Boosting Power Production

Project Report on Nebraska Public Power District Vindicator® LWS Field Trial

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Abstract

This paper analyzes the data collected during a one-month field trial program with Nebraska Public Power District (NPPD) in August 2009 assessing the benefit of a nacelle-mounted laser wind sensor to optimally align a wind turbine with the approaching wind. A Vindicator® Laser Wind Sensor (LWS) was installed on a Vestas V-82 NPPD turbine in Ainsworth, Nebraska and the wind direction measurement was integrated into the yaw control. Very conservative control laws were implemented causing the Vindicator® LWS to provide control inputs to the turbine 56% of the month. The increased pointing accuracy and increased gust detection led to an average of 12.3% power production increase by utilizing the wind direction data from the Vindicator® LWS over that of the wind vane.

A Catch the Wind, Inc. Published Paper




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1 Introduction

Design of control algorithms for wind turbines requires accurate and timely knowledge of the inflow. This information traditionally comes from wind vanes and anemometers. Though the wind that hits the turbine comes from in front of the blades, the only practical mounting position for the wind measurement devices is on top of the nacelle behind the blades. However, mounting the meteorological devices on the nacelle leads to the coupling of blade and nacelle interference effects into the measurements, so the raw data they produce no longer represent the true wind that hits the turbine blades.

One way to compensate for these effects is to measure the transfer function for the wind as it passes through the blades and over the nacelle and perform a correction of the measured values within the control system. Generally, this function is measured and modeled for the turbine as a function of the inflow characteristics. The model is then used to correct the wind vane direction measurements and better align the turbine with the wind in front of the blades. However, in order to make the wind vane information useful for the transfer function, the stochastic aerodynamic effects of the rotors and nacelle must be filtered out. Unfortunately, this filter also eliminates the stochastic component of the inflow that may be relevant within the controller.

The only way to obtain an accurate measurement of the incoming wind is to measure it 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 remotely measures the wind ahead of the rotors so that it can rotate with the nacelle and make measurements in the direction the turbine is pointing. This can be accomplished with a laser-based wind sensor.

Recently, a hub mountable, forward-looking, multiple point reporting remote laser wind sensor called the Vindicator® Laser Wind Sensor (LWS), manufactured by Catch the Wind, Inc. (CTW) in Manassas, Virginia, USA, was mounted to a Nebraska Public Power District (NPPD) Vestas V-82 Turbine in Ainsworth, Nebraska. The wind sensor utilized the wind measurement taken 150m ahead of the turbine. The controller used the Vindicator® LWS wind direction data input to control the yaw direction of the turbine.

This report will present data demonstrating how, in helping the turbine to point accurately into the oncoming wind and detecting gust presence, the sensor increased the turbine's power production by over 12% using a non-optimized very conservative control algorithm. This is in addition to the reduction in loads on the turbine.

2 Equipment

The Vindicator® LWS is a Class I eye-safe laser product designed to remotely measure wind speed and wind direction at 100 m, 150 m, and 200 m ahead of the sensor. CTW installed one Vindicator® LWS on Turbine T22 at the NPPD Ainsworth Wind Energy Facility in Ainsworth, Nebraska. The Vindicator® sensor was commissioned on July 8th, 2009 and the NPPD 30 day field trial of the sensor was conducted during the month of August 2009.

The Vindicator® system consists of four individual sub-assemblies: (1) Base Laser Unit (BLU), (2) Remote Lens Unit (RLU), (3) Environmental Control Unit (ECU), and (4) Programmable Logic Controller (PLC). The mounting locations of these units within and on the nacelle are identified in Figure 2.

The BLU is located inside the nacelle and securely mounted to the side of the generator housing, as shown in Figure 2. It is connected to the RLU which is secured to the top of the nacelle (shown in Figure 1) and is oriented facing forward such that the RLU window has a clear line of sight ahead of the turbine. The ECU is located inside of the nacelle and controls the environmental functions for the RLU.

The PLC is installed in the nacelle as shown in Figure 2. Electrically, it is placed logically in line with the existing turbine PLC (TOI) such that the yaw control functions of the turbine are managed by the Vindicator® PLC. Through the PLC, data was recorded at 1 Hz from the Vindicator® LWS and the existing anemometer and wind vanes. Data was also analyzed from the site Supervisory Control and Data Acquisition (SCADA) system from which the 10-minute averaged relative wind direction, anemometer wind speed, yaw angle and average active power production data were obtained.

