# Yaw Control

*The Forgotten Controls Problem*

Dr. Priyavadan Mamidipudi • Dr. Elizabeth Dakin • Dr. Andrew Hopkins
Frederick C. Belen • Dr. J. Gordon Leishman

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Catch the Wind, Inc. | 10781 James Payne Court, Manassas, Virginia 20110
(703) 393-0754 | Fax: (703) 393-0745 | www.catchthewindinc.com

## 1 Introduction

In the field of modern turbine control design, current yaw control methodology is believed to be as good as it can be. Utility scale turbines are presumed to already be accurately pointing into the wind and novel turbine control methods being developed are focused on advanced blade pitch controls based on that assumption. However, due to the lack of timely and accurate inflow information, and the resulting lack of responsiveness and precision of yaw control, turbines rarely point within ±10 degrees of the wind. In addition to producing significant loading on the blades, blade hub, main bearing and gearbox, this misalignment with the wind reduces the amount of on-axis wind that the turbine can capture and, therefore, lowers the overall energy that the turbine can capture in Region II winds.

Through the use of the wind direction and output power data, it is possible to measure the amount of power that is lost when the turbine is out of yaw. This was originally done as part of a study conducted in 2003 by Risø National Laboratory, a national laboratory under the Danish Ministry of Science, Technology and Innovation[1], where the Risø scientists monitored the power output as a function of yaw angle of a turbine. This study reported that power generated by a wind turbine is proportional to the cosine-square of the wind angle error (yaw). A further review of data collected in the Risø study indicates that there is, rather, a cosine-cube relationship between these two parameters for wind angle errors between ±20°.

Over the past several years, look-ahead laser wind sensors have been deployed on wind turbines throughout North America and Europe and have collected significant data on the yaw misalignment of large utility-scale wind turbines. The actual power curves produced by these turbines are significantly affected by the turbines' misalignment in yaw, confirming the results of the Risø study. This misalignment translates into a substantial reduction of turbine performance and may be a major contributing factor to wind farm underperformance.

This paper presents yaw misalignment and power data collected from an operating utility-scale wind turbine. We further present statistics indicating that all farms considered in this study demonstrated similar results. Finally, we demonstrate that accurate alignment with the inflow increases the captured power and energy.

## 2 Yaw Misalignment

For stall regulated and collective blade pitch control turbines, yaw and pitch control operations can be separated and treated independently. A typical yaw control loop is relatively straightforward, taking wind direction input from the measurement device(s), applying a transfer function, and deciding if the turbine should move, and, if so, in which direction. Controls developers generally assume that this control loop performs optimally (or at least sufficiently) and focus on the more difficult and complicated problem of blade pitch control.

The traditional yaw control approach is, however, only as good as the wind direction measurement feeding into it. In the standard implementation, wind direction measurements are made using wind vanes and/or ultrasonic anemometers located behind the blades on top of the turbine nacelle. This wind direction information is then averaged and a transfer function is applied in an attempt to account for the wind flow disturbance effects of the rotor and the nacelle. Knowledge of the wind field in front of the rotor plane is essential to quantitatively determine the efficacy of this traditional yaw control approach.

A forward-looking Vindicator® Laser Wind Sensor (LWS) was installed on a Nordex N60 turbine in Alberta, Canada, where wind speed and direction data were collected ahead of the turbine for one month. Figure 1 shows a three-dimensional plot of the wind speed, wind direction, and power output data collected from this N60 turbine.


