TURBULENCE CONSIDERATION ON WIND RESOURCE ASSESSMENT: STATE OF THE ART

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ABSTRACT

Nowadays, the interest on turbulence effect related to wind turbines has extensively growth within the wind energy community. Turbulence and wind shear are essential characteristic of wind, which can provide indications about the behavior of wind itself. It is well-know that a slight variance in wind speed generate large deviation in the output energy of wind turbine because of the cubic relationship between wind velocity and power output. Although, the phenomenon of turbulence is still not complete solved, both in terms of mathematical and intuitive understanding, the practical implications of this issue have encouraged multiple efforts at turbulence predictions by any reasonable approach. The present study is an attempt to pull together current finding related to the effect of turbulent loading on the wind turbine performance assessments. Accordingly, an exhaustive compilation regarding the issue of turbulence on wind resource assessment and a comprehensive literature review covering the different methodologies considering the subject within wind turbine application are presented. The issue of turbulence is discussed focusing on the wind speeds from various directions. Furthermore, the study presents a preliminary overview of the state of the art of the numerical calculation of wind-turbine aerodynamics. Moreover, a comprehensive examination of the status of research around turbulence treatment on wind turbine applications is presented. Hence the relevance of considering turbulence on wind resource assessment and the techniques and methods used for it are highlighted.

KEY WORDS: Turbulence effect on wind turbines, Wind resource assessment, Wind turbine applications.

CONSIDERACIÓN DE TURBULENCIA EN LA EVALUACIÓN DE RECURSOS EÓLICOS: ESTADO DEL ARTE

RESUMEN

En la actualidad, el interés por el efecto de la turbulencia en las turbinas eólicas ha tenido un gran crecimiento dentro de la comunidad de la energía eólica. La turbulencia y la cizalladura del viento son características esenciales del mismo, que pueden proporcionar indicaciones sobre su comportamiento. Es conocido que una ligera variación en la velocidad del viento genera una gran desviación en la energía entregada por la turbina eólica debido a la relación cúbica entre la velocidad del viento y la potencia de salida. Aunque el fenómeno de la turbulencia todavía no está completamente resuelto, tanto en términos de comprensión matemática como intuitiva, las implicaciones prácticas de este problema han alentado múltiples esfuerzos en la obtención de predicciones adecuadas de los efectos de la turbulencia. El presente estudio reúne los resultados actuales relacionados con el efecto de la turbulencia en el funcionamiento de turbinas eólicas. En consecuencia, se presenta una compilación detallada sobre la consideración de la turbulencia en la evaluación de los recursos eólicos y una revisión exhaustiva de la literatura que cubre las diferentes metodologías que toman en cuenta el tema. También se examinan los diferentes modelos de turbulencia existentes para estudiar los efectos de la estela de las turbinas eólicas. Presentando además una perspectiva preliminar del estado del arte del cálculo numérico de la aerodinámica de estela de turbina eólica. Consecuentemente, la importancia de considerar la turbulencia en la evaluación de los recursos eólicos y las técnicas y métodos utilizados para ello es resaltado.

PALABRAS CLAVES: Turbulencia en turbinas eólicas, Evaluación de recursos eólicos

1. INTRODUCTION

With the worldwide increasing concern to achieve more environmentally friendly and sustainable global energy solutions, wind energy has resurged as one of the most attractive alternative of renewable energy sources utilization. It is well-known that wind energy is one of the most consistent growing areas among renewable energy sources [1,2]. The average annual growth rate of world installed capacity of wind power from 1994 to 2016 has been over 30% [3-10]. Nevertheless, despite of the environmental benefits and technological maturity of wind conversion systems, reliability and stability of the power grids represent a challenge to penetration of wind-generated power, due to the highly variable and intermittent nature of the winds [9]. As was pointed out in [9], wind energy resource relies on the incident wind speed and direction, both of which vary in time and space due to changes in largescale and small-scale circulations, surface energy fluxes, and topography [11-15]. In general, it is widely known that the atmospheric boundary layer (lowest part of the atmosphere) is characterized by high turbulence [16]. Therefore, wind turbines are influenced by the turbulence in the atmospheric boundary layer [17]. Consequently, the interest on turbulence effect related to wind turbines has extensively growth within the wind energy community. Several studies have focused on the impacts of turbulence intensity on wind turbines, including the impacts on power output and aerodynamic loads [18-23]. In fact, a slight variance in wind speed generate large deviation in the output energy of wind turbine because of the cubic relationship between wind velocity and power output.

