Impact of ambient turbulence on performance of a small wind turbine

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Abstract: High resolution measurements of wind speed and energy generation from an instrumented Bergey XL.1 small wind turbine were used to investigate the effect of ambient turbulence levels on wind turbine energy production. It was found that ambient turbulent intensity impacts energy production, but that the impact is different at different wind speeds. At low wind speeds, increased turbulence appeared to increase energy production from the turbine. However, at wind speeds near the turbine furling speed, elevated turbulence resulted in decreased energy production, likely to turbulent gusts initiating furling events. Investigation of measurements recorded at 1 Hz showed a time lag of one to two seconds between a change in wind speed and the resulting change in energy production. Transient changes in wind speed of only one second duration did not impact energy production, however, longer duration changes in wind speed were tracked reasonably well by energy production.

Keywords: Small Wind Turbine, Turbulence, Gusts, Wind Energy

1. Introduction

Turbulence in the approaching wind can have a significant impact on the power output of wind turbines. This is particularly important for smaller wind turbines, which in practice are often located near buildings, trees and other obstacles. Some small wind turbine installations may experience inflow turbulence intensity many times greater than an open field site.

Current power curve representations do not account for the impact of turbulence on small turbine energy production. For example, curves based on IEC 16400-12-1 are statistical averages of power measurements binned by wind speed, whereby the variance of the data is lost [1]. This approach cannot properly account for site-varying levels of turbulence [2]. IEC 16400-12-1 does not specifically limit turbulence levels of measurements used in power curves, and the resulting power curves provide no guidance on how differing levels of turbulence will affect the power production of the turbine. It can be argued that the effect of site specific turbulence levels in large turbines is manageable, however small turbines may be tested under this or a similar standard while experiencing a wider range of ambient turbulence levels, creating an immediate need to address the impact of site turbulence and provide useful information in the context of the wind turbine power curve.

Ambient turbulence and wind direction variance both have significant impacts on small wind turbines. The smaller masses and length scales of small wind turbines mean that the impacts of turbulence on small turbines will be different from utility scale turbines [3]. Elevated turbulence levels can result in lower wind energy production and greater mechanical stresses on turbine components [4]. The smaller size, gustier operating environment and passive yaw systems associated with small turbines mean they are much more likely to be operating in a yawed state when the turbine cannot align itself to gusting winds [5]. The power output of a horizontal axis wind turbine falls rapidly when the turbine is not aligned to the wind, with a $\cos^2$ dependence on relative wind angle [6]. Elevated turbulence intensity has been found to be the most important factor in reducing turbine structure fatigue life [4], and turbulence intensity impacts furling behaviour [7].

The effect of turbulence on power output is more difficult to generalize, since turbulent gusts impact wind alignment, airfoil performance and furling/power limiting. A small turbine tested in a high turbulence intensity environment was found to temporarily shut down more often due to high gust speeds exceeding limits [8]. Smith [9] used long term small wind turbine performance measurements collected at the National Renewable Energy Laboratory (NREL) to produce power curves and estimate annual energy production (AEP) for seven small wind turbines at varying levels of observed turbulence intensity. The small wind turbines showed a 9% to 32% difference between AEP at the best and worst turbulence levels. Most of the turbines had lower AEP in both the extreme high and low turbulence levels, although one (Skystream) exhibited a trend of increasing AEP with increasing turbulence intensity..

The goal of this study was to determine the impact of varying turbulence conditions on the performance of a representative small wind turbine. High resolution (1 minute and 1 Hz) data from a Bergey XL.1 1 kW capacity horizontal axis wind turbine were analyzed to explore the impact of turbulence on turbine power output.

2. Methodology

A Bergey XL.1 small wind turbine was used in this study. The Bergey XL.1 is an upwind, horizontal axis SWT with a rated capacity of 1.0 kW. It consists of a three blade, 2.5 m diameter fixed-blade rotor directly coupled to a variable speed permanent magnet alternator. This turbine was chosen due to its mechanical and control system simplicity, and because it has been the subject of a wide body of prior studies documenting its performance and operation [10-13].

