



Catching the Wind

An Update on Improved Yaw Alignment

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1 Introduction

Design of control algorithms for wind turbines relies upon accurate and timely knowledge of the inflow. Traditionally, inflow speed and direction information comes from nacelle mounted wind vanes and mechanical anemometers or from a combined ultrasonic anemometer. However, mounting these meteorological devices on the nacelle leads to the coupling of blade and nacelle interference effects into the measurements, consistently producing raw data that no longer represent the free stream wind hitting the turbine blades. To make this measurement information useful, it is averaged and a transfer function is applied in an attempt to account for these disturbance effects; however, these corrections still fall short of measuring the undisturbed wind in front of the rotor disk.

As a result of using wind direction data from the disturbed flow behind the blades, turbines spend much of their time out of yaw with the wind. This not only produces extra loading on the blade root and the main bearing, but also significantly reduces the amount of power that is produced in Region II wind.

The only way to obtain an accurate measurement of the incoming wind and optimally control the turbine is to measure the wind ahead of the rotor. The most practical way to measure the incoming wind is to use a measurement device that can be mounted on the turbine and that remotely measures the wind speed and direction ahead of the rotors so that it always takes measurements of the volume of air in the direction the turbine is pointing. This can be accomplished with a look ahead laser-based wind sensor.

Nacelle mounted Vindicator[®] Laser Wind Sensor (LWS) units and associated turbine control hardware have been installed on several utility scale wind turbines throughout North America and Europe. Data has previously been presented demonstrating a 10.7% average energy increase on a Vestas V82 turbine in Nebraska, USA over an eight-month period using a non-optimized control algorithm. Data gathering from the V82 turbine continued for an additional three months, at which time control algorithm optimization began. During the installation of additional loads measurement devices, a power optimization was conducted and data was gathered on the possible effects of optimized control algorithms based on the Vindicator[®] LWS wind measurements. A Vindicator[®] LWS was also integrated with a Nordex N60 turbine Alberta, Canada, and additional data was gathered.

This report presents power and energy data from the V82 turbine, demonstrating 14% average energy increase over an 11-month period prior to the optimization program. It also presents the results of a preliminary optimization experiment on the same V82 turbine, demonstrating the ability to achieve a greater than 20% average energy increase using a more optimized control algorithm. Further, the results from the N60 turbine, demonstrating an 11.1% average energy increase by simply more accurately aligning the turbine with the wind, will be shown. Finally, the average yaw error of these turbines will be shown, as well as those of other turbines on which the Vindicator[®] LWS is installed, demonstrating that the average yaw error of these turbines using traditional wind measurement instrumentation is consistent across different makes and models of wind turbines and different sites.

2 Methodology

The power and energy data presented in this report originate from two different geographic locations and types of wind turbines: a Vestas V82 turbine in Nebraska, USA and a Nordex N60 turbine in Alberta, Canada. With respect to the V82 turbine, a third party developed and installed a new controller to control the yaw motors independent of the legacy controller when using the Vindicator[®] LWS wind direction signal and is engaged in the optimization and collection of data.

Details of the sensor and control hardware and software integration can be found in [Boosting Power Production](#) (Dakin, 2009). All of the installation configurations have remained unchanged and, as of this report, the Vindicator[®] LWS and associated control hardware have been in control of the turbine for 19 months. To our knowledge, this represents the longest period of time to date a LIDAR wind direction input has been used to control a utility scale wind turbine. Further testing on the V82 turbine will focus on reducing stress loads.

For the Nordex N60 turbine, CTW has taken an alternative integration approach. On the N60, the legacy controller remains in control of the turbine and wind direction inputs were toggled between the Vindicator[®] LWS direction and the legacy nacelle sonic anemometer wind direction.

All energy calculations were made using the methodology outlined in [Boosting Power Production Update](#) (Dakin, Pal, Belen and Küpper, 2010).

3 V82 Nebraska, USA

3.1 Phase 1

The test on the V82 turbine in Nebraska consists of two phases. The initial phase was conducted to assess the ability of the Vindicator[®] LWS unit and associated control system to reduce loads on the turbine. The initial loads reduction resulting from the Vindicator[®] LWS control was reported by SWANTech[™] (SWANTech[™] 2009). During Phase 1, it was also demonstrated that, in addition to loads reduction, the integration of the Vindicator[®] LWS also increased the average energy production of the turbine. The results during the initial phase of the test were reported in [Boosting Power Production](#) in December 2009. Further data was presented in [Boosting Power Production Update](#) (Dakin et al., 2010) for eight months of collected data, which demonstrated a 10.7% energy increase when the Vindicator[®] LWS control system was in control of the yaw of the turbine. Data collection continued for an additional three months, resulting in a total of 11 months. This data is presented in Figure 1 and translates into an average energy increase of 14% using the Vindicator[®] LWS control system throughout the 11-month data collection period.