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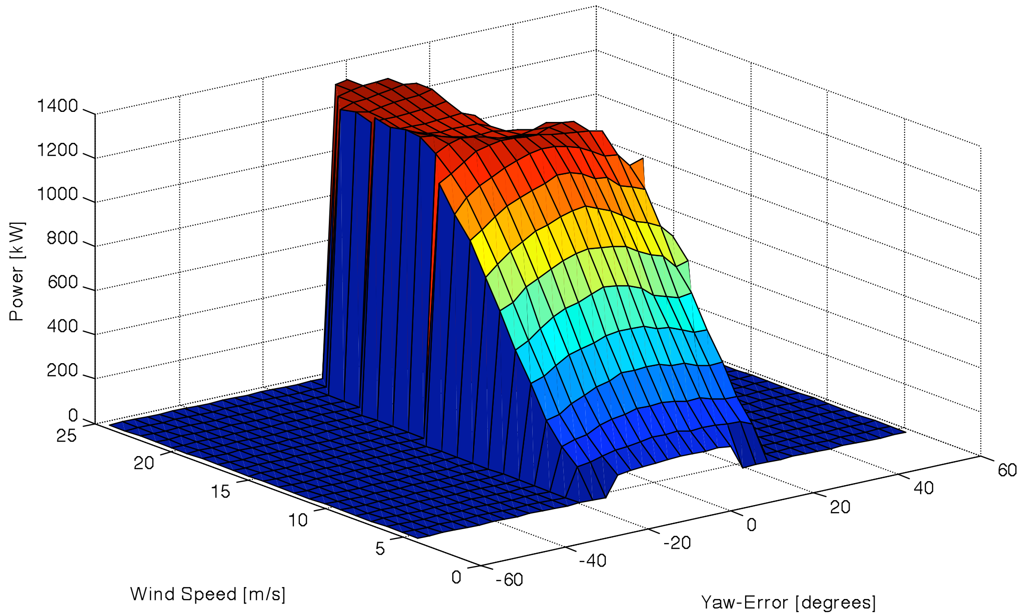


**Figure 1 Three-dimensional plot of the power versus wind speed and yaw angle of an N60 turbine.**

Figure 2 shows the wind speed versus power slice, which represents the power curve for the turbine at zero yaw angle. Figure 3 shows the power versus yaw angle, where the solid lines represent different wind speed bins. Data is only presented for yaw angles of ±20°. It is evident from Figure 3 that: 1) the turbine spent significant time out of alignment with the wind, and 2) these out of yaw events resulted in non-optimal power performance of the turbine.

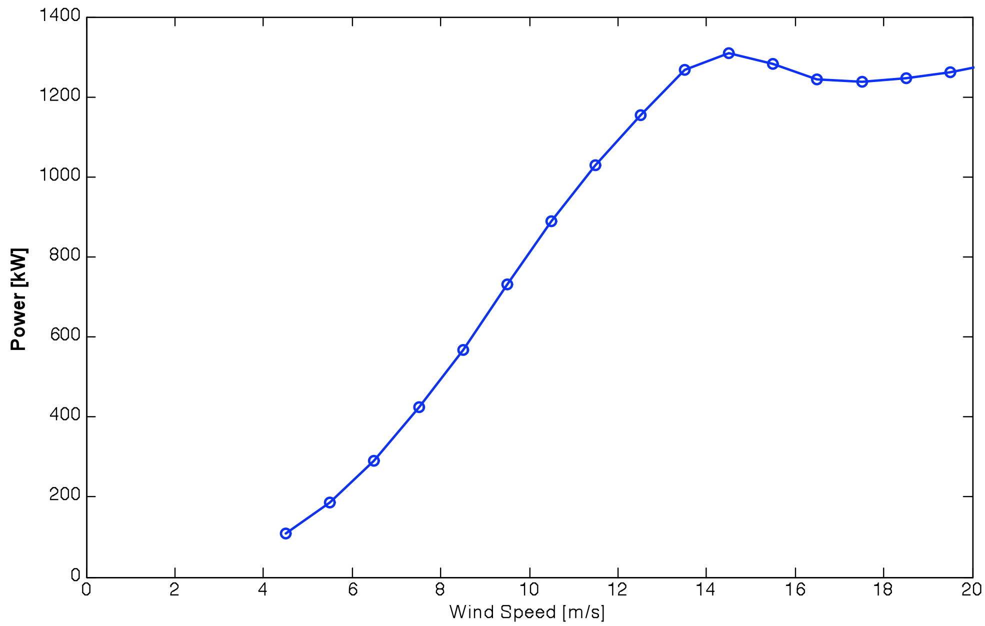


Figure 2 Power vs. Wind Speed slice at zero yaw angle. Wind speed measured by mean of the anemometers on the back of the turbine.