Figure 1 shows the Vindicator® LWS mounted on the top of the V-82 Vestas NPPD Turbine T22. As shown in the picture, it was mounted in front of the heat exchanger, below the current anemometers and wind vane so as not to disturb the airflow over the legacy instrumentation.

Figure 1 Vindicator® LWS Installed on T22

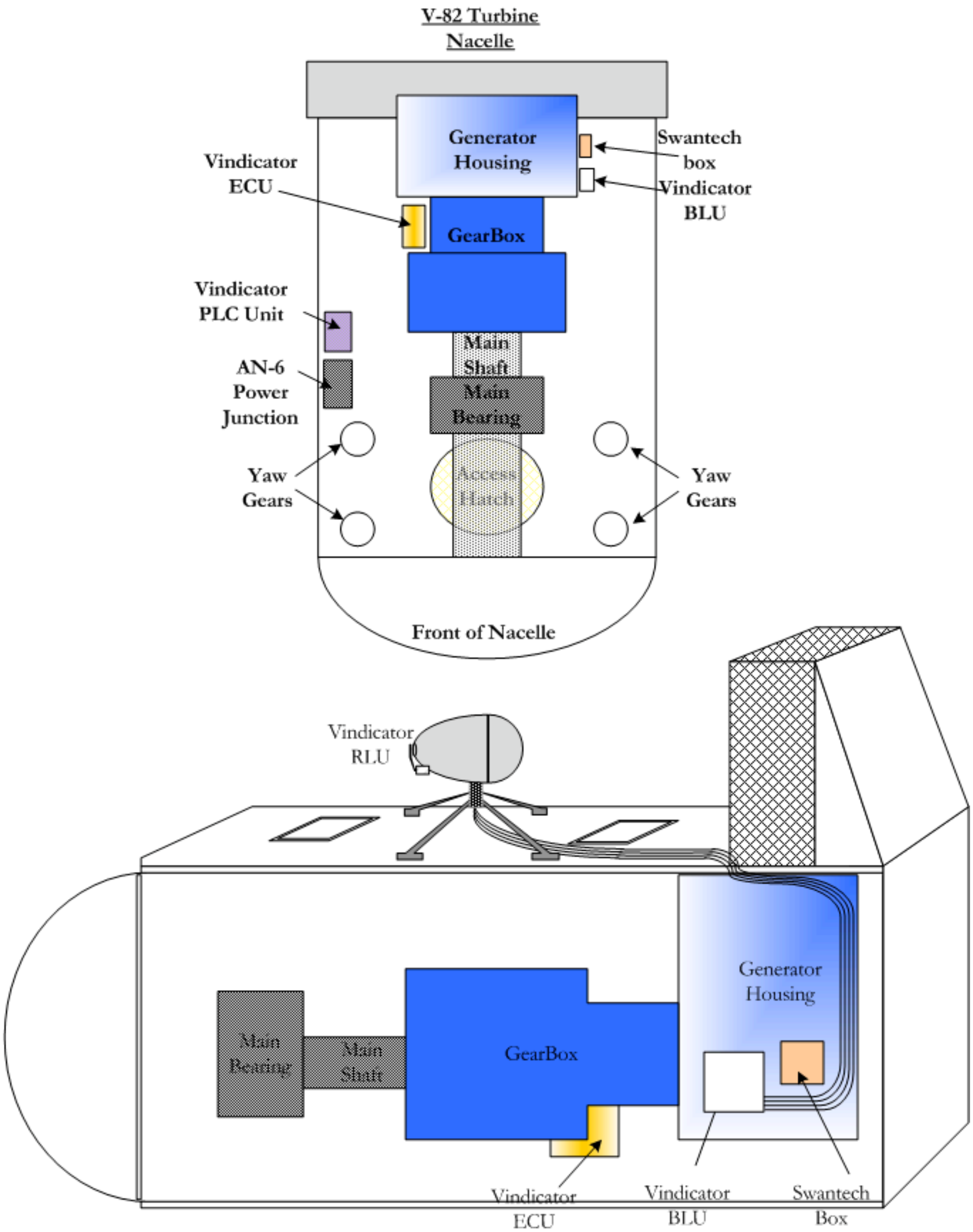

Figure 2 Mounting Locations of the Vindicator® LWS in the T22 Nacelle (not to scale)

3 Control Algorithm

The new PLC controls all yaw functions for the turbine, but takes inputs from the legacy controller for yaw events initiated by emergencies, unwraps and wind vane control. Therefore, all wind vane correction factors remained in place when the wind vane was in control. When the Vindicator® LWS was in control, the PLC used three-minute running averages for the wind direction. Since this was the first time a Vindicator® system was used to control a large-scale wind turbine, very conservative control laws were put in place. These control laws are outlined below.