August 2009-June 2010 Power Curve

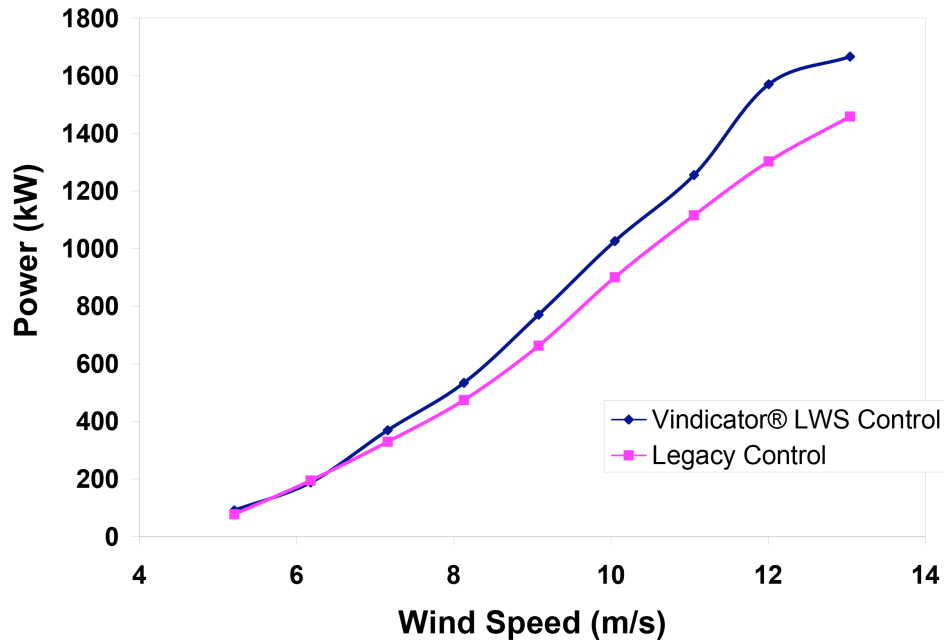


Figure 1 The power curve for 11 months of V82 testing in Nebraska, USA. The curve shows that the turbine consistently generated more power when under Vindicator® LWS control. This increase in power translated into a 14% increase in average energy output using the Vindicator® LWS control system during the 11 month period.

3.2 Phase 2

The second phase of the trial on the V82 is designed to optimize the control system to further reduce the stress loads on the turbine. It was necessary to install a new set of stress monitoring sensors in order to adequately measure the stress loads on a meaningful time scale. The sensor installation commenced during the summer of 2010 and was completed in March 2011 by the instrument supplier. During this installation period, a preliminary power optimization experiment was conducted, whereby the averaging time of the Vindicator® LWS wind direction signal in the controller was varied, as was the degree of misalignment the turbine could achieve before the system yawed (i.e., the yaw deadband). The Vindicator® LWS controller alternated control of the V82 turbine in 1 hour increments with the legacy turbine controller with data collected by the third party integrator. The third party integrator collected the data. This experiment helped to define the relationship between the averaging period of the wind direction signal, the permitted yaw deadband and the amount of time that the turbine spends yawing. It also demonstrated a significant improvement in energy capture obtained by decreasing the averaging time and decreasing the yaw deadband. Figure 2 shows the results from one of such experimental test configurations. In this configuration, the averaging time of the signal was decreased by 30% while the yaw deadband was left at the baseline. This configuration led to only an **8%** increase in the amount of time the turbine spent yawing while the simultaneous increase in power in each wind speed bin led to an overall average energy increase of over **20%** when the Vindicator® LWS controller was active.