The Bergey XL.1 was mounted on an 18 m tall, 0.114 m diameter galvanized steel tubular tilt-up tower. An additional 18 m tall, 0.152 m diameter tubular tilt-up tower was installed 13.4 m to the north of the turbine tower to serve as a meteorological mast for obtaining reference measurements of hub-height wind speed.

NRG 40C cup anemometers and one R.M. Young 81000 three-dimensional sonic anemometer were used for this study. The sonic anemometer was mounted on a short arm such that it's sensing volume was 20 cm directly below the rotor disk when the wind was from the prevailing direction of southwest. One NRG 40C and an NRG 200S wind direction sensor were located at the top of the reference mast 1 m above hub-height on separate 1.53 m booms. All NRG 40C anemometers used in this study were manufactured during the initial months of 2009 and calibrated by Otech Engineering (Davis, CA, USA). These calibrations were verified in the University of Guelph wind tunnel before experiment installation.

Power from the turbine was measured by tracking the voltage across a 2180 W , 2.0 Ω dynamic breaking resistor that dissipated the turbine's electrical power output. The 2.0 Ω resistance was selected to mimic the turbine's intended operation as part of a battery charging system under high load, while keeping the parameters needed to characterize electrical performance to a minimum. Additional sensors were installed to measure the yaw angle and rotor speed of the turbine. Ziter [14] gives further details of the experimental equipment.

The turbine and meteorological tower were installed at a representative SWT site on a farm in Oxford County, southwestern Ontario (43°18'N, 80°33'W). The collocated towers were installed in a field (grass, approximately 0.1 m tall) open for several hundred meters to the west and predominantly open to the north and southwest as well. The prevailing wind was from the southwest. Low rise buildings and trees to the east were all more than 100 m distant.

Other potentially significant obstacles included a small cluster of trees located 160 m to the northwest and a barn located almost 200 m to the southwest. Potentially disturbed direction sectors were determined according to IEC 61400-12-1 criteria [1]. Data from disturbed sectors were not used.

3. Results

3.1. One Minute Data

Fig. 1 shows the overall measured XL.1 power curve, based on binning and averaging of 1 minute averaging period, air density-corrected data from undisturbed sectors. The study turbine exhibited a cut-in speed of 4 m/s, and began furling at 9 m/s. Note that because a constant $2.0\ \Omega$ load was used, these power curves are not comparable to the manufacturer's or other power curves measured using a grid connection or battery charging controller. The reduced energy generation above 9 m/s for the study turbine is believed to be due to the addition of a nacelle anemometer and solar panel on the tail boom (that were not used in this study), which resulted in earlier furling than would otherwise occur.

Figure 1. Measured Bergey XL. 1 power curve using a $2\ \Omega$ resistive load, with comparisons to UCD [12] and Clarkson [10] XL.1 power curves also measured with a $2.0\ \Omega$ load.

Next, the data from the turbine was divided into three categories based on turbulence intensity (which is the standard deviation of the wind speed divided by the mean wind speed during the 1 minute averaging period). The median turbulence intensity for the entire dataset was 0.173. Low turbulence intensity was classified as turbulence intensity less than 0.14. Turbulence intensity greater than 0.18 was considered high. Turbulence intensity between these two values was classified as intermediate. Figure 2 shows the number of observations in each wind speed bin and turbulence category.

Figure 3 shows the percentage difference between the overall power curve and three power curves derived from the categorized data. Low turbulence intensity consistently results in reduced power output (approximately -2%) between 4 m/s and 7 m/s, corresponding roughly to the operating range above cut-in and below the beginning of furling. The results for the

case of high turbulence are less consistent, with the percent increase in power output varying between 0% and +4% in the wind speed bins between 4 m/s and 7 m/s. This variability is likely due to the reduced number of high turbulence intensity observations in individual bins, compared to low turbulence observations. The intermediate differences are almost a mirror image of the low turbulence differences in Figure 3, again supported that these make up most of the observations.

