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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 2 s between a change in wind speed and the resulting change in energy production. Transient changes in wind speed of only 1 s duration did not impact energy production, however, longer duration changes in wind speed were tracked reasonably well by energy production.

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 61400-12-1 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 61400-12-1 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 behavior [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. More turbulent winds have greater power than less turbulent winds with the same mean wind speed, due to the cubic variation of power with wind speed [8]. 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 [9]. Smith [10] 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%–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,

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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 in a representative open field environment. High resolution (1 min 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 turbine 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 [11–14].

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 81,000 three-dimensional sonic anemometer were used for this study. The sonic anemometer was mounted on a short arm such that its 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. Additional sensors were installed to measure the yaw angle and rotor speed of the turbine. Ziter [15] gives further details of the experimental equipment.

Power from the turbine was measured by tracking the voltage across a 2180 W, 2.0 Ω dynamic braking resistor that dissipated the turbine's electrical power output. Seitzler tried several different load resistances and noted that 2.0 Ω provided the closest match to the Bergey XL.1 performance reported by the manufacturer utilizing a battery charge controller [13]. Importantly, a constant resistance load does not mimic the variable electrical loads that are applied by charge controllers (for battery charging) or inverters (for grid connections). 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.

The turbine and meteorological tower were installed at a representative small wind turbine site on a farm in Oxford County, southwestern Ontario, Canada (43°18′N, 80°33′W). The collocated towers were located 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]. The wakes of obstacles such as buildings are dependant on variables such as obstacle geometry, atmospheric conditions and the distance between the obstacle and the turbine, and turbulence produced by these wakes would be expected to vary significantly between sites, or even within the same site. The goal of this study was to investigate the impact of ambient turbulence on a turbine situated well away from obstacles. Data from disturbed sectors were not used in order to keep the results as generalizable as possible by not including wake effects from individual buildings and nearby trees in the analysis.

3. Results

3.1. One minute data

Fig. 1 shows the overall measured XL.1 power curve, based on binning and averaging of 1 min 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 Ω load was used, these power curves are

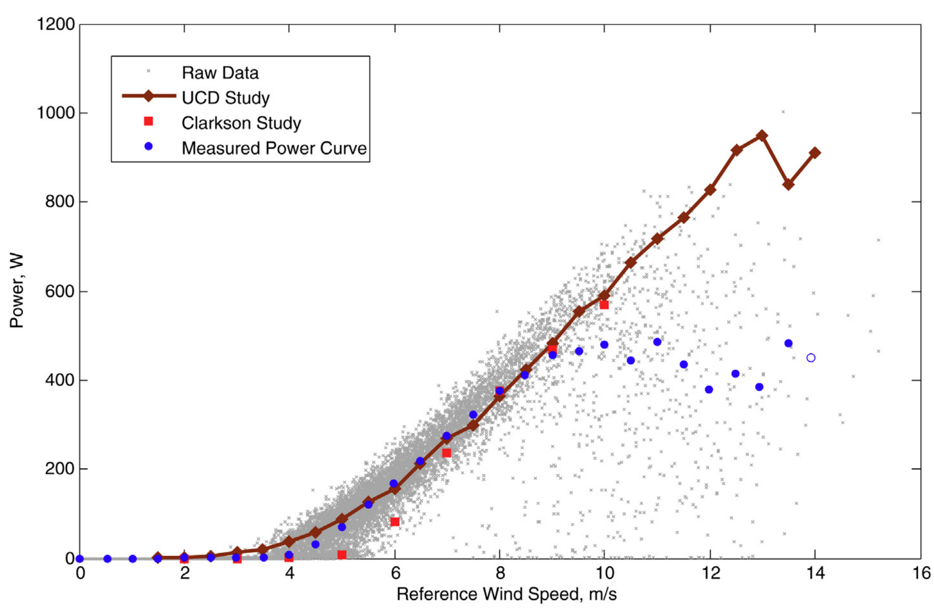

Fig. 1. Measured Bergey XL. 1 Power curve using a 2 Ω resistive load, with comparisons to UCD [12] and Clarkson [10] XL.1 power curves also measured with a 2.0 Ω load.