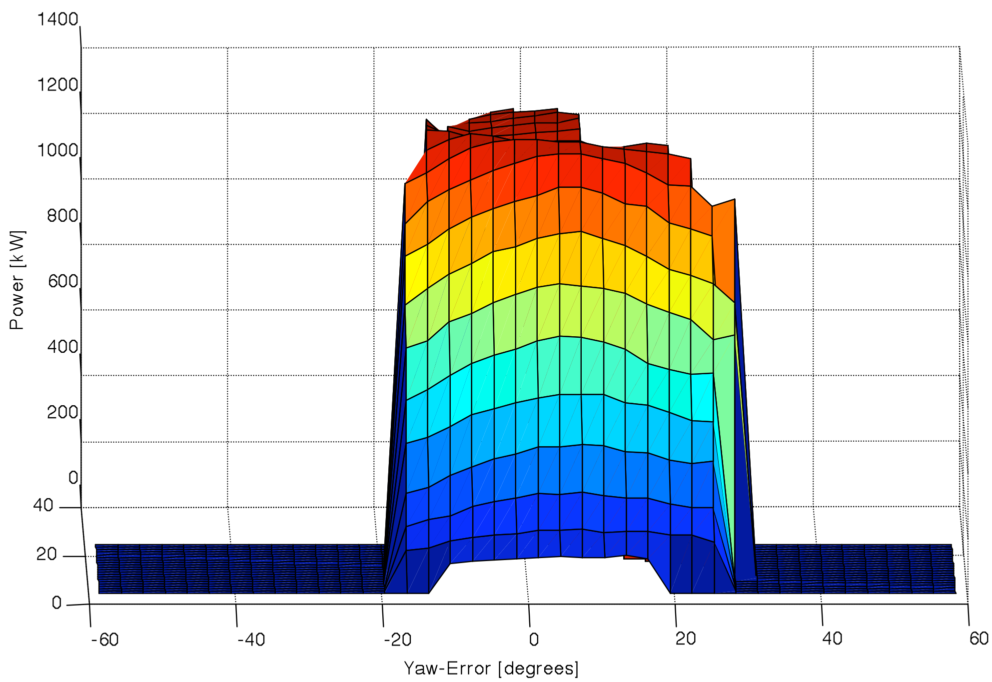


Figure 3 View of the 3D plot from the Power vs. Wind Direction side. This figure shows the roll off of power wind yaw angle. The turbine spends time up to $25^0$ out of yaw.



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Figure 4 (a) and (b) are slices from the power versus yaw plot in two different wind speed bins. From Figure 4 (a) and (b), it is further evident that there is, indeed, at least a $\cos^3$ dependency between loss of power and yaw misalignments between $-20^0$ and $+20^0$, verifying, from a large utility-scale turbine, an even stronger mathematical relationship between power generation and yaw misalignment than outlined in the 2003 Risø study.[1)]