Figure 2. Number of observations by turbulence level and wind speed bin.

Figure 3. Percent difference between stratified and overall power curves.

The impacts of turbulence on furling were more pronounced. Figure 4 shows the wind percent difference between each of the three stratified turbulence power curves and the overall power curve, over the full range of available data. It is apparent that low turbulence intensity results in increased energy production, likely due to a reduction in intermittent furling and associated hunting. It should be noted that significant variability between bins is likely due to the small number of observations in each bin (Figure 2) at the higher wind speeds.

Figure 4. Percent difference between stratified and overall power curves.

Some impact of turbulence was noted at intermediate wind speeds above the cut-in wind speed. The effects of turbulence were found to be most pronounced at wind speeds approaching the furling speed of the turbine, and gusting was observed to cause intermittent

furling and consequently significant hunting and off-axis orientation, reducing power generation.

3.2. One Second Data: Transient Effects

The one second data from the turbine allows direct observation of the turbine response to variations in wind speed. Figure 4 shows 100 seconds of energy production and wind speed. Note that the wind speed shown is that measured by the sonic anemometer immediately below the rotor disk. A prior study [14] found the magnitude of this wind speed to be higher than the reference wind speed, however, turbulence levels were consistent between the two anemometers, and the sonic anemometer is a much closer indication of the wind experienced by the turbine rotor than the reference wind speed, which is over 13 m horizontally distant from the turbine.

Figure 4. Example of 1 second sonic anemometer wind speed measurements and turbine energy production as measured by voltage across the resistor.

It is apparent that the turbine energy production is approximately one to two seconds delayed relative to the wind at the rotor disk, however, the rate of change and duration of wind speed perturbations appears to influence this. The circle in figure 4 s shows a transient gust of approximately one second duration that is not apparent in turbine energy production. However, changes in wind speed with time constants of many seconds are reasonably well tracked by energy production, factoring in the one to two second delay.

4. Discussion

The UC Davis turbine shown in Figure 1 is mounted on a 9 m mast on the roof of a 3 storey building that contains a penthouse and other roof top infrastructure, on a campus surrounded by other buildings and trees. It would be expected that this turbine would experience higher

ambient turbulence than the Clarkson turbine or the one in this study. With that in mind, it is interesting to note that the UC Davis turbine appears to have a lower cut-in wind speed (at about 3 m/s) than the 4 m/s overall cut-in speed observed for our own turbine, and the 5 m/s cut-in speed of the Clarkson turbine.

Very high turbulence levels resulted in overall decreased performance. It should be noted there are inherent limitations in using a single value of turbulence intensity, which combines all turbulence scales in a single measurement, as the only measure of wind speed variability. It was observed that turbulence impacts depended on the time scale of the turbulence: due to inertia, the turbine had difficulty responding to short time scale turbulence events. This could lead to reduced power output. However longer time period gust events that could be tracked by the turbine would be expected to result in greater overall performance when data was averaged, due to the non-linearity of turbine response to wind speed.

Applying a power curve produced at one level of ambient turbulence to a site with different ambient turbulence is likely to introduce significant errors in site-specific predictions of power output. The results of this study suggest that including additional turbulence information in the performance evaluation of small wind turbines could result in more accurate characterization turbine performance.

5. Conclusions

Measured data from a small wind turbine showed that turbulence has a range of impacts on a small wind turbine. Specifically,

- Turbulence levels had a small but noticeable impact on overall power output at wind speeds between cut-in and furling.
- Low turbulence levels resulted in increased power output at wind speeds associated with furling, likely due delayed onset of furling because of the presence of fewer gusts above the mean wind speed.
- Turbine energy production lagged changes in wind speed by one to two seconds. While changes in wind speed occurring over many seconds were reasonably well tracked by energy production, transient events of approximately one second duration were not tracked by energy production.

The results found here were broadly in agreement with other studies of the impact of turbulence on small wind turbines. The interaction of turbine with turbulent winds is complex and will vary depending on turbine characteristics.

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