The Vindicator® LWS three-minute running average wind direction was used to control the yaw unless the following conditions were met:

1. If the wind speed measurements of the Vindicator® LWS and the nacelle anemometer differed by more than 3 m/s, the control shifted to the wind vane until the two measurements agreed to within 3 m/s for 30 minutes, although the Vindicator® LWS wind speed measurement was not used as a control input.
2. If the wind direction measurements of the Vindicator® LWS and the raw wind vanes disagreed by greater than 60^0, control input shifted to the wind vane until the two measurements agreed to within 60^0 for 15 minutes.
3. If Vindicator® LWS indicated a bad data flag, wind direction input was provided by the wind vane until the flag cleared.

Due to these conservative control rules, Vindicator® LWS was used as the direction input to the control algorithm for 56% of the month. Following the conclusion of the NPPD field trial on August 31, 2009, the optimization of the control algorithm commenced with the first two criteria being relaxed to increase the amount of time the Vindicator® LWS is providing inputs to the control algorithm.

4 Results and Analysis

4.1 Power Production Results

Improved knowledge of the inflow leads to more efficient power capture by the turbine. Since the test's conservative control laws resulted in the Vindicator® LWS providing control inputs to T22 only 56% of the time during the month of August 2009, a comparison of the power produced by turbine T22 with and without Vindicator® LWS control inputs is possible. Figure 3 shows the average power produced with Vindicator® LWS control inputs (blue) and wind vane control inputs (red), binned by wind speed. The wind speed used to bin the power data was measured by the anemometer on the nacelle due to the inaccessibility of the met tower data. The figure illustrates that the turbine produced more power with the accurate inflow direction measurements of the Vindicator® LWS at all wind speeds.

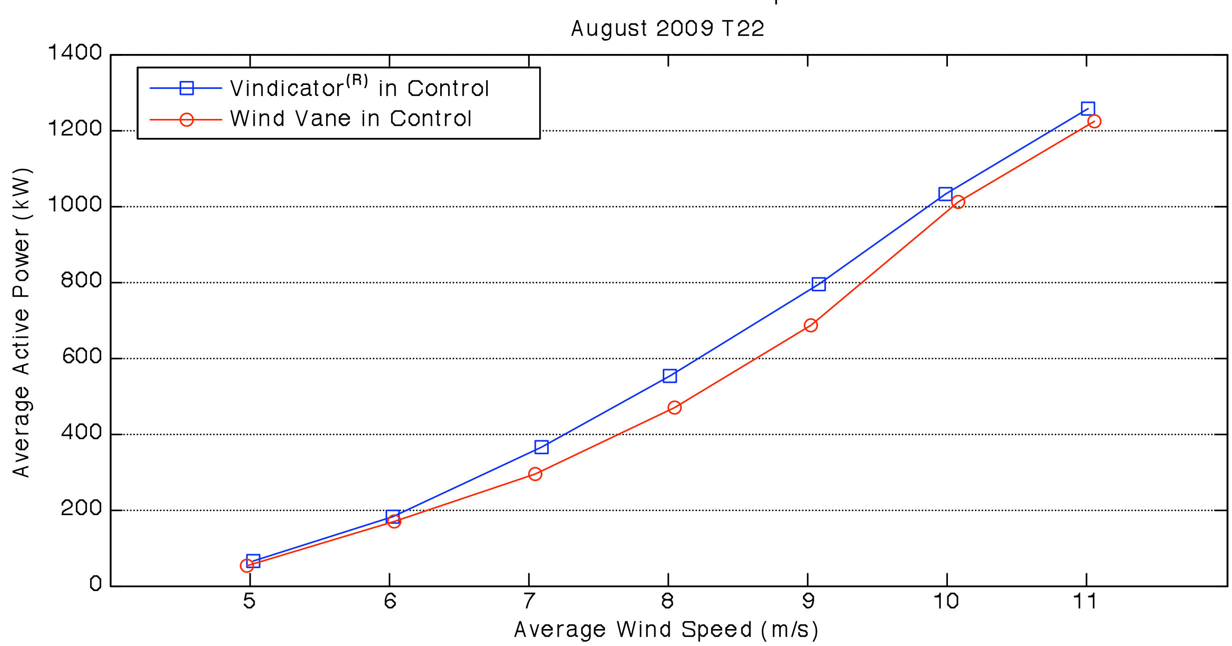

Figure 3 Power Curve showing the active power produced comparing when Vindicator® LWS was in control (Blue) and the wind vane was in control (Red) during the month of August 2009. T22 produced more power using the wind direction measurements of the Vindicator® LWS than the wind vane in all wind speed bins.