Preliminary Optimization Trial 1

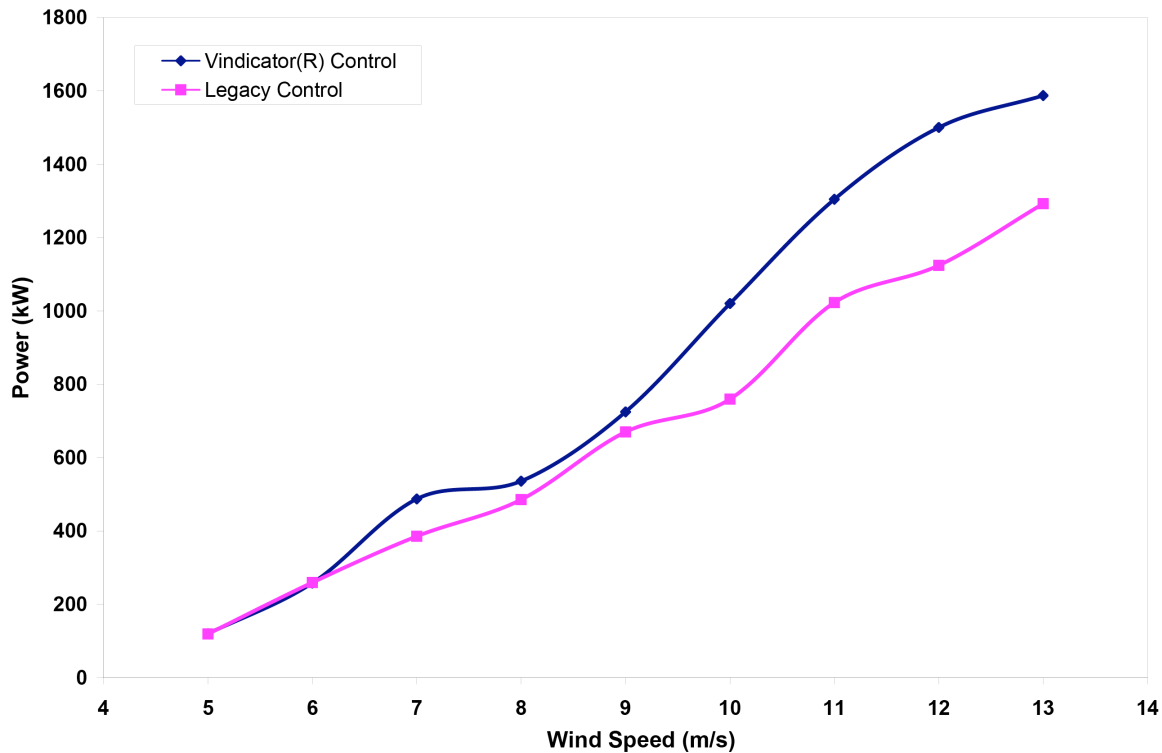


Figure 2 Power curves resulting from one set of power optimization experiment test configurations. In this run, the yaw deadband was left in baseline condition, while the wind direction time averaging was decreased by 30%. Using these parameters, the resultant power curve translates into over 20% greater average energy production using the Vindicator[®] LWS control system while only yawing for approximately 8% more of the time than under legacy control.

4 Nordex N60

A Vindicator LWS was installed on a Nordex N60 turbine in Alberta, Canada in 2009 and was integrated into the control system in December 2010. In order to demonstrate the benefit to power generation of simply pointing the turbine more accurately into the wind, the Vindicator[®] LWS wind direction measurement was simply substituted for the legacy sonic anemometer signal into the legacy controller. Therefore, the turbine provides its own time averaging and the yaw deadband and **does not yaw more with one input than the other**. Data was then collected over a one-month test period. This substitution approach, though simple, does not allow for further optimization due to a lack of control over turbine control parameters. However, by simply pointing the turbine more accurately into the wind, the turbine produced an average of 11.1% more energy with the Vindicator[®] LWS over the one-month trial period when the control inputs were toggled every 1.5 hours. The power curve showing the corresponding power produced in each wind speed bin is shown in Figure 3.

