EFFECTS OF COMPLEX WIND REGIMES AND METEORLOGICAL PARAMETERS ON WIND TURBINE PERFORMANCES

Radian Belu, Member IEEE, and Darko Koracin et al.

Abstract - Wind turbine power performance for the energy production calculations has traditionally been modeled assuming a set of simple average input meteorological conditions. Wind turbine power curve tests are also performed with this assumption, based on criteria defined in the IEC-12-1 standard. While this approach has proven to be adequate for the wind industry for several years, the increasing size of wind turbines (WT)--coupled with an improved awareness of the wind flow variation throughout the boundary layer—has generated concern that the effects of complex meteorological conditions on turbine power performance are not well understood. However, the uncertainty of power performance measurements is closely related to the uncertainty in the wind velocity, turbulence and other meteorological parameters and their effects on the wind turbine performances.

Index Terms - Air density, atmospheric stability, equivalent wind speed, power curve, wind profile, turbulence intensity, wind shear, wind turbine power

I. INTRODUCTION

Wind energy has become a techno-economically viable renewable energy resource. In recent years, we have seen a steady growth in the utilization of wind energy in power production. The surrounding terrain and the height above ground will influence wind speed. Usually the wind speed for a particular site is given at a standard reference height of 10 meters. However, in the context of wind turbines, the hub height is a natural choice for estimating the power potential at a given site. The objective of this paper is to determine and look into the effect of upstream conditions towards the power contribution available at a location. Power performance verification is considered a vital tool in the development of an efficient wind energy project. However, there are intense discussions about effects on the power performance of a wind turbine operating in complex terrain sites. Spatial variations in wind speed, flow in inclination relative to the rotor, and parameters that have strong effects on power of large differences in air density are some of the performance of a wind turbine operating in complex terrain sites. Considerable efforts by both the scientific community and industry have been made to assess the above issues, but the actual physical problem is not yet fully addressed. Furthermore, the urgent need to have workable tools to do power performance verification in complex terrain sites has led standardization organizations and expertise networks to include in their special guidelines aiming at reducing uncertainties associated with complex terrain sites.

As utility-scale deployment of wind energy expands, turbine sizes and generating capacities also are increasing. For example, many wind turbines currently in operation in the USA and Europe have power-producing capacities larger than 2 MW, with hub heights ranging from 60 to 100 m above ground level and rotor diameters on the order of 80 m. As turbines penetrate higher altitudes, the area swept by the blades expands beyond the atmospheric surface layer (approximately the bottom 10% of the boundary layer) and into the convective mixed layer with complex flows driven by buoyant turbulent mixing. Although the mean wind velocity in the turbine rotor disk largely determines the amount of power that is generated, wind shear and turbulence intensity, which are measures of atmospheric stability, also appear to play a role in power output. Thus, accurate descriptions of how wind velocity, air density, wind shear and turbulence vary across the turbine rotor may prove very beneficial to wind farm operations.

In wind energy, power output estimates at a potential wind farm site and the accuracy of the assessment are critical to the profit of a project. The standard procedure for power curve measurements is given by the IEC standard [1] where the wind speed at hub height is considered to be representative of the wind over the whole turbine rotor area. This assumption is at least questionable for large WT and could lead to considerable wind power estimate inaccuracies [2]. Wind varies temporally and spatially in the surface layer, therefore it is expected that the wind inflow will be non-uniform and unsteady over the rotor area. Moreover, this effect is amplified by the cubic relationship of wind power with wind speed.

