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ANALYSIS OF WIND SHEAR AND TURBULENCE INTENSITY INFLUENCE ON WIND POWER PERFORMANCE USING SCADA AND LIDAR DATA

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Abstract. : *Wind power has gained significant share in the global power production. However, the wind power output efficiency is only about 30% of the wind kinetic energy. Because of that, it is essential to study the efficiency of these power generation systems by assessing the effects that wind parameters and wakes will have on the whole system. This study aims to investigate the efficiency of wind energy generation in two North American Wind Farms by means of wind data investigation. The available data obtained from SCADA and collected by LiDAR measurements. Statistical analysis was performed using two selected parameters for the wind turbine performance, where graphical analysis of power against the freestream wind velocity, as function of wind shear and turbulence intensity ranges. The wind data analysis has estimated parameters as wind shear, wind rose, wind speed profile and turbulence intensity. Results showed that wind shear was found to vary around 0 to 0.2 for higher velocities, although for lower wind speeds the wind shear could reach 0.4. Therefore, for high turbulence intensities the power could be overestimate in 20%.*

Keywords: *wind power, LiDAR, wind shear, turbulence intensity.*

1. INTRODUCTION

The demand for energy has been increasing in the last decade due to the global economic growth. Such development has risen quickly over the past three decades. Therefore, the development of several sources of renewable energies, such as solar, hydropower and wind energy is extremely important. Within these renewable resources, wind energy has offered a range of advantages, as the technology has been developed along with a prospection on the market (Leung and Yang, 2012).

The most significant regions of new expansion are located in Brazil, Mexico and South Africa. Brazil is the leader in wind power installed capacity. The wind resources in the country represent an enormous potential. After a reluctant start to wind power growth in the beginning of the 2000 decade, the Brazilian wind market has now advanced significantly. In 2011, Brazil reached 1.5 GW of installed capacity, and by the end of 2013 the total installed capacity exceeded 3.4 GW. The country reached over 10 GW in February of 2017, representing a considerable cumulative growth, which is not frequently observed, apart from China in the period 2005-2010 (GWEC, 2014; ABEEólica, 2017).

A comprehensive evaluation of wind resources is crucial to retain full advantage of wind power. For instance, accurate and correct measurements of wind characteristics decrease the needs of massive investments (Rehman and Al-Abbadi, 2005; Wharton and Lundquist, 2012). Field measurements allow the development of solid databases, which can be used in statistical analysis for assessing wind-power performance. With this aspect in mind, this study aims to assess the performance curves of wind energy generation by means of vertical wind profile analysis, seeking to determine the influence of wind characteristics parameters (i.e., wind shear exponent and turbulence intensity) on wind energy production using data from two different wind farms. The data used in the analysis were obtained by SCADA and LiDAR measurements.

2. METHODOLOGY

The study area comprise a wind farm located in North America. Due to security contracts established with the company that provided the data, Sgurr Energy, it was not possible to describe the wind farms locations and more detailed information. The site had the system operating for approximately 93% of the time and the LiDAR deployment with 61% of the data available to analyze.

Attaining a valid data set of the wind direction during the period of production is very important due to the large variation in wind farm production over just a few degrees. Then, the wind rose diagrams were used in this work for visualizing the wind patterns. This approach is the most common instrument to display wind data in terms of velocity and frequency distributions.

To study the influence of wind shear and turbulence intensity on power performance, this work used the described SCADA and LiDAR data for developing the relations between power production and wind velocities (the so-called performance curves) for different levels of wind shear exponents and for different levels of turbulence intensities. This was performed by scatter plots that showed power generation against the freestream wind speed, as functions of wind shear exponent and turbulence intensity.

2.1 Wind shear

Wind shear is defined as the local variation of wind speeds with altitude. For practical purposes, wind shear is assumed to be the variation of wind speed with height above ground level (Mclaughlin, 2012). Over rough terrain, the wind shear decreases near the ground, but there is a compensated increase in higher layers. Unstable air tends to rise, intensifying the vertical mixing and reducing vertical wind shear in most part of the layers. However, in stable conditions, the vertical motion slows down and consequently vertical wind shear might become extremely high. Vertical wind shear is a crucial parameter in wind energy projects, since it is directly correlated to the productivity of wind turbine output and it reduces the lifetime of the turbine rotor blade (Honrubia *et al.*, 2009).