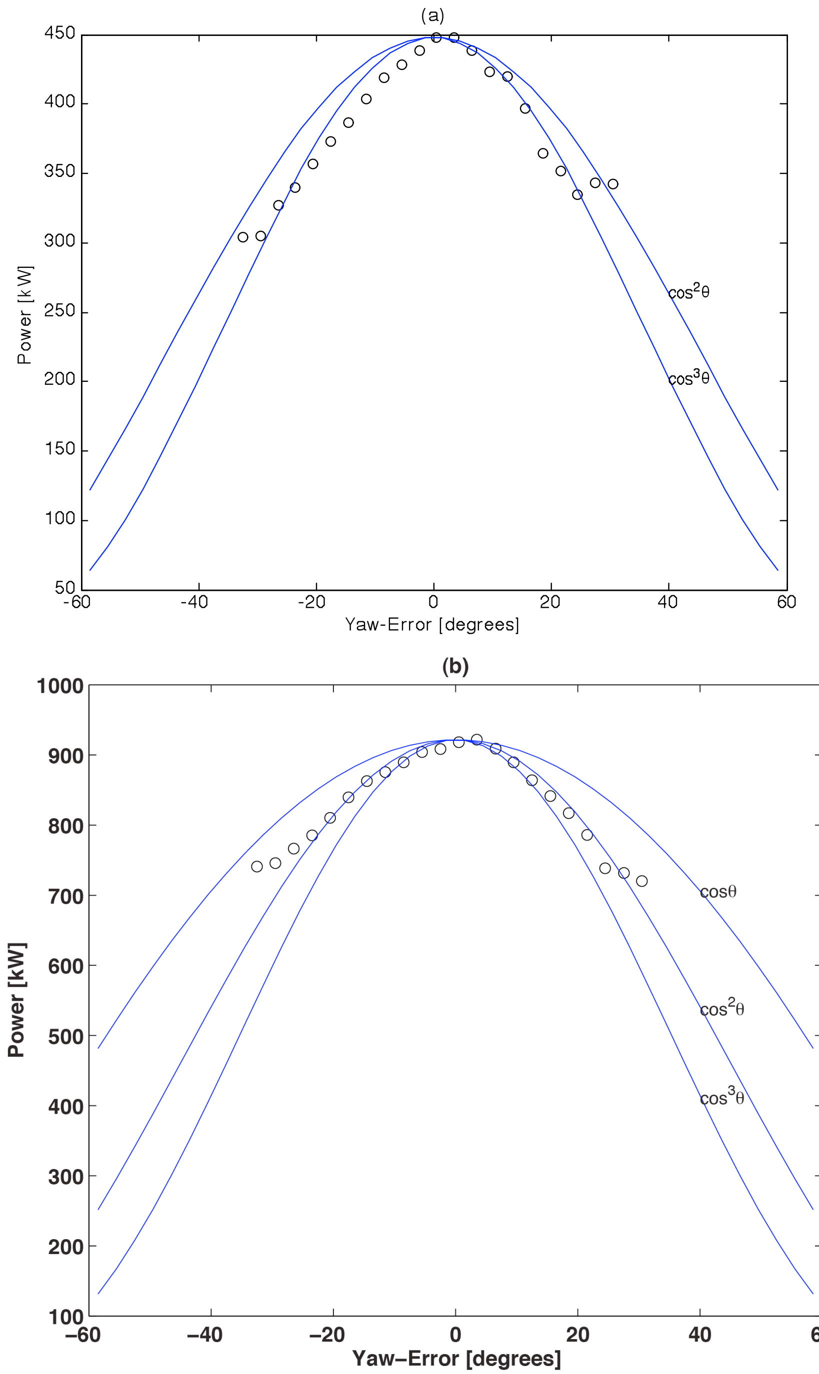


Figure 4 Slices of the Power vs. Yaw angle for (a) the 7-8 m/s wind speed bin and (b) the 10-11 m/s wind speed bin. The cosine cube roll of is evident in these plots between $-20^0$ and $20^0$.


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## 3 Yaw Error/RMS Yaw Error

The amount of time the turbine spent out of yaw and the amount of misalignment were also quantified. Two metrics were used in the analysis of average yaw error. The first metric is an integrated yaw error, which is defined as the mean of the absolute value of the yaw error from zero degrees. The second metric is an RMS yaw error, which is defined as the square root of the mean of the squares of the yaw misalignment values. While the integrated yaw error represents the average angular displacement of the turbine relative to zero yaw, the RMS error highlights the large excursions.

Data collected one month show the N60 turbine had an integrated yaw error of approximately 130 and an RMS error of 160. Yaw errors for other turbines on which Vindicator® LWS units have been mounted to measure inflow direction have also been calculated and are shown in Table 1. As can be seen from the table, all of the turbines are out of yaw by similar amounts.