The study deals with a subject undertaken within the framework of the on-going international VLIR UOS TEAM project, *"Renewable energy and bioclimatic architecture improving sustainability and development in Eco-touristic settlement: Las Terrazas"*, carry out between a Cuban and Belgian universities i.e (The Technological University of Havana and Ghent University). The project aims to develop sustainable solutions for Cuban rural communities and ecotourism locations by mean of setting up a demonstration case of sustainability improvement in such of mountainous settlement. It is well known that winds associated with mountainous terrain are generally of two types: (i) terrain-forced flows, produced when large-scale winds are modified or channelled by the underlying complex terrain; (ii) thermally-driven circulations, produced by temperature contrasts that form within the mountains or between the mountains and the surrounding plains [24,25]. Hence, it is expected that a complex wind regime for wind energy generation with the presence of high level of wind variability, effects of air density and temperature and turbulence on this site will be found. In fluid dynamics, turbulence is a flow regime characterized by chaotic and stochastic property changes. This includes low momentum diffusion, high momentum convection, and rapid variation of pressure and velocity in space and time.

Turbulence and wind shear are essential characteristic of wind, which can provide indications about the behavior of wind itself. Although, the phenomenon of turbulence is still not complete solved, both in terms of mathematical and intuitive understanding, the practical implications of this issue have encouraged multiple efforts at turbulence modelling by any reasonable approach. The present study is an attempt to pull together current finding related to the effect of turbulent loading on the wind turbine performance assessments. Accordingly, an exhaustive compilation regarding the issue of turbulence on wind resource assessment covering the different methodologies considering the subject within wind turbine application is presented. The issue of turbulence is discussed focusing on the wind speeds from various directions. Furthermore, the study presents a preliminary overview of the state of the art of the numerical calculation of wind-turbine aerodynamics. Moreover, a comprehensive examination of the status of research in the field of turbulence treatment on wind turbine applications is presented.

2. WIND TURBINE PERFORMANCE ASSESSMENTS

The target of a wind turbine is capturing the wind kinetic energy from the wind to convert part of the wind energy into useful mechanical and then electrical power. Therefore, to understand the factors affecting the wind energy, play an important role both during the wind turbine design and/or during the use of wind power. Following, the main factors influencing the wind energy performance are described [26,27]. Power is the rate at which the kinetic energy of the air is used. In an interval of time, blades can extract power from a cylindrical volume of air that is equal to the product of the rotor swept area A and the length equal to the product of the velocity (v) and the time interval. So, the extractable wind power (P_w), under the ducted flow, can be identified [9] as:

$$P_w = \frac{m_w v^2}{2} = \frac{\rho A v^3}{2} \qquad [W] \tag{1}$$

Where m_w is the wind mass flow rate, v is the velocity in (*m/s*), ρ is the density of the air in (kg/m^3), and A is the shaded place in (m^2). As seen from Eq. (1), the wind power varies as the cube of the wind velocity. Unfortunately, the total wind energy cannot be regained in a wind turbine because the output wind velocity cannot be reduced to zero, otherwise there would be no flow through the turbine [26,28]. The maximum power obtained from a wind system is 59.3% of the total wind power. This is referred to as the Betz Criterion or the Betz Limit. It is the theoretical power fraction that can be extracted from an ideal wind stream and applies to all wind turbine designs.

A detail inside of the definition of the Betz criterion can be found in [29]. However, the actual turbine power (P_{wT}) that is captured from the wind field is lower than the above stated maximum theoretical extraction. The fraction of power extracted is reduced because of loss factors such as friction, turbulence, shear, and coherent eddies [7,10] and can be described by a nonlinear function:

$$P_{wT} = \frac{\rho C_P(\alpha,\lambda) A_R v^3}{2} \qquad [W] \tag{2}$$

Here $C_P(\alpha,\lambda)$ is the wind turbine capacity factor or the aerodynamic efficiency of the rotor, and v is the effective wind speed. $CP(\alpha,\lambda)$ describes the fraction of the power in the wind that may be converted by the turbine into mechanical work [9]. The rotor power coefficient is usually given as a function of the tip-speed ratio λ and the blade pitch angle α. The blade pitch angle is defined as the angle between the plane of rotation and the blade cross-section chord. The tip speed ratio is defined as:

$$\lambda = \frac{\omega R}{v} \tag{3}$$

Where ω is the angular velocity of the rotor, and R is the rotor radius (blade length). The power production of a wind turbine depends upon many parameters such as wind speed, wind direction, air density and turbine parameters [30]. Certainly, it is challenging to assess the output power using the theoretical equations due to the difficulty involved in considering the effects of all driving factors correctly. Power curve of a wind turbine, which gives the output power of turbine at a specific wind speed, provides a convenient way to model the performance of wind turbines [31]. In wind turbine design and site planning, the probability distribution of wind speed becomes critically important in estimating the energy production [56]. It has been defined in engineering practice, the average wind turbine power, ($\bar{P}_w$) associated with the Probability Density Function (PDF) of wind speeds, (v) [55]

$$\bar{P}_w = \int_0^{\infty} P_w(v)\, f(v) dv \tag{4}$$

where, $f(v)$ is the probability density function of v and $P_w(v)$ is the turbine power curve that is used to describe the power output of wind speed

3. POWER CURVE MODELLING

The power curve provided by the manufacturers, usually, in graphical form indicates its performance of a wind turbine. Figure 1 displays a typical power curve for a wind turbine. In the first region when the wind speed is less than a threshold minimum, known as the cut-in speed, the power output is zero. In the second region between the cut-in and the rated speed, there is a rapid growth of power produced. In the third region, a constant output (rated) is produced until the cut-off speed is attained. Beyond this speed (region 4) the turbine is taken out of operation to protect its components from high winds; hence it produces zero power in this region [31].

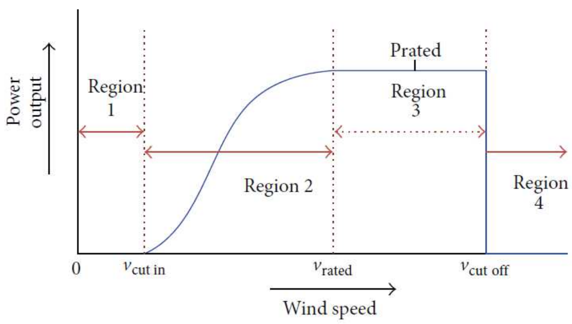

Figure 1: Typical power curve of a pitch regulated wind turbine [31].

The power curve of a wind turbine is mainly dependent on wind speed, density, vertical wind shear, vertical wind swing and turbulence intensity. However, the effects of wind shear, turbulence intensity, and atmospheric stability on wind turbine energy production are not fully understood, therefore, wind resource assessment studies can have large uncertainties. [9]. Several methods have been developed to understand and predict the power of a wind turbine under a range of inflow conditions. For instance, in [32], the author suggests probability models for the natural variability of wind energy resources that include air density, mean wind velocity and associated Weibull parameters, surface roughness exponent and error for prediction of long-term wind velocity. In function of atmospheric site-specific conditions, field-deployed power curves can be very different from certified ones [9,12]; [33-37].

Several aspects require consideration while modelling the power curves of wind turbines. Since, the power curves vary with different manufacturers and models, the model used to describe them should also be different [38]. In addition, the cut-off hysteresis which occurs during the period between shut down and restart of turbine affects the productivity of turbine [39]. Hysteresis effects can be more significant with certain wind patterns and terrains such as unsteady and gusty winds requiring frequent starting and shutting down, resulting in considerable loss of energy production [31]. It is well-known that wind at a site is determined by weather phenomena and topology of the site. Wind is generally intermittent and variable in speed and direction [40].

Therefore, because of the site properties and scales of motion, the flow can become turbulent with stochastic and chaotic properties [41,42]. The decrease of air density with height is another factor that have an impact on the computed power, since wind power is directly proportional to air density [9]. Effect of varying air density has been considered for developing site specific curves [43]. Moreover, in several studies considering power calculations, either the power or velocity is normalized, depending on the turbine's method of control [9, 34-37].

