Anthony Falls Laboratory as an undergraduate in 2009 and started to work with the Eolos Wind Energy Research program in January of 2011. During construction of the University's 2.5MW Clipper Liberty wind turbine, Chris served as the University's field engineer, overseeing construction of the wind turbine. Since completion of the wind turbine in October 2011, Chris has worked to install sensors for foundation and tower research and has participated in many other research projects involving the Eolos turbine.

UNIVERSITY OF MINNESOTA

Twin Cities Campus

College of Science and Engineering
Office of the Dean

105 Walter Library
117 Pleasant Street S.E.
Minneapolis, MN 55455

Office: 612-624-2006
Fax: 612-624-2841
cse.umn.edu

December 21, 2015

To: XCEL Energy administrator of project RD 4-13

From: M. Kaveh M. Kaveh
Associate Dean for Research and Planning

Subject: Commitment of the University of Minnesota EOLOS facility to Research Project RD 4-13

This letter is to confirm that the University of Minnesota EOLOS wind energy research facility in Rosemount, Minnesota, is under the control of the University, and will be made available to researchers of the RD 4-13 project to conduct project related investigations. The facility consists of a 2.5 MW Clipper Liberty wind turbine and a 130-meter-tall meteorological tower located 160 meters south of the turbine. Research at this site in support of this project will include wake measurements using SODAR and snow PIV, data collection from the sensors on the meteorological tower, turbine blades and foundation, and manipulation of the turbine control algorithms to test advanced control strategies.

The research will be led by the project PI, Professor Fotis Sotiropoulos, presently dean of the College of Engineering and Applied Sciences at Stony Brook University, and adjunct professor of Civil, Environmental and Geo-Engineering at the University of Minnesota.