The influence and effects of wind shear, turbulence intensity and atmospheric stability on wind turbine production are still not fully understood, and for this reason many wind resource

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assessment studies can be affected by large uncertainties. The estimation of the magnitude of the uncertainty source is often related to empirical considerations rather than scientific theories. They are determined by particular atmospheric conditions and/or complex terrain; in such situations, a wind turbine is operating far from the design and test environment and the power curve can be very different from the certified one. Wind shear, direction changes, turbulence and atmospheric stability vary with height as a result of terrain and/or meteorological conditions. It is more than clear that there is a need for adoption of new measurement and power estimation methods. The rotor size combined with the turbine hub height implies that turbines are often exposed to highly varying wind conditions with large wind shear, direction shear, turbulence and atmospheric stability variations within the rotor span, affecting both the turbine production and structural safety. Better predictions of power or loads require more representative wind measurements and power computations over the rotor area.

We are attempting in the present work to examine and estimate the effects that parameters like wind shear, turbulence intensity or differences in air density have on wind turbine power performance. Variations in the power curve can lead to noticeable or even substantial differences in the real energy production. This paper presents some power performance simulations showing that the power estimate uncertainty can significantly be reduced if additional information on the wind and atmospheric conditions over the whole turbine rotor is used. In the following, the data collection and experimental siting is first reviewed in Section II. Section III presents the effects of the complex wind field and atmospheric conditions on power performance are described. Results and discussions are given in Section IV. Section V concludes the paper.

I. SITE AND EXEPRIMENT OVERVIEW

The experimental data from the sonic anemometer used in this study were collected over 14 months from an 80 m meteorological tower with instruments at four levels (10 m, 40 m, 60 m, and 80 m). The tower was located in western Nevada, near Tonopah [3]. Wind velocity data was collected from sonic anemometers sampling at 20 Hz at four levels 10 m, 40 m, 60 m and 80 m. Besides the wind velocity, air temperature, atmospheric pressure, humidity, and solar radiation (which are all used in the present analysis) were measured at a surface weather station located near the tower base [3], [6]. The goal of the experiment was to analyze and assess the wind energy potential in this area of western Nevada. Wind velocities less than 0.5 m/s were recorded as calm and are not included in this analysis. Before the statistical and spectral analysis of the data, a quality control check of all data was performed to remove outliers and to interpolate over small data gaps that may be present. Overall, the corrected data are of sufficient quality, with less than 3% of the data removed as unacceptable data.

II. WIND TURBINE POWER CURVES

The power that a turbine can extract from a volume of wind is [3]:

$$P = 0.5 C_P(\beta, \lambda) \cdot A \cdot \rho \cdot v^3 \qquad (1)$$

where v is the horizontal wind speed, A is the rotor swept area, ρ is the air density and C_P is the power coefficient (see Fig. 1). P is the wind turbine power, β is the pitch angle, and λ is the tip speed ratio ($\lambda = \omega R/v$, here ω is the rotor angular velocity and R the rotor radius). For a given rotational speed, electrical power of a wind turbine is a function of wind velocity, temperature, air density, turbulence, wind direction, wind shear, Reynolds number, and other operational parameters.

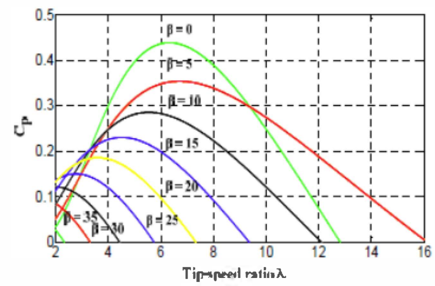

Fig.1. Power versus tip-speed ratio, for different pitch angles (β)

The typical power-performance curve of a modern wind turbine is generally linear at low wind velocities and bell-shaped at moderate wind velocities; an essentially constant level of power output occurs during higher wind velocities (Fig. 2). Polynomial regression seems to be inadequate to capture these features of power performance curves, especially when few recordings are available. At high wind velocities, the data scattering clearly makes the shape of the resulting regression curve unrealistic. The performances of a wind turbine are often reported in non-dimensional form, using the following non-dimensional parameters:

$$C_P(\beta, \lambda) = \frac{P}{0.5 \cdot v^3 \cdot \pi R^2} \qquad (2)$$

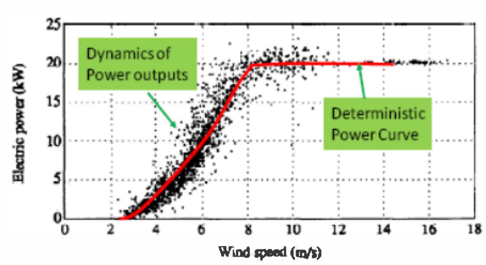

Fig. 2: Dynamic WTG Power Outputs Curve

III. DEPENDENCE OF WIND TURBINE POWER ON ATMOSPHERIC PARAMETERS

We are investigating the effects of wind shear, air density, atmospheric stability, and turbulence on the wind turbine output power. It is shown that all mentioned atmospheric conditions have effects on the power curve. The wind velocity profile, temperature, and turbulence intensity are generated using experimental data and a model developed from Monin-

Obukov similarity theory [4], [6]-[10]. The resulting system of nonlinear equations was solved numerically and tested against field observations.

A. Air Density and Temperature

Clearly, the power depends on the air density and therefore so does the power curve. The air density values encountered at our measurement sites are mostly between 0.936 kg/m^3 and 1. 025kg/m^3 with a multi-annual mean value of 0.982 kg/m^3, significantly lower than the mean standard air density, 1.25 kg/m^3 [3]. Power curves for various values of the air density can clearly be distinguished, and this effect must be accounted for in order to improve the power output estimate accuracy. Because the air density is usually calculated from temperature and pressure measurements, it is obvious that the two are related. This is also reflected in the power curves (see Fig. 3 for details). Depending on the turbine's method of control, either the power or velocity is normalized [6-14]. For the case of a turbine with active pitch control, the velocity is normalized to a reference air density ρ_0:

$$v_{norm} = \bar{v}\left(\frac{\bar{\rho}}{\rho_0}\right)^{1/3} \qquad (3)$$

The atmosphere cycles through discrete states defined by its thermal stability. In the morning, as the sun warms the ground, air close to the surface begins to be heated. Eventually, the heat flux from the ground becomes significant and the resulting temperature gradient causes turbulent mixing. Thus, the afternoon wind speed profile is fairly uniform due to this added turbulence. At night, the ground changes from a heat source to a heat sink, and the lower atmosphere tends to become stably stratified.

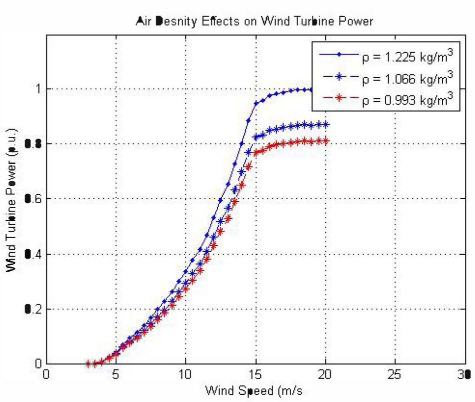

Fig. 3. Power curves for different values of the air density.

To model the lower atmosphere's relatively complex behavior, Monin-Obukhov similarity theory was used [5, 13, 14]. Although limited to conditions that can be considered horizontally homogeneous and statistically stationary, it is quite powerful for predicting boundary layer flows. Atmospheric conditions with z/*L<0* were grouped as unstable case, z/*L>0* as stable, and remaining conditions as neutral. z/*L = 0* is the Monin-Obukov length given by:

$$L = \frac{-u_*^3 \overline{T_0}}{gK\overline{w'T'}} \qquad (4)$$

where u_* is the friction velocity, $\overline{T_0}$ is the mean air temperature in Kelvin, g = 9.816 m/s the gravitational acceleration, K = 0.4 is the von Karman constant, z is the height and , is the kinetic heat flux. In reality, neutral conditions are extremely rare. Instead, near neutral conditions with a small span so that z/*L ≈ 0* for near neutral conditions.