Table 1 The Integrated Yaw Error and RMS Error for six utility scale wind turbines throughout North America and Europe

| 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° |

The primary factor contributing to the yaw misalignment is the placement of the wind direction measurement devices. The placement of these devices on the rear of the nacelle (i.e., behind the turbine blades) renders them unable to accurately measure the inflow and align the turbine. Figure 5(a) shows a comparison between 10-minute averaged wind speed as measured by the nacelle-mounted sonic anemometer against Vindicator® LWS wind speed measured ahead of the turbine. A similar comparison of 10-minute averaged wind direction data as measured by the sonic anemometer and the Vindicator® LWS is shown in Figure 5(b). These figures demonstrate that there is no linear relationship between the wind measurement made on the back of the turbine and the wind measurements of the undisturbed inflow ahead of the rotors.


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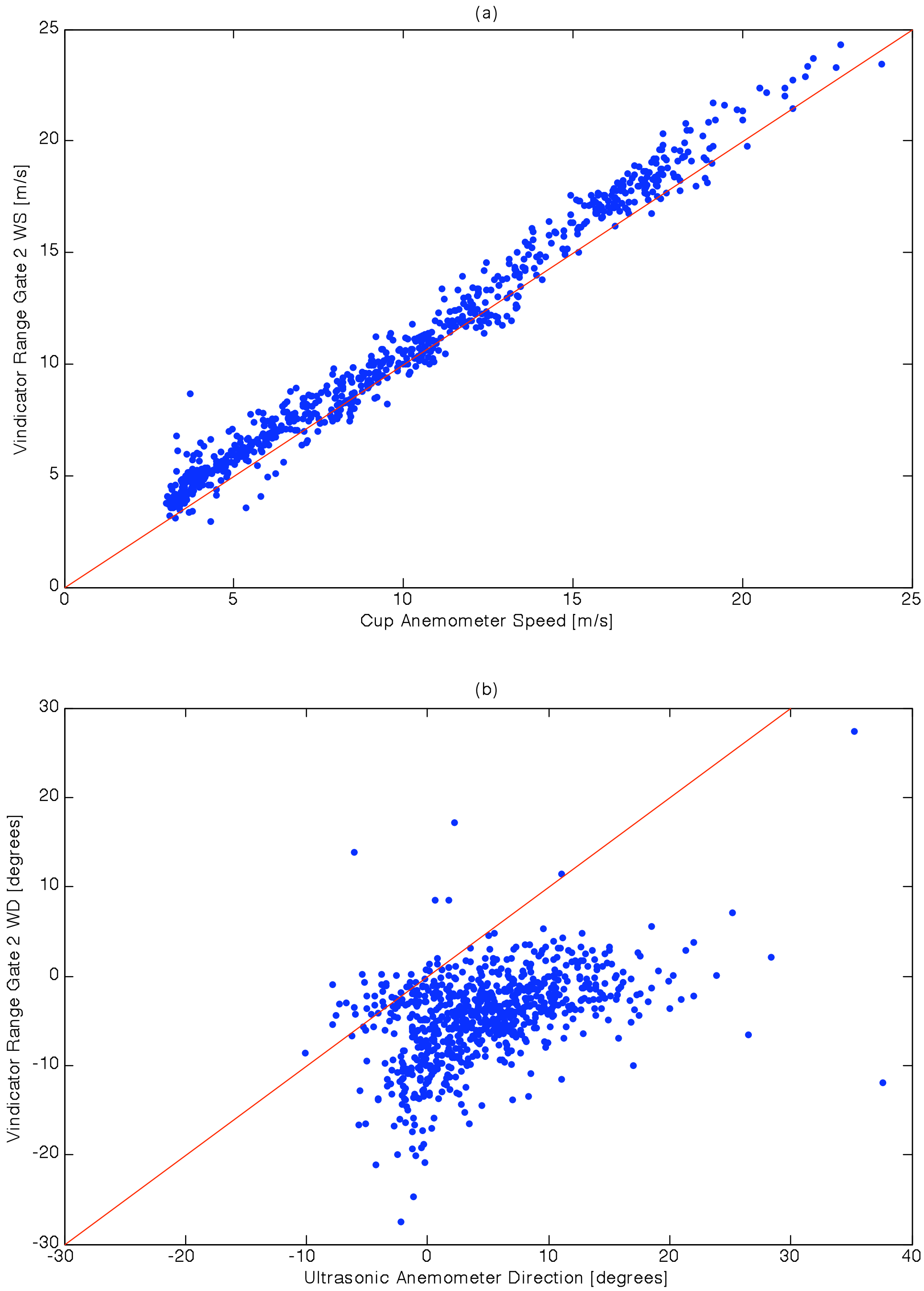