A dimensionless wind shear exponent was calculated using wind speed data at two heights, by the simple power law (Chehouri *et al.*, 2015), as the following the equation,

$$V_2(z) = V_1\left(\frac{z_2}{z_1}\right)^{\alpha}, \tag{1}$$

where z_2 and z_1 are two heights above the ground level in meters, $V_2(z)$ is the mean horizontal wind speed (m/s) at height z_2, V_1 is the wind speed (m/s) at the reference altitude z_1, and α is the wind shear exponent or coefficient. The wind shear exponent estimates atmospheric stability, but it is not a straightforward measure of stability (Wharton and Lundquist, 2010).

In this work, wind shear exponents were calculated at three distinct heights from LiDAR measurement data. The locations of the calculation points are: (a) at the bottom tip, (b) at the hub height and (c) at the top tip of the wind turbine.

2.2 Turbulence intensity

Turbulence intensity (*TI*) involves straight measurements of horizontal turbulence fluctuations at the site. In this work, turbulence intensity was calculated by the ratio of the standard deviation, σ, in (ms^{-1}) of the wind speed with a time step of each 10-minute period by the corresponding mean wind speed, $\overline{V}$, in (ms^{-1}) at the 80m height (Wharton and Lundquist, 2010), according to,

$$TI = \frac{\sigma}{\overline{V}}. \tag{2}$$

Power performance curves were implemented for comparing evaluations between observed power curves and the fabricator power curves.

Important turbulence intensity effects on power production were reported by Sheinman and Rosen (1992). These authors demonstrated that neglecting the effect of wake turbulence in the incoming wind speed can lead to an overestimation of turbine output slightly over 10%. In particular, the velocity deficit, which is highly related to power losses in wind farms, recovers faster when the turbulence intensity level of the incoming flow is higher, which usually occurs near to the high turbulence turbine zone (Wu and Porté-Agel, 2012). Turbulence from the upwind turbines affects the power performance of the downwind turbines whenever the wind direction gets aligned with the wind farm turbines.

Steady wind flows deliver lower turbulence intensity, on the contrary, the turbulence is high when wind fluctuates fast. Hence, often the literature reports values of horizontal turbulence intensity in the range from 3% to 20% (Wharton and Lundquist, 2010). Low turbulence conditions are linked with stable conditions, which describes the persistence or consistence of wind speeds, whereas in unstable conditions the wind speed strongly changes with height therefore the turbulence intensity is high (Kaiser *et al*., 2007).

3. RESULTS AND DISCUSSION

The mean wind velocity from the LiDAR dataset was 7.76 ms^{-1}. The dominant wind direction was 139°, corresponding to the southeastern quadrant. The mean temperature was 21°C, associated with a mean air density of 1.221 kgm^{-3}, which was a little higher than the normal temperature and pressure at sea level (20°C). The wind temporal variability is shown in Fig. 1, through the comparison of the wind velocity histogram with the fitted Weibull distribution.