Power curves for stable, unstable and near-neutral atmospheric conditions have been constructed and, generally, the differences between the various power curves are small. For wind speeds above, say, 5 m/s the difference between the power for neutral atmospheric conditions and stable conditions and between neutral atmospheric conditions and unstable conditions is lower than 3% (see Fig. 4 for details).

B. Turbulence Intensity

The turbulence intensity is defined as [2],[4]:

$$TI = \frac{\sigma_v}{v} \qquad (5)$$

σ_v is the wind sped standard deviation (m/s) at the nacelle height, over some averaging period (10 min).
From the power curves for different turbulence intensity classes we noticed that for low wind speeds (4m/s – 10 m/s) high TI classes yield the most power and for high wind (10 m/s -15 m/s) speeds low TI classes yield the most power, as was noticed before [8]. There also are differences in the standard deviations of the output power. In the wind speed range 4 m/s – 15 m/s we saw that the standard deviation of certain turbulence intensity classes (4% - 8% and 10% -15%) differ up to about 50% with the standard deviation for all turbulence intensities (the graphs are not included for sake of the paper brevity). However, the average of the power depends on the average of the cubed wind speed. It can be shown [5-8] that in this way a correction factor is added or, equivalently, a corrected wind speed is defined:

$$v_{corr} = v_{norm}\left(1 + 3\left(\frac{\sigma_v}{v}\right)^2\right)^{1/3} \qquad (6)$$

Here, σ_v/v is the turbulence intensity as given by (5).

C. Wind Shear and Wind Profile

Vertical wind shear is important as wind turbines become larger and larger. It is therefore questionable whether the hub height wind speed is still representative. Various methods exist in the literature concerning the extrapolation of wind speed to the hub height of a wind turbine. There are several theoretical expressions used for determining the wind speed profile. The Monin–Obukhov method is used to determine the wind speed v at height z by:

$$v(z) = \frac{u_*}{K}\left[ln\frac{z}{z_0} - \Psi\left(\frac{z}{L}\right)\right] \qquad (7)$$

The function Ψ(z/L) is determined by the solar radiation at the site under survey. This equation is valid for short periods of time, e.g. minutes and average wind speeds, and not for monthly or annual average readings. This equation has proven satisfactory for detailed surveys at critical sites; however, such a method is difficult to use for general engineering studies. Thus the surveys must resort to simpler expressions and secure satisfactory results even when they are not theoretically accurate [4], [9]. The most commonly used of these simpler expressions is the Hellmann exponential law is expressed by:

$$\frac{v(z)}{v_0} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \qquad (8)$$

where, v(z) is the wind speed at height z, v_0 is the speed at z_{ref} (usually 10 m height, the standard meteorological wind measurement level), and α is the friction coefficient or power low index. This coefficient is a function of the topography at a specific site and frequently assumed to be 1/7 for open land [2]-[10]. However, it must be borne in mind that this parameter can vary for one place to other, during the day and year [5]. Another formula, known as the logarithmic wind profile law and widely used across Europe, is the following:

$$\frac{v}{v_0} = \frac{\ln(z/z_0)}{ln(z_{ref}/z_0)} \qquad (9)$$

where z_0 is called the roughness coefficient length and is expressed in meters; it depends basically on the land type, spacing and height of the roughness factor (water, grass, etc.) and it ranges from 0.0002 up to 1.6 or more. These values can be found in the common literature [2, 3]. In addition to the land roughness, these values depend on several factors: they can vary during the day and at night, and even during the year. For instance, the reading or monitoring stations can be within farming land; it follows that the height/length of the crops will change. However, once the speeds have been calculated at other heights, the relevant equations can be used for calculating the power or average useful energy potential via different methods such as Weibull or Rayleigh probability distributions.