Figure 5 (a) Free stream wind speed as measured by the Vindicator® LWS versus the wind speed measured by the sonic anemometer on the rear of the nacelle. The comparison shows that there is no linear relationship between the free stream wind speed and the wind speed on the rear of the nacelle. (b) Free stream wind direction as measured by the Vindicator® LWS versus the wind direction as measured by the sonic anemometer on the rear of the nacelle. There is very little correlation between the two velocities due to the turbulent shedding from the rotor.

Figure 6 shows similar comparisons of wind data from a nacelle-mounted cup anemometer and wind vane against Vindicator® LWS data. This data was collected from a Vestas V82 turbine in Nebraska. Consistent results between these sites indicate that the findings of this study are not due to measurement errors of a specific type of measurement device or environmental conditions unique to a specific geographic location, but rather due to the systemic problem of measuring the disturbed air volume behind the rotors.

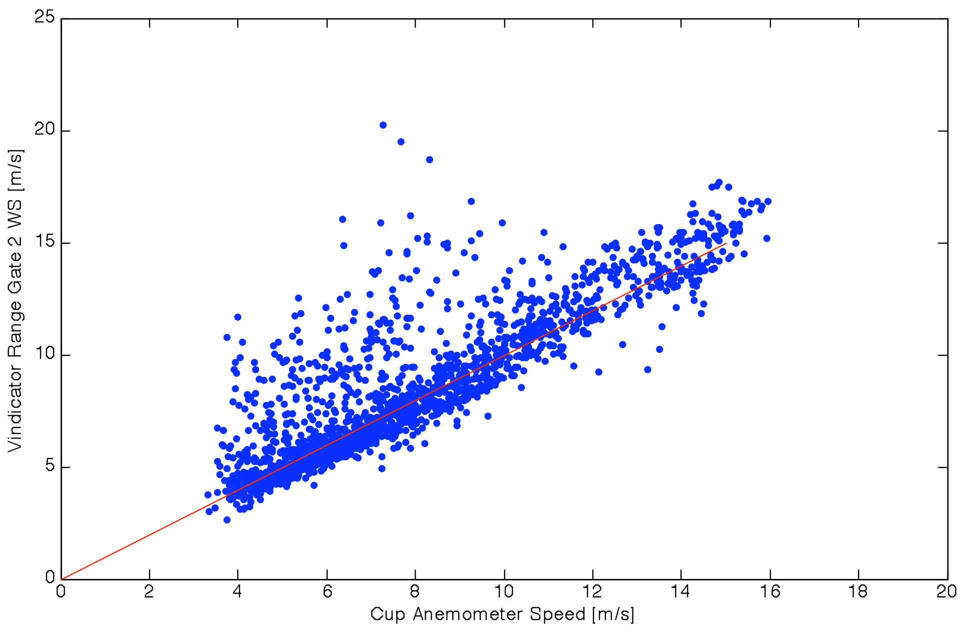


**Figure 6 Free stream wind speed versus wind direction measured on the rear of the nacelle from a Vestas V-82. This confirms that there is not a linear relationship between the free stream wind velocity and the velocity on the rear of the nacelle.**