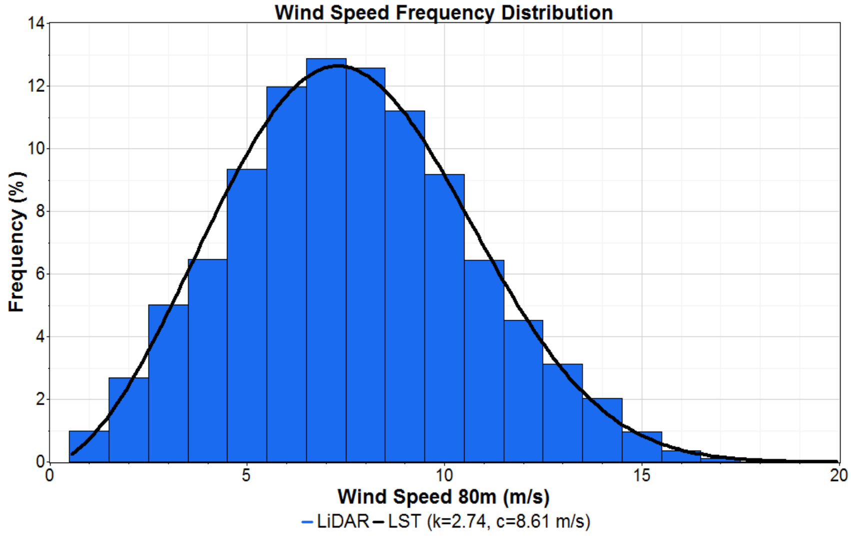

Figure 1. Wind speed frequency distribution and the Weibull distribution

The Weibull fit produced by the Windographer software is based on the Least Squares Technique (LST); where the two parameters of the Weibull distribution (k is the shape parameter and c is the scale parameter) are fitted to the measured velocity histogram. The shape parameter was k=2.74 and the scale parameter was c=8.61 ms^{-1}.

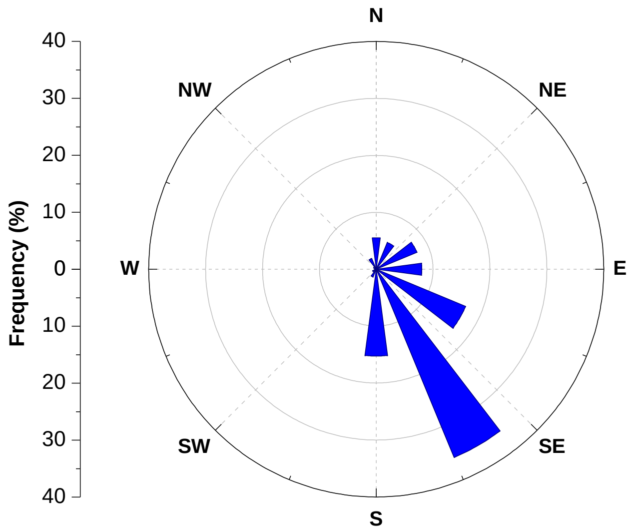

Figure 2. Wind rose diagram

The wind rose obtained from LiDAR measurements data is shown in Fig. 2, where winds from the southeast sector were dominant, corresponding to 78% of the events. The highest frequency was 35% for the 150° direction, followed by 15% for 120° and 180° directions.

3.1 Wind shear analysis

The wind shear exponents were determined following eq. (1) at three different heights. The resulting median wind shear exponent obtained from the calculations were used in the analysis. Such coefficients were binned in six ranges (from 0 to 0.4) in order to have enough data to plot the power performance curves.

Figure 3 depicts the wind speed histogram conditioned on wind shear exponents, which was designed to enhance the understanding of the wind shear exponents behavior for different wind speeds. The wind speed bins of 5 to 10 ms^{-1}, comprised 65% of the events, which were mostly associated with the 0 to 0.1 shear range.