In addition, the wind speed changes with height, wind shear effect, influenced by the roughness of terrain. Wind shear or wind slope is stated as the difference in wind speed or wind direction in a relatively small region in the atmosphere. It is generally termed as vertical wind shear or horizontal wind shear [44]. Wind speed is usually measured at the standard meteorological height of 10 m, while nowadays, the modern wind turbine hub heights are normally available in the range of 50 -120 m. Usually, hub height wind velocity is estimated by applying a vertical extrapolation coefficient to surface measurements [45]. However, the vertical extrapolation coefficient can contain errors and uncertainties due to terrain complexity, atmospheric stability, and turbulence. Several methods have been used in the literature to express the variation of wind speed with height [38]. Most of these methods are completely based on the experience, mathematical models commonly known as power law, logarithmic law, and numerical models. The modelling requires an exponent α known as power exponent or wind shear exponent whose value is mainly decided by the terrain surface roughness, atmospheric boundary layer, and wind direction [46]. The mathematical model for power law is described in the Eq. (5)

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{5}$$

Where v_1 (m/s) is the measured value of wind speed at reference heights h_1 (m), v_2 (m/s) is the measured value of wind speed at heights h_2 (m), and α designates the power law exponent or wind shear exponent. This coefficient is a function of the surface roughness at a specific site and the thermal stability of the Prandtl layer [9]. It is frequently assumed to be *1/7* for open land. However, this parameter can vary diurnally and seasonally as well as spatially. Belu and Koračin in [12] reported significant discrepancies of values for α for a given specific site, ranging from 0.09 to 0.120, quite smaller compared to the usually assumed value of 0.143 (1/7). In the same way, the wind speed $v(h)$ at a height h can also be calculated using the roughness length z_0 from the wind speed $v(h_0)$ at height h_0 (usually the standard measurement level) from the logarithmic law, Eq (6). Where parameter d expresses the displacement of the boundary layer from the ground caused by obstacles of a given terrain.

$$v(h) = v(h_0)\frac{ln\left(\frac{h-d}{z_0}\right)}{ln\left(\frac{h_0-d}{z_0}\right)} \tag{6}$$

In most of the dispersed obstacles, parameter d is zero, while in other cases it is expressed as 70% of the obstacle height [7,9,14,40,45]. The roughness length (z_0) describes the height at which the wind is zero, meaning that surfaces with a large roughness length have a large effect on the wind. It ranges from 0.0002 m for open sea, 0.005-0.03 m for open land, 0.03-0.1 m for agricultural land, and 0.5-2 m for very rough terrain or urban areas [9]. Additionally, the accuracy of conversion of the measured wind speed to wind speed at hub height and at the turbine location depends on factors such as the vertical wind profile at the site, position of masts relative to the turbine, and the method used for extrapolation [31]. The authors of the afore-mentioned paper reported that the power curve modelling methods can be classified into *discrete*, *deterministic/probabilistic*, *parametric/nonparametric*, and *stochastic* methods or they can be classified based on data used for modelling. In the *Discrete Models,* which is the method described in IEC 61400-12 all the wind speeds are discretized into

0.5m/s bins [47]. A *deterministic power curve model* assumes a fixed relation between the output power and wind speed [31]. While a *probabilistic power curve model* characterizes the relationship between wind speed and actual output powers incorporating the possibility of different power production, even if the wind speed is the same, when a fleet of wind turbines are deployed on a wind farm [48-50]. The international standard procedure commonly adopted for power performance characterization of single wind turbines is specified in the *IEC 61400-12-1 Standard* [47].

The standard describes the measurement methodology for the measured power curve which is determined by simultaneous measurement of wind speed and power output at the test site. [31]. However, considerable wind power estimate inaccuracies can occur, since the standard assume that the wind speed at the hub height is representative of the wind over the whole turbine rotor area [33, 35]. While actual inflow is often non-uniform and unsteady over the rotor-swept area. Although the IEC power curve considers the wind condition of the current site it may not always be appropriate to apply to the wind conditions of other sites [31]. Methodologies of the power curve estimation which considers the influence of site parameters such as topology, obstacles as well as weather phenomena can result in more accurate models [43].