A common perception is that, if there would be any difference between what is measured in front of the rotors and behind the nacelle, that such alterations behind-the-nacelle are caused by the effects of rotor blockage and a "speed up" (Bernoulli) effect over the nacelle, and that, for the most part, the rotor blockage and the "speed up" effects cancel each other out. In 2001, the National Renewable Energy Laboratory (NREL) conducted a study to research the validity of this perception, in which a small turbine was placed in the NASA Ames wind tunnel.[2] For one series of tests, sonic anemometers were placed behind the nacelle and the wind speed was recorded for various yaw angles and power settings. The results of these studies indicate that the issue is far more complex, as shown in Figure 7. Though this blockage plays a large part in the reduction of the wind speed through the rotors, as the turbine begins to produce power, the dominant effect becomes the thrust produced by the rotors, which is related to the amount of power produced by the turbine. The relationship between the inflow and the wind measured behind rotors on the nacelle is highly nonlinear and cannot be related by a simple linear transfer function.


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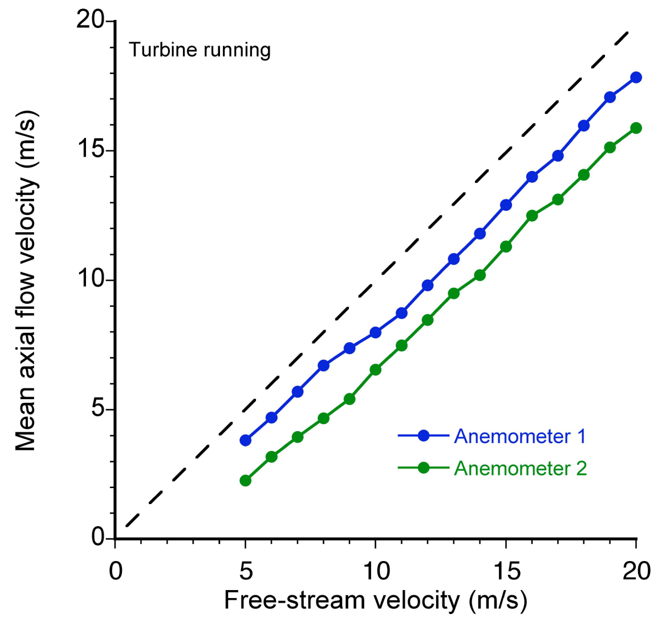


**Figure 7 Wind speed comparisons from the NASA Ames NREL test in 2001. This figure shows that there is no linear relationship between the free stream wind velocity and the velocity behind the rotors. The green curve represents a comparison between the Wind Tunnel Wind Speed and the speed as measured by the sonic 2 m off of the centerline of the turbine. The blue curve represents the wind speed as measured directly along the centerline.**

The other parameters that affect the yaw alignment of the turbine are: 1) the averaging time of the wind direction measurement used in the control algorithm, and 2) yaw deadband (or the amount the turbine must be misaligned before it begins to yaw). These parameters determine the amount of time before corrective yaw actions begin, the time the turbine spends yawing, and the number of times the turbine yaws. Due to the use of anemometers and wind vanes (which are not accurate on short time scales), it was not possible to vary these parameters over a large range. However, with accurate remote measurements of the inflow on very short (greater than 1 Hz) time scales, the parameters in the yaw control algorithms can be optimized over a large range of values, including the possibility of a continuously yawing turbine.

## 4 Yaw Misalignment Matters

This study has shown that utility scale turbines of different makes and models and in different geographic locations all spend much of their time out of alignment with the wind. However, the fundamental question is: Does that matter, and if so, how much? In order to show that the wind direction input to the control algorithm makes a dramatic difference in the performance of the turbine, an experiment was conducted on the Nordex N60 turbine in Alberta, Canada. The only parameter varied during this experiment was the input to the control algorithm, while the yaw control of the turbine remained with the original Nordex controller. Figure 8 shows power curves from this test. In the figure, the blue line depicts the power curve with the Vindicator® LWS direction input, while the red curve corresponds to the legacy sonic anemometer control input. As can be seen, the blue curve is substantially higher than the red curve throughout all of Region II, indicating that the turbine produces more power at each wind speed while it is better aligned with the wind. This increase in power performance translates to an 11.1% increase in captured energy during the test period simply by substituting the legacy wind direction input with a look-ahead wind direction input. During this test, with the Vindicator® LWS, the integrated yaw error was decreased from 13 to 10 degrees and the RMS yaw error was decreased from 16 to 13 degrees. Since the control algorithm was not changed, the turbine did not yaw more often with the Vindicator® LWS input than with the legacy input. In other tests, the control system of the Nebraska V-82 turbine has been modified to take advantage of the look-ahead measurements and the optimization has shown significant improvement over the legacy control system, above and beyond the improvement demonstrated by merely changing the control input. This indicates that given more timely and accurate information, yaw control algorithms can be improved.