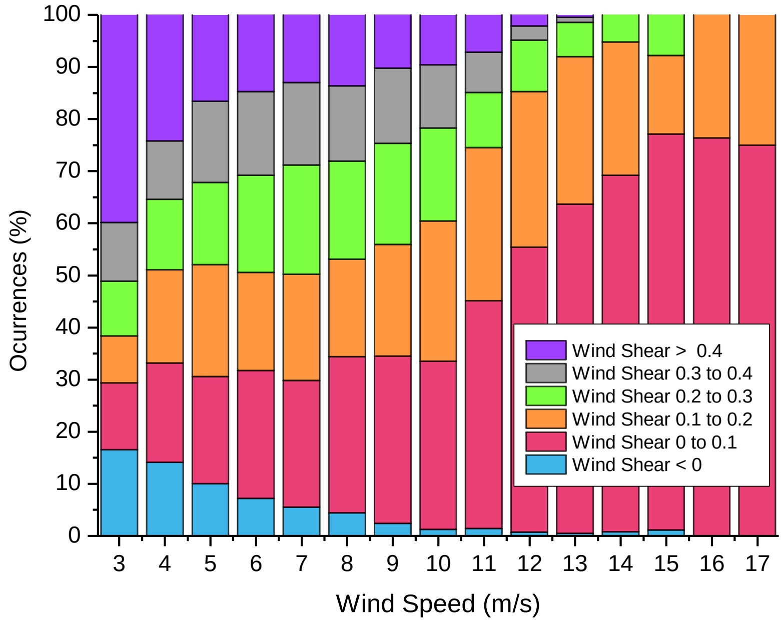

Figure 3. Wind speed histogram conditioned on wind shear coefficients

The highest single occurrence at one wind shear range occurred at 8 ms^{-1} with a value of 832 counts at 0 to 0.1 wind shear coefficient. As soon as the wind speed develops, and exceeds the coefficients between 0 and 0.1, it becomes more substantial than other ranges. The wind speed bins of 3 and 4 ms^{-1} are characterized to be the unique bins that presented the bigger occurrences at wind shear greater than 0.4. This is a large coefficient, but it might not affect the wind turbine lifetime considerably due to the lower wind speeds.

Figure 4 shows the power performance curves for wind shear coefficients varying from 0.1 to 0.4. It is possible to observe that all wind shear ranges presented similar pattern in terms of power curves. Nevertheless, the negative shear range demonstrated a visible underestimation of 11 ms^{-1}, while the range greater than 0.4 seemed to have an overestimation at the same wind speed bin.

Note that the wind shear range of 0 to 0.1 was taken as the base power curve, due to the highest data counts in this interval, and due to the finest representation for every single wind speed bin. These data were used to calculate the performance of negative and higher shears in the power output of the wind turbine. The wind speed bin that presented highest differences was the 3 ms^{-1}, which deviated more than 10% for all of the wind shear ranges in relation to the base shear range of 0 to 0.1.

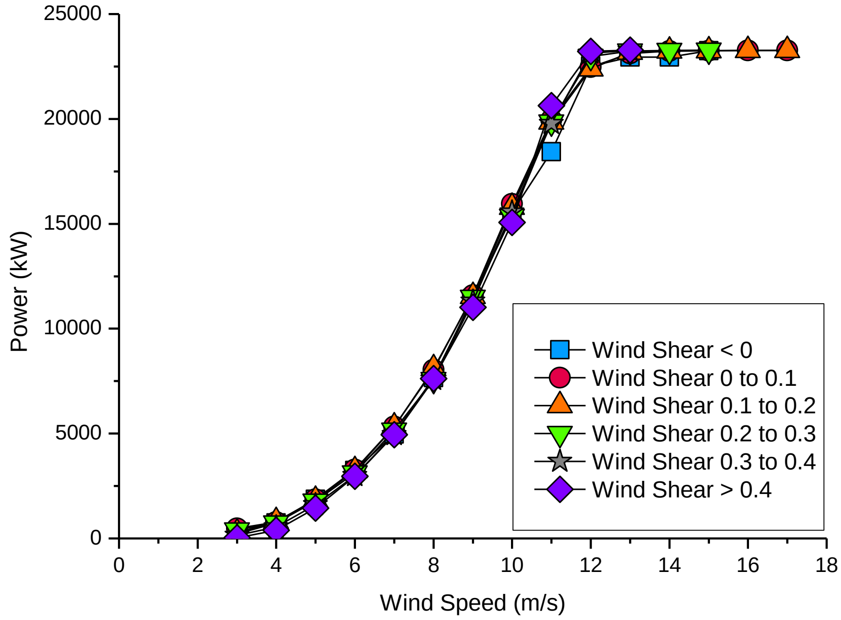

Figure 4. Power performance curves of six wind shear coefficients ranges

In addition, for wind speeds higher than 3 ms^{-1}, the power curve conditioned on negative shear performed similarly to the base curve. However, wind shear ranges of [0.3 - 0.4] and [>0.4] displayed two wind speed bins in which there was at least 14% power underestimation with respect to the base curve. Both bins, at lower wind speeds of 4 and 5 ms^{-1}, were associated with power underestimation of 30% and 14%, respectively, for shear between [0.3 - 0.4], and power underestimation of 50% and 23% respectively for wind shear coefficients [>0.4].