The power produced under the two control inputs was compared and the average percentage difference was calculated. A graph of the percentage power increase per wind speed bin under Vindicator® LWS wind direction input is presented in Figure 4. It is evident that the power production increased using the Vindicator® LWS control input for all wind speed bins. The average power increase across all wind speed bins was 12.3% as depicted by the red line on the graph in Figure 4. It is also evident that there was a much greater than average percentage power increase for wind speed bins at 5, 7, 8, and 9 m/s. Figure 5 shows the number of data records recorded in each wind speed bin. The nacelle anemometer is susceptible to effects from the turbine nacelle and blades that can cause either speed up or slow down effects in the reported wind speeds. In order to ensure that the power produced within a wind speed bin is actually representative of the power produced at that inflow wind speed, a threshold for the number of data records captured must be set before a bin is considered valid so that the data is not skewed. An empirical threshold of 125 records generally ensures that there is an even distribution of wind speeds within the bin. Based on this threshold of 125 data records for both control inputs, Figure 5 demonstrates that only wind speed bins at 5, 7, 8, and 9 m/s are useful and the power values of wind speed bins 6, 10 and 11 should be disregarded. Employing only wind speed bins 5, 7, 8, and 9 m/s, the average power production increase using Vindicator® LWS wind direction inputs rises to 18%.

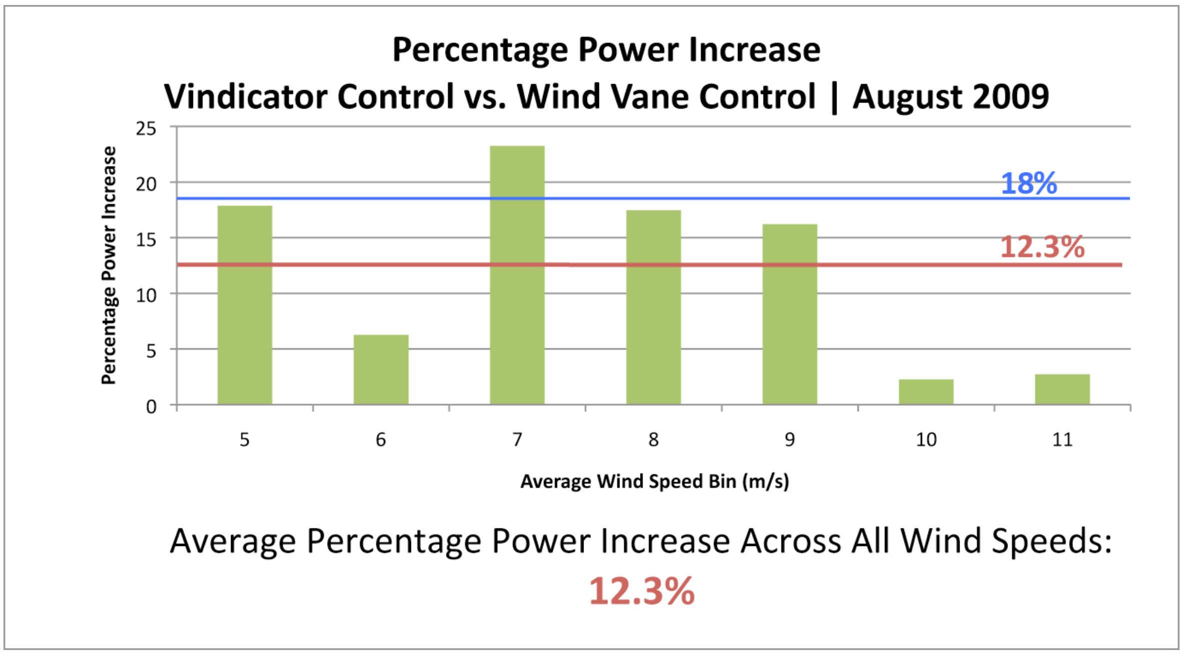

Figure 4 Percentage power increase binned by wind speed with an average active power increase of 12.3% (depicted by the red line). The Vindicator® LWS wind direction control input improves the power output at all wind speeds. Employing only those bins with enough data records to be statistically significant, the average power production increase using Vindicator® LWS wind direction input rises to 18% (depicted by the blue line).