In most studies about the effect of wind shear on power performance, the wind speed shear is described by the shear exponent ꞉ obtained from the assumption of a power law profile. Because the horizontal wind speed is measured at three different heights, two α exponents are determined: α_1 for the heights 80 m and 60 m and α_2 for the heights 40 m and 60 m. However, for the western Nevada climate, the power index values are significantly lower than the standard 1/7 values [2]-[7]. The monthly power index values are from 0.098 to 0.139, with lower values during the spring-summer period, the windy season in this area. By integrating the wind profile over the rotor span, the corrected wind speed at the turbine nacelle can be obtained:

$$U_{avrg} = \frac{1}{2R}\int_{H-\frac{D}{2}}^{H+\frac{D}{2}} v(z)dz = \qquad (10)$$

$$= v(H)\cdot\frac{1}{\alpha+1}\cdot\left(\left(\frac{3}{2}\right)^{\alpha+1} - \left(\frac{1}{2}\right)^{\alpha+1}\right)$$

where H is the nacelle height and D = 2R is the rotor diameter. From (10), it is obvious that the hub height wind speed z(H) is α corrected based on the profile it is experiencing [7]-[10] Also in this case the hub height wind speed is α corrected based on the actual wind profile. Now, the corrections are in the range 0.9918 - 1.0259 for the α range found in western Nevada [3],[6].

It is observed that both corrections have more or less the same effect. A difference between the corrected and uncorrected power of up to 10 % was seen occasionally in our data sets. For wind speeds in the range 5 m/s to 20 m/s (the useful wind turbine speed regime) the corrected power differs in general less than 3% from the uncorrected power. In all cases the corrected power is larger than the uncorrected power. In Fig .4 the relative difference in the standard deviation of the corrected and uncorrected power is shown. For most wind speeds a decrease in the standard deviation of at most 10% is seen as a result of the α correction. However, for some wind speeds in the regime up to 12m/s an increase is seen.

IV. RESULTS AND DISCUSSIONS

It is concluded that the air density correction based on (3), as prescribed by [7],[11], is indeed effective. On the other hand, the temperature and air density are correlated. Therefore air density correction is implicitly also temperature correction

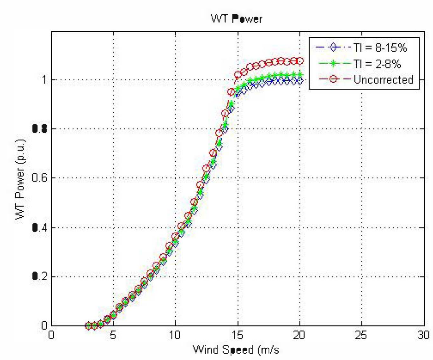

Fig. 4. Power curves for different TI classes.

The turbulence corrected power is shown in Fig. 4 for two different values of TI. The two curves are in the corrected case somewhat closer together with respect to the uncorrected case. The correction (6) is based on the cubical dependence of the power on the wind speed. This behavior is most pronounced in the mentioned wind speed range. Therefore, it is concluded that the turbulence correction (6) is effective. A difference in corrected and uncorrected power up to 8% is observed for higher wind speeds (> 4 m/s) this is less than 3%. For almost all wind speeds the corrected power is lower than the uncorrected power.

Recent works [8] suggested to use a wind speed representative of the disk area for use in power curves. In the case where the wind speed is known over a number of heights within the swept rotor area, the weighted or "equivalent" wind speed, is defined by weighting the averaged wind speed, within the measurement bin, at the corresponding height by the corresponding area ratio A_i/A:

$$U_{eqv,M} = \frac{1}{A}\sum_{i} A_i \sqrt[3]{\overline{U_i^3}} \qquad (11)$$

where A_i is the area corresponding to the specific data point height and A is the swept rotor area. Figure 2 shows an example for the swept rotor area divided into three segments, corresponding to the 40 m, 60 m and 80 m measurement levels. If the turbulence intensity, air density or wind shear corrections are accounted for, as in (3), (6), (10) or (11), the above equation takes the form:

The WTG output power can be determined from its power curve. Fig. 2 shows a typical power curve for a type of WTG systems. The relationship between the power output and the wind speed is treated as a non-linear function of the wind speed. When a WTG operates in the useful wind speed region, the system reaches the maximum power output and remains at that constant level.