3.2 Turbulence intensity analysis

When the turbulent intensity analysis was concerned, it was possible to note a rising standard variation of the power generation. As velocity oscillated around the rated velocity, the power output was restricted to the rated power. Only when the immediate velocity was below rated velocity that the wind was converted into power oscillation.

Table 1 summarized four turbulence intensity ranges and Figure 5 shows the power curves behavior with different turbulence bands.

Table 1. Turbulence intensity statistics.

TI range	Number of Occurrences	Median TI
< 0.05	1405	0.033
0.05 to 0.1	1230	0.070
0.1 to 0.15	412	0.121
> 0.15	370	0.200

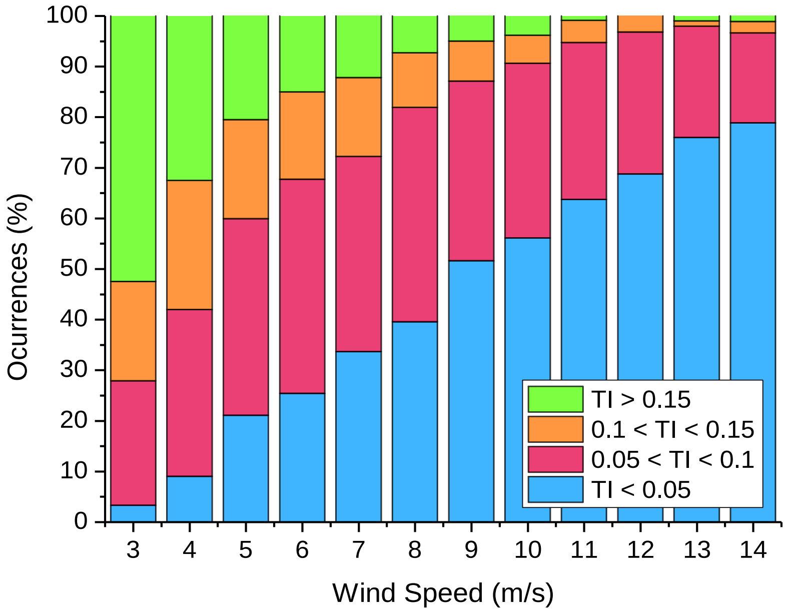

Figure 5. TI frequency diagram

Figure 5 suggests that obtained low turbulence intensity have bigger occurrences than high turbulence levels, showing that low turbulence events occur more often (77% of time) than high turbulence events (23% of time). It was also possible to define that at high levels of turbulence intensity there were a lack of median power output. This probably happened due to the low density of points at turbulence ranges from 0.1 to 0.15 and to ranges greater than 0.15.

High velocities are associated with low turbulence, as one can see for the wind speed bins from 9 to 14 ms^{-1}, in which TI lower than 0.05 is dominant. Low velocities are associated with enhanced turbulence intensity, shown by [0.05 - 0.10] dominant events for wind speed bins from 4 to 8 ms^{-1}. High turbulence events TI [>0.15] were registered only for the 3 to 10 ms^{-1} velocity range.

Figure 6 depicts the power curves conditioned on turbulence intensity, in order to assess the effect of turbulence intensity on power output.