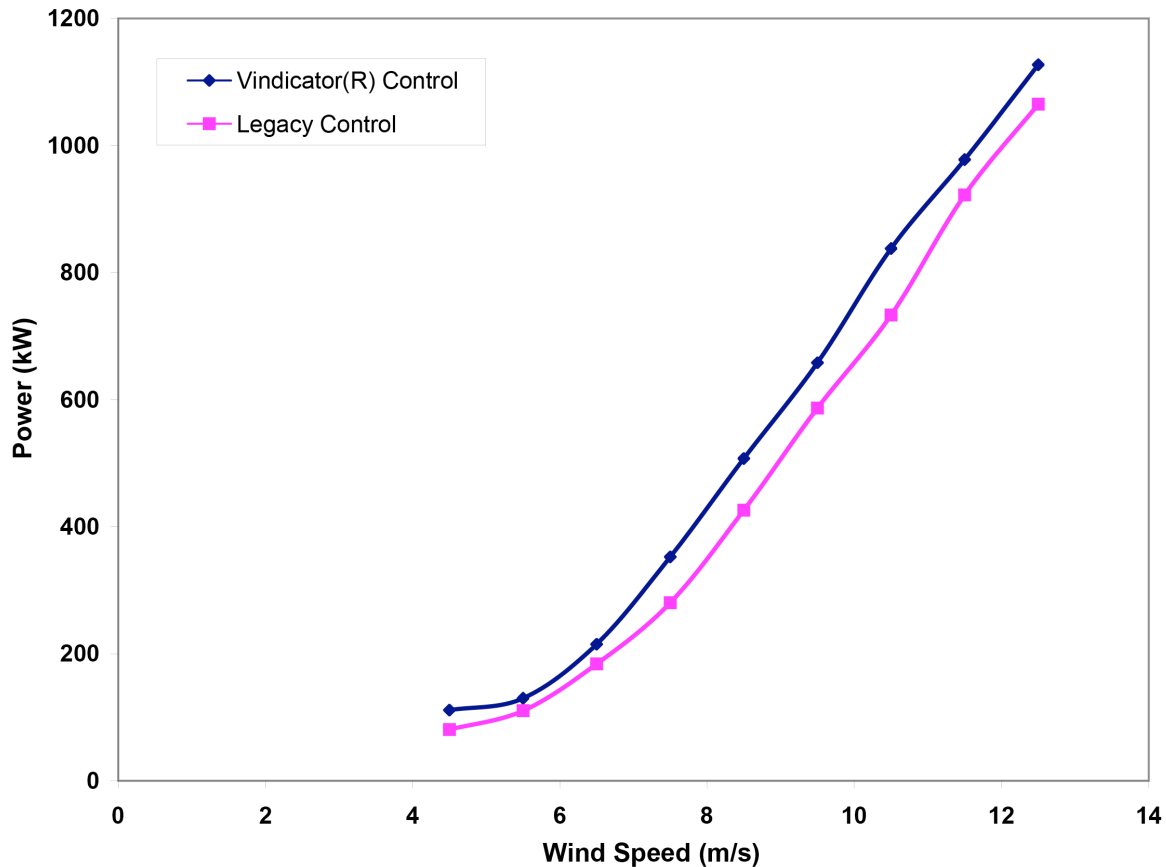


Figure 3 Power curve showing the average power produced comparing when Vindicator[®] LWS was in control (Blue) and the ultrasonic anemometer was in control (Magenta) during the trial period. The turbine produced more power using the wind direction measurements of the Vindicator[®] LWS than the ultrasonic anemometer in all wind speed bins.

5 Yaw Error Analysis

The increase in power production with the Vindicator[®] LWS is attributed to improved pointing accuracy of the yaw position and increased large-scale gust detection. During the year that the Vindicator[®] LWS was collecting data and prior to the integration of the Vindicator LWS into the control, the yaw error of the Nordex N60 was recorded. The integrated yaw error is defined as the mean of the absolute value of the instantaneous wind direction measurement with respect to the nacelle. Yaw error data was also recorded at several other sites at which Vindicator[®] LWS units were installed. Table 1 shows the integrated yaw errors and the RMS yaw errors for all of these sites for periods when legacy wind measurements and controls were used. This represents two ways of calculating an average yaw error over time when wind direction data ahead of the turbine is not used.



Table 1 Integrated Yaw Error for Four Wind Farms

Turbine Model	Avg. Integrated Yaw Error	RMS Error
Vestas V-82	15°	21°
Nordex N60	13°	16°
Vestas V-82	15°	19°
Other 2.0 MW	15°	19°
Other >2.0 MW	12°	17°

As Table 1 indicates, all of the turbines on which Vindicator® LWS units have been used to measure actual inflow direction, while instruments behind the blades are in control, show similar yaw errors. These errors far exceed those used in the design standard for wind turbines. This yaw misalignment leads to reduced power performance potential and significant wear and tear on the blades, blade roots, the main shaft bearing and the gearbox.

6 Conclusions

This report presents power and energy data from two different turbine types at different geographic locations that show similar power performance improvements when using wind direction signals measured in front of the turbines, including when simply substituting the legacy signals with the more accurate look-ahead signals and without any further control optimization. The Vindicator® LWS control system has been in operation on the V82 turbine for 19 months and, during that time, has shown significant improvements in power and energy capture. Feeding the Vindicator® LWS direction information into the existing control system of an N60 turbine also significantly increased the power and energy capture by simply pointing the turbine more accurately into the wind. Through optimization, the energy capture should be even more significant as demonstrated by the preliminary optimization experiment performed on the V82 turbine. The power and energy improvement results should be consistent for all makes and models of turbines and at all geographic wind sites, as the V82 and N60 results in this report are consistent with the significant average yaw misalignment of each one of the turbines on which a Vindicator® LWS has measured inflow direction. The significant yaw misalignment of wind turbines highlights the magnitude of the need for a wind sensor that can accurately sense and report the free stream wind conditions.

7 References

- 1) Catch the Wind, Inc., Boosting Power Production, Dr. Elizabeth Dakin, December 2009
- 2) Catch the Wind, Inc., Boosting Power Production Update, Dr. Elizabeth Dakin, Dr. Avishekh Pal, Frederick C. Belen and Dr. Michael Küpper, May 2010
- 3) SWANTech™, a Curtiss-Wright Flow Control Company, SWANTech Data Summary NPPD - Ainsworth, Nebraska Turbines T21-T24, 2009