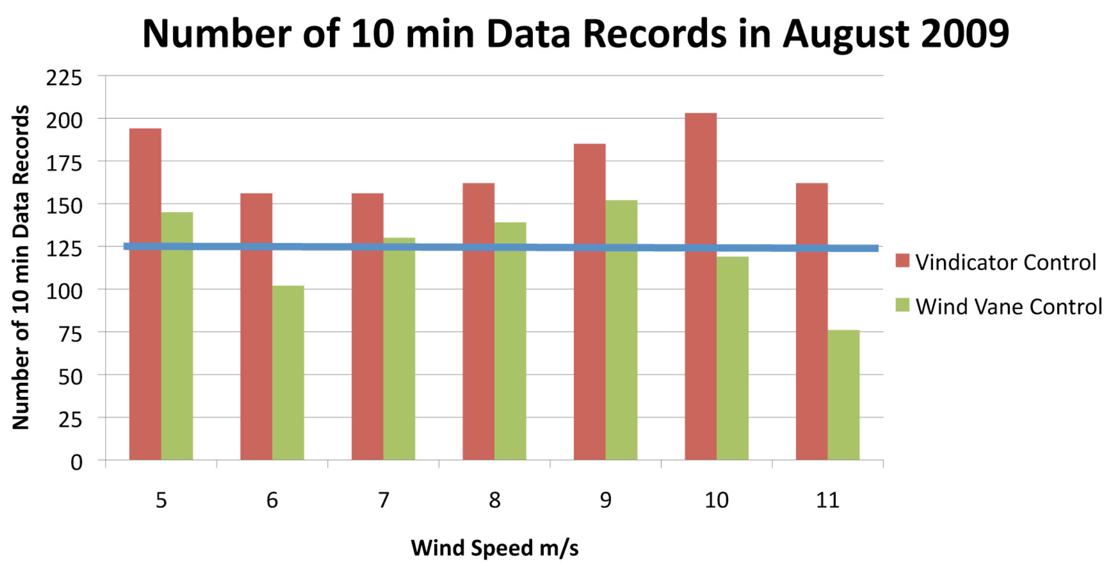

Figure 5 Number of data records in each wind speed bin for Vindicator® LWS yaw control input (red) and nacelle wind vane control input (green). 125 data records per bin are required to overcome anomalies in reported wind speed.

4.2 Analysis

Both the increase in the power production and the decrease in the stress on the main shaft bearing (SwanTech 2009) can be attributed to improved pointing accuracy of the yaw position and increased large scale gust detection. Figure 6 shows both the three-minute averaged wind direction that was used to control the turbine and the yaw angle of the turbine while it was under Vindicator® LWS control during a three hour period on August 14, 2009. The red lines depict examples of the relative wind direction out of alignment by 10 degrees or more with the nacelle and the turbine yaw and the yaw angle reacting. As can be seen by this figure, with the Vindicator® LWS providing wind direction inputs, the turbine reacts to the changing wind direction quite often. Figure 7 shows the three-minute relative wind direction as measured by the Vindicator® LWS overlaid on the SCADA Relative Wind Direction data as reported by wind vane #2. The horizontal lines indicate +/-10 degrees and the vertical red lines highlight the same yaw events during the time period shown in Figure 6. This figure shows that the wind vane does not report most of the gusts whose energy is absorbed by the turbine while under Vindicator® LWS control. Figure 7 illustrates that, by accurately and precisely measuring the inflow, the Vindicator® LWS is able to report, and the control system is able to react to, the changing wind direction. This simultaneously increases power and decreases loads on the turbine.