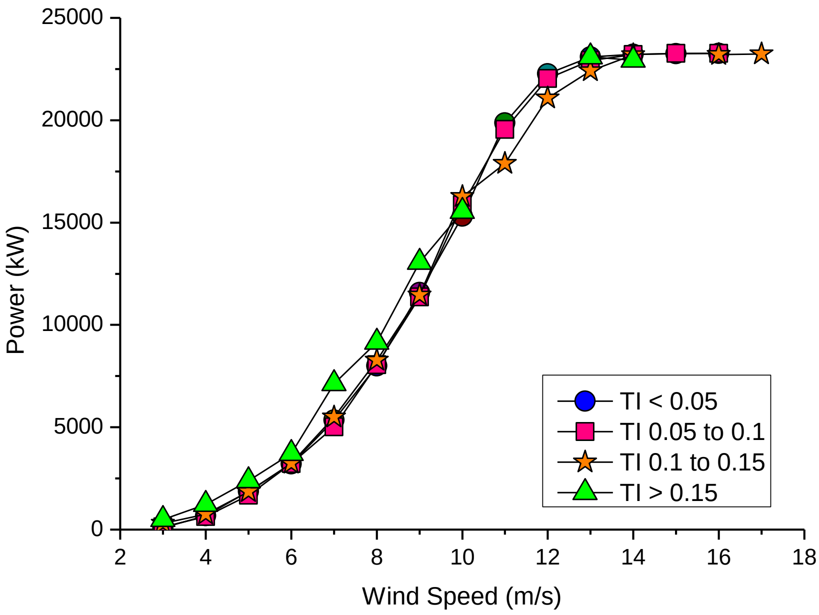

Figure 6. Power performance curves of four turbulence intensity ranges

For wind velocity ranging from cut in to 10 ms^{-1} the power output is enhanced by turbulence intensity. However, the power output drops with high turbulence intensities, for high wind speeds (V>10 ms^{-1}). It is important to point out that there were no events of TI [>0.15] for the 12, 15, 16, 17 ms^{-1} wind speed bins. Also at the 17 ms^{-1} wind speed bin there were no events for the TI [<0.05] and [0.05 - 0.1] ranges.

For the wind speed bin of 7 ms^{-1} and turbulence intensity greater than 0.15 the power output exceeded in 33% to the base curve. However, for the 11 ms^{-1} wind speed bin the power for high turbulence [0.1 – 0.15] underestimates more than 10% the base power. Therefore, increasing turbulence intensity the power output is overestimated at moderate wind speeds, and underestimated at greater than 10 ms^{-1} wind speeds, in agreement to Langreder *et al*. (2004). The only exception for that occurred at 11 ms^{-1} to [> 0.15] turbulence intensity range, which is associated with the low data count at the range.

4. CONCLUSIONS

This study has examined the wind components, which can affected the power production of a single wind turbine localized in a North American Wind Farm. The wind resource was deployed according to Galion LiDAR measurements applying a scan geometry, where the dispositive had been mounted closed to the wind turbine.

Hence, the LiDAR results presented to describe properly the local wind components, indicating a mean wind speed around 7.76 m/s, being also sustained by the Weibull wind speed distribution that granted to obtain the shape parameter, k, equals to 2.70 and the scale parameter, c, equivalent to 8.63 m/s. Therefore, the southeast wind direction was prevalent during the deployed period. The mean temperature occurred to be around 21°C, which is a moderate condition that the Galion LiDAR can operate without any difficulty.

The accomplished results allows the conclusion that disregarding the turbulence intensity impact in the inflow velocity, which arrives at wind turbine might overestimate the power output by 20%. In the meantime, the wind shear coefficients oscillate at intervals of 0 to 0.2 for higher wind speed bins, however large values around to 0.4 were remarkably identified at lower wind speeds, mostly of the occurrences demonstrated an underestimation greater than 20%. Thereupon, whenever low turbulence intensity occurs in combination with high levels of wind shear, the power generation capability can be restricted.

This study can be considered part of the LiDAR's technology development, considering the application of LiDAR for acquiring data. Leading the way for the wind power market and academic purposes, in order to contribute for the Brazilian wind energy. For future researches would be indicate extended sampling periods that will get better seasonal representation of the site and full advantage of the LiDAR's technology, looking to achieve strong validation of the wind turbine performance.

5. ACKNOWLEDGEMENTS

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