Wind power generated is highly correlated with the wind speed distribution across the region where the wind turbine is located. The natural variability of wind speed at a site over a period can be represented by probability distribution functions (PDF). Although, the most commonly used and accepted distribution is the two-parameter Weibull distribution [49, 54], for certain wind regimes it is not a suitable option, for example, those having high frequencies of null winds, and for short time horizons [52, 53]. As was reported in [55], an accurate determination of the probability distribution of wind speed is an important parameter to measure before estimating the wind energy potential over a region. Utilizing an accurate distribution will minimize the uncertainty in wind resource estimates and improve the site assessment phase of planning. Each site has its own wind regimes; thus, different wind distributions will be found for different regions. As can be seen in table1, several statistical distributions functions found in the literature used to fit actual wind data at specific place are displayed.

Table 1 demonstrates that several wind speed frequency distributions represented by various probability density functions including the gamma function, the exponential function, the lognormal function, Rayleigh, Weibull among other distributions have been widely used by the practitioner in practical engineering applications. Several authors have shown that different distributions perform better for different metrics suggests that the selection of model depends on the wind energy application [56]. In general, in terms of characterizing entire wind speed samples, the Bimodal Weibull mixture distribution offer significantly better fits than other models, giving in most of the cases the highest R^2 values [55, 56]. Nevertheless, this model is quite complex, with 4 or 5 parameters. When considering the simpler models (2 or 3 parameters), the traditional Weibull two parameters distribution generally gives larger R^2 values than several 2 parameter models, and some of the 3 parameter models.

However, as was observed in [57,58], despite of the high contribution of power curve definition for estimation of annual energy, they may not represent the realistic conditions of the site under consideration, since the manufacturers power curves are created under standard conditions. Current power curve representations do not account for the impact of turbulence on small turbine energy production. Curves based on IEC 61400-12-1 are statistical averages of power measurements binned by wind speed, hence the variance of the data is lost [47]. This approach cannot properly account for site-varying levels of turbulence [59]. 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 different levels of turbulence will affect the power production of the turbine [60].

Table 1: List of probability density functions and statistic parameters function

Distribution Function	Probability Distribution Function,	Parameters	Ref.
Weibull 2P	$f(v)=\frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left(-\frac{v}{c}\right)^{k}$	$k(\sigma,\bar{v})$ $c(\Gamma,\bar{v},k)$	[49] [57]
Weibull	$f(v)=\frac{\beta}{\alpha}\left(\frac{v}{\alpha}\right)^{\beta-1} exp\left(-\frac{v}{\alpha}\right)^{\beta}$	$\beta(\beta,v)$ $\alpha(\beta,v)$	[7,10] [57]
Rayleigh	$f(v)=\frac{2v}{c^2} exp\left(-\frac{v}{c}\right)^{2}$	$k=2;$ $c(\pi,\bar{v})$	[43] [53]
Gamma 2P	$f(v)=\frac{v^{\eta-1}}{\beta^{\eta}\Gamma(\eta)} exp\left(-\frac{v}{\beta}\right)$	$\beta(\sigma,\bar{v})$ $\eta(\sigma,\bar{v})$	[57]

Exponential	$f(v) = \frac{1}{\theta} exp\left(-\frac{v}{\theta}\right)$	$\theta = \bar{v}$	[53] [55]
Pearson 3P	$f(v) = (v-\tau)^{\alpha-1} \frac{exp\left(-\frac{v-\tau}{\beta}\right)}{\beta^{\alpha}\Gamma(\alpha)}$	$\beta(S,G)$ $\alpha(G)$ $\tau(\bar{v},S,G)$	[56]
Lognormal 2P	$f(v) = \frac{1}{v\beta\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{\ln(v)-\alpha}{\beta}\right)^2\right]$	$\beta(\sigma,\bar{v})$ $\alpha(\sigma,\bar{v})$	[57]
Inverse Gaussian 2P	$f(v) = \frac{\beta}{2\pi v^3} exp\left[-\frac{\beta(v-\alpha)^2}{2v\alpha^2}\right]$	$\beta(\sigma,\bar{v})$ $\alpha(\bar{v})$	[53]
Burr	$f(v) = \frac{aqv^{a-1}}{b^a\left[1+\left({}^{v}/_{b}\right)^a\right]^{1+q}}$	$a(q,b,v)$ $b(q,a,v)$ $q(a,b,v)$	[53] [55] [56]
Inverse Gamma	$f(v) = \frac{\beta^p}{\Gamma(p)} v^{-p-1} exp\left(-\frac{\beta}{v}\right)$	$\beta(p,v)$ $p(\beta,v)$	[53] [55] [56]
Bimodal Weibull Mixture	$f(v) = \omega \frac{\beta_1 v^{\beta_1-1}}{\alpha_1^{\beta_1}} exp\left[-\left(\frac{v}{\alpha_1}\right)^{\beta_1}\right] + (1-\omega)\frac{\beta_2 v^{\beta_2-1}}{\alpha_2^{\beta_2}} exp\left[-\left(\frac{v}{\alpha_2}\right)^{\beta_2}\right]$	$\beta(v)$ $\alpha(v,\beta)$	[56] [51]
k- shape parameter; *c*- scale parameter; *Γ* gamma function; *α,β,η,a,b,p,q*- parameters of the distribution			