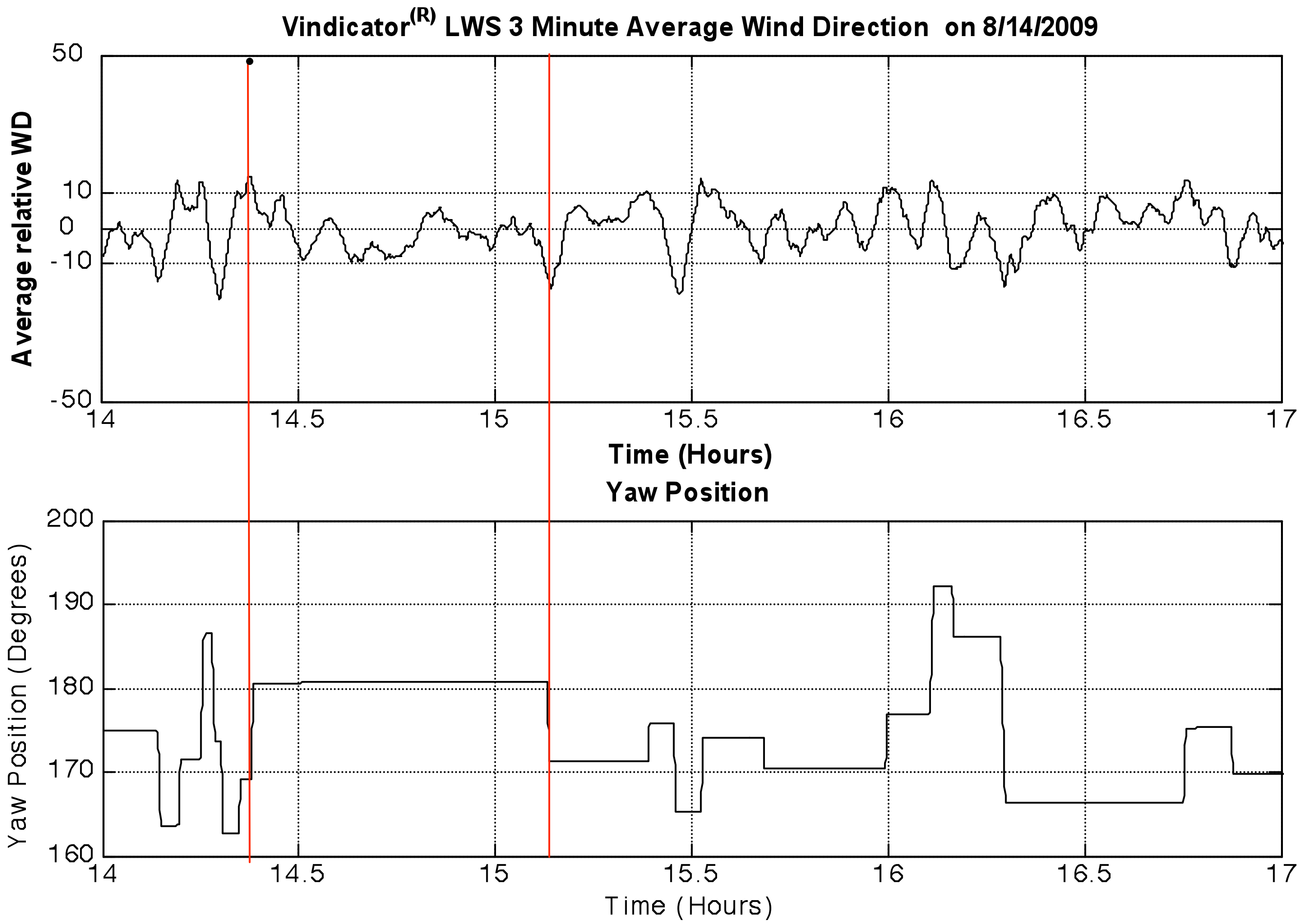

Figure 6 The top plot depicts the Vindicator® LWS three-minute average wind direction used to control T22. The bottom plot depicts T22's yaw position as a function of time. When viewed together, the figures demonstrate that a relative wind direction reading greater than or equal to 10 degrees resulted in a yaw of the turbine. Vertical red lines highlight two examples of yaw events triggered by a wind direction shift.