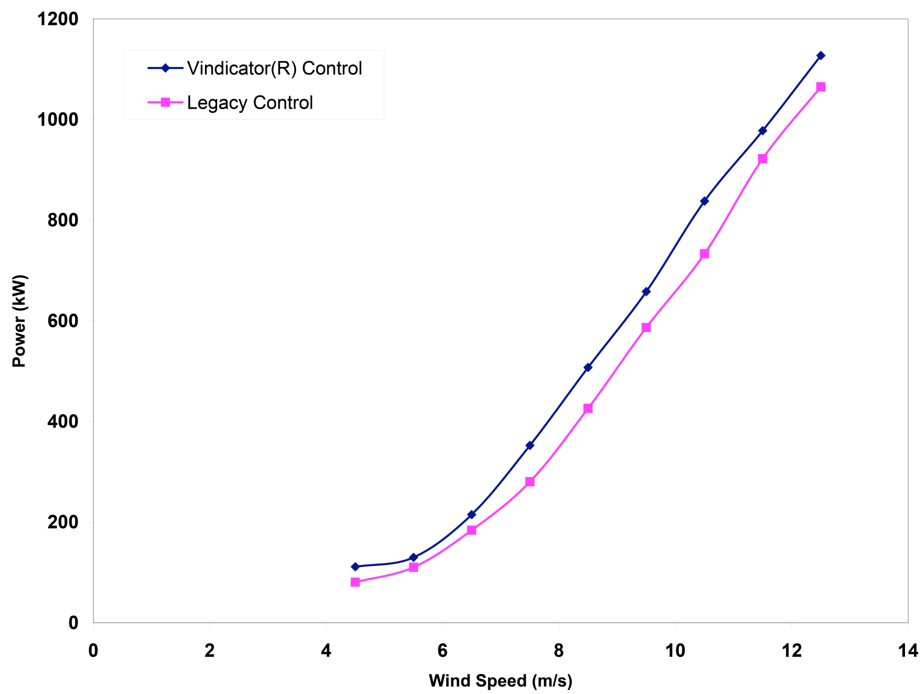


Figure 8 Power vs Wind Speed for the N60 turbine. The red curve is the power produced in each wind speed bin using the legacy wind direction input from the rear of the nacelle. The blue curve is the power produced in each wind speed bin with the free stream wind direction as measured by the Vindicator® LWS. The turbine produced more power in each wind speed bin when given accurate information about the free stream wind direction.

## 5 Conclusion

Timely and accurate knowledge of the inflow is essential for effective yaw control. This study demonstrates that wind vanes and sonic anemometers placed on the nacelle behind the turbine rotor do not give accurate information about the inflow conditions and are not correctable using a pre-defined linear transfer function. Furthermore, it is not possible to use these instruments without significant averaging. With accurate look-ahead wind information, yaw control systems can perform up to their theoretical limits and can be improved to take advantage of the more timely data. This will result in overall better turbine performance.

## 6 References

1) Risø National Laboratory, TF Pederson, et al, Wind Turbine Power Performance Verification in Complex Terrain and Wind Farms (RISO-R-1330)

2) NREL Technical Report, Unsteady Aerodynamics Experiment Phase VI: Wind Tunnel Test Configurations and Available Data Campaigns, M.M. Hand, D.A. Simms, L.J. Fingersh, D.W. Jager, J.R. Cotrell, S. Schreck, and S.M. Larwoo, December, 2001 (NREL/TP-500-29955)