4. MODELLING TURBULENCE EFFECT

Wind energy resource rely on the incident wind speed and direction, both of which vary in time and space due to changes in largescale and small-scale circulations, surface energy fluxes, and topography [11-15]. Wind power is proportional to the cube of the wind speed, therefore, an accurate assessment and forecasting of the spatial and temporal characteristics of the winds and turbulence remains the most significant challenge in wind energy production [9]. Turbulence can be assumed as a disorderly fluctuation in the wind, caused by dissipation of the wind's kinetic energy into thermal energy. This happens through formation and destruction of progressively smaller eddies and seems to arise quite randomly. This causes the reduction in wind power generation, increases the dynamic load on the wind turbine blades, and increases wear and tear and thus will further shorten the life time of wind turbine [44]. Usually places with high wind speeds tend to have less effect from turbulence, which is an undesirable condition for wind turbine operation.

As was observed in [44], the strict indications for high turbulence are heterogeneous landscapes, steep cliffs, and regions with several buildings. Temperature gradient of the atmospheric boundary layer has a significant impact on turbulence, which is also influenced by stability conditions such as stable, neutral, and unstable in the atmosphere. In an unstable boundary layers, the turbulence can extend vertically for a substantial distance, whereas in neutral conditions the atmospheric air is well mixed as a result no temperature gradient exists and hence the turbulence or resilience forces are negligible. In case of high wind speeds temperature gradient formation is avoided and thus leads to a neutral atmospheric condition [61]. The turbulent wind speeds can abruptly double or triple within a few seconds, thus resulting in the wind power increase of 8 or 27 times, respectively [44]. The wind's variability has some distinct features, which can be described by several statistical properties. One of these is turbulence intensity (*TI*), which can be referred to as the level of turbulence in the wind [10]. The physical significance of *TI* is a measure of the wind speed gustiness. The turbulence intensity (*TI*) is a measure of the overall level of turbulence and is defined as the ratio of standard deviation (σ) of normalized wind speed to its mean wind speed (v) [33,35,36,46].

$$TI = \frac{\sigma_v}{v} \quad (6)$$

According to the IEC 61400-12-1 standard, the turbulence and wind speed also help in classifying the wind turbines and its design features [62]. However, the current standard for power performance measurements of wind turbines, IEC 61400-12-1, is based on hub height wind speed and does hence not account for wind shear or veer. Neither does it correct for turbulence intensity. The statistics of these parameters might be site specific and variations will increase the scatter of the power curve. Several previous studies have examined the effect of wind shear and turbulence on the power curve. The effect of wind veer causing a partial yaw error over the rotor span is however rarely considered. Such effects become increasingly important as the dimensions of the wind turbine rotors increase [63]. However, a revision of the IEC standard is in progress and the new edition addresses vertical shear, directional shear and Turbulence [47]. An overview of aspects of the development of the new standard is discussed in [64].

In general, turbulence will increase the kinetic energy flux during a ten-minute averaging period compared to a steady mean wind. Earlier studies have suggested a simple correction of the wind speed adding the increased kinetic energy associated with turbulence using the turbulence intensity (*TI*) as the input parameter [65]. This would give a more realistic measure of the efficiency of the wind turbine but would not reduce the scatter of the power curve. This is because the turbine is not able to utilize all the turbulent energy in the wind. As was observed in [63], around the rated wind speed *TI* has a large influence on the power curve causing high scatter. In this region power output is reduced by pitching the blades for gusts higher than the rated wind speed, and hence only the negative wind fluctuations will affect the power output. However, it is difficult to isolate the effects of a single parameter from field data, since wind parameters are also coupled, meaning that situations with high shear are related