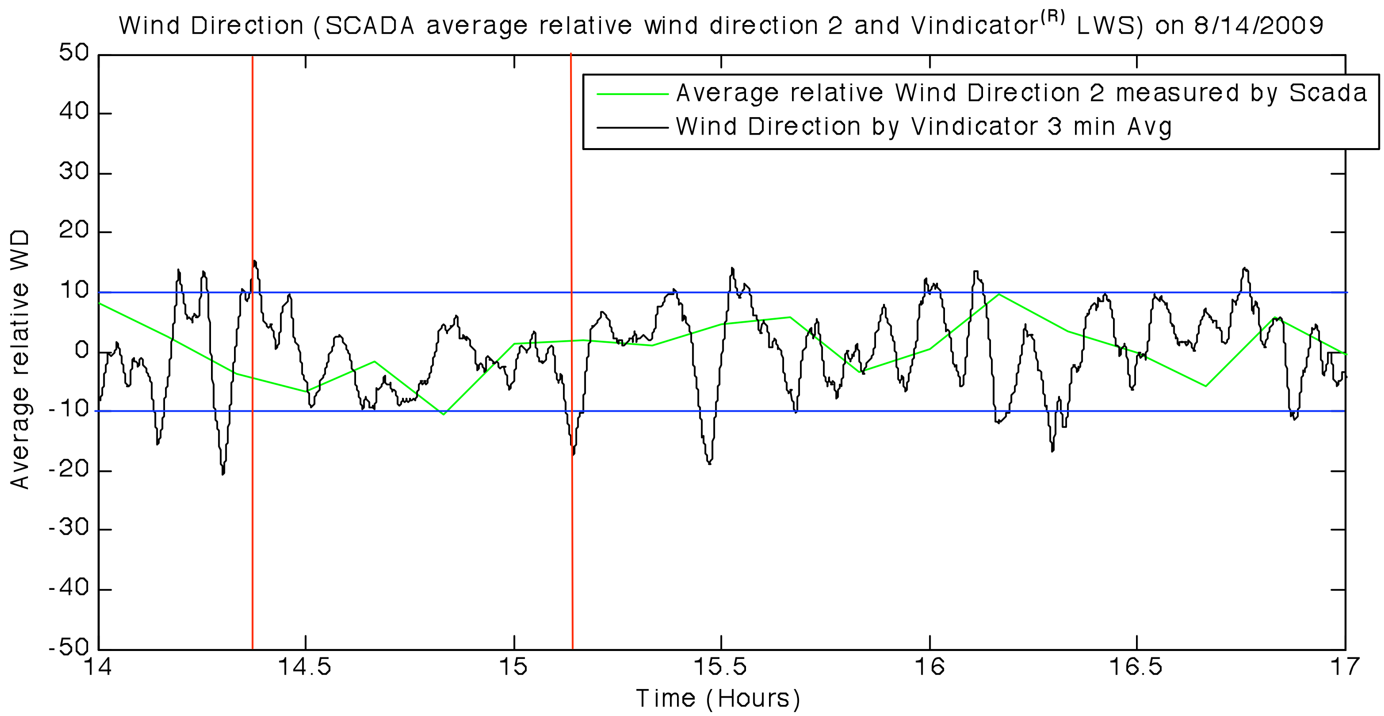

Figure 7 Wind direction as measured by the SCADA (corrected relative wind direction) and the Vindicator® LWS three-minute averaged wind direction, with the turbine control yaw input using the Vindicator® LWS direction. The new PLC was programmed to yaw when the relative wind measurement was greater than 10 degrees out of alignment with the nacelle (i.e., outside of the blue lines). Vertical red lines highlight the same yaw events for the time period as shown in Figure 6.

4.3 Wind Data

The raw wind vane data was captured by the Vindicator® PLC and analyzed to determine the reasons for the underreporting of large-scale wind gusts. The 1 Hz wind vane data is shown in Figure 8 by the red and green line for the same three hour period on August 14, 2009 as the data above. The Vindicator® LWS three-minute averaged data is depicted in black. It is evident from the frequency of the fluctuations on the plot that the two wind vanes are low-pass filtered with a cut-off frequency that imitates a 10-minute average. By low-pass filtering the data before it reaches the controller, the wind vane is not reporting many of the large-scale gusts that hit the turbine. This is necessary because the time and length scale of the large gusts mean they become indistinguishable from the effects of the nacelle and blades on the wind interacting with the wind vane. In order to produce a signal that is useful to the controller, the wind vane must filter the nacelle effects out and, in doing so, filter many useful measurements of the inflow. The Vindicator® LWS outputs the raw 1 Hz data to the controller, allowing the control system to optimize the averaging so as to only react to gusts that affect the turbine. In the case of the V-82 turbine, it was determined that three-minute averaging was appropriate to maximize power output and minimize loads and yaw motor wear.