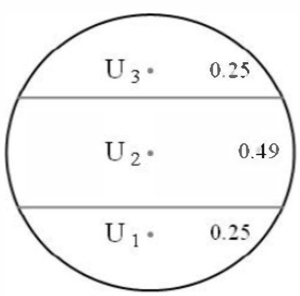

Fig. 5. Swept rotor area of a wind turbine divided into 3 segments

The effects of wind shear, turbulence intensity and atmospheric stability on the wind turbine power performance are complicated and not fully understood. They depend on the aerodynamics and the inertia of the rotor and the control strategy of the wind turbine [6]-[9]. However, the turbine always responds to changes in the mean wind speed. That the turbine power curve has traditionally been measured as a function of the mean wind speed at hub height is a convenient simplification based on the assumption that the wind speed at hub height is representative of the wind over the whole swept rotor area. Clearly, the measurement of the wind speed at more heights within the swept rotor area gives a better representation of the wind field, and the incoming energy, than the hub-height speed measurement only.

The air-density-corrected wind turbine power curves are shown in Fig. 3. It is clear that the corrected power curves for different values of air density are different, being about 5 to 8 % less than the un-normalized power. The wind speed range 4 m/s to 20 m/s is shown, because in this range the cubic dependence of power is most pronounced and is here the most effective.

Using the wind shear parameters (α80-10, α80-40, and α60-10, height differences), the power data were computed according to the stability regimes. The results are shown in Fig. 6. The wind shear seems to have no significant impact on the wind turbine power output (less than 3% on average). However, more studies for various stability regimes and the eventual inclusion of turbulent kinetic energy into power output calculations may be needed.

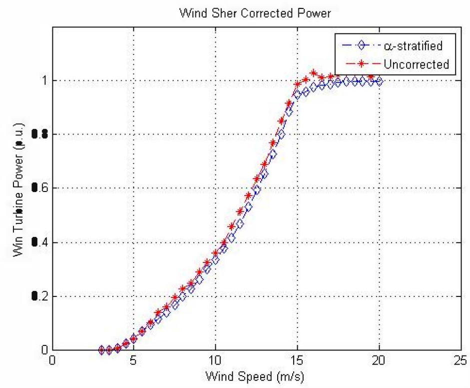

Fig 6. Wind shear corrected power output

V. CONCLUSIONS AND FUTURE WORK

There is a significant effect of ignoring the wind speed shear, turbulence intensity and atmospheric stability on power performance measurement (especially for power law profile) – as done in IEC 61400-12-1 [1]. The standard procedures are valid only for neutral conditions and a small wind turbine. The results from the simulations indicate that measuring the wind speed at an increased number of points over the whole swept rotor area profile would improve the correlation between wind input and power output. In our study, all of the atmospheric conditions that have been considered, i.e. air density, temperature, turbulence and vertical wind shear, have been shown to have an effect on the wind turbine power curves.

Corrections with respect to air density, turbulence and vertical wind shear are examined. Corrections with respect to temperature, turbulent kinetic energy and stability are not considered directly but through the way that wind profiles were computed. This is in part because temperature is correlated to air density and stability is correlated to turbulence and wind shear, as we have seen. These results support the need for the introduction of a new definition for power performance measurements using distributed measurement of the wind over the swept rotor area instead of using only the hub-height wind speed, and the corrected wind speed due to the effects of turbulence, atmospheric stability, air density, etc. Eventually this may lead to a new standard regarding the wind turbine power measurements.

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