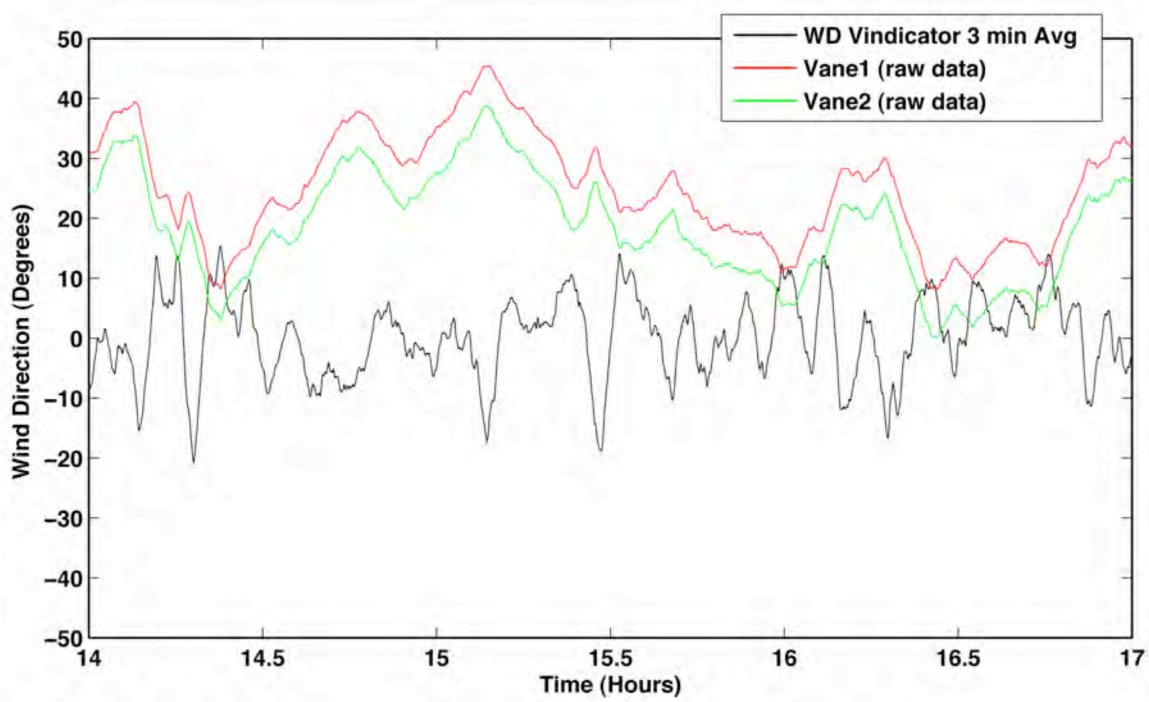

Figure 8 Wind direction as measured by the Vindicator® LWS (black) and the two wind vanes on the turbine nacelle (red and green). The three-minute running average of the Vindicator® LWS and the raw data from the wind vanes are shown, though it appears that the wind vanes have internal low pass filtering. Unlike the corrected SCADA data presented in Figure 7, this wind vane data reported above was taken with no correction factors for the flow over the nacelle.

In the case of wind vane inputs to the turbine controller, the wind vane direction measurement is averaged and corrected using a transfer function in the controller so that it better represents the wind hitting the turbine. This corrected, 10-minute averaged data is then recorded by the SCADA system as the wind vane relative wind direction. Though the transfer function brings the wind direction closer to the data reported by the Vindicator® LWS, the data that is used to control the wind turbine is so highly filtered that it bears little resemblance to the actual inflow hitting the turbine over time as is evident in Figure 7. Accurate and timely gust reporting by the Vindicator® LWS allows the turbine to both increase the power output and, as reported by the SwanTech data cited above, decrease main shaft bearing loads.

5 Conclusions

During August 2009, the Vindicator® LWS wind direction measurement was used as the yaw control input on an NPPD Vestas V-82 wind turbine in Ainsworth, Nebraska. The increased pointing accuracy and increased gust detection led to a significant power increase during the times in August 2009 when Vindicator® LWS wind direction input was used to control T22 instead of the wind vane.

CTW is still measuring data and optimizing various parameters of the T22 control algorithm, including those discussed in Section 3. The results indicate that, with accurate and timely inflow measurement on the 1 Hz timescale, more sophisticated feedback control algorithms can now be developed. The averaging and filtering applied to the input data can be optimized taking into account number of turbine yaws, a reduction of stress loads and increased power production, ultimately enabling more efficient turbine design and operation.

6 Bibliography

SwanTech™, a Curtiss-Wright Flow Control Company, SwanTech Data Summary NPPD - Ainsworth, Nebraska Turbines T21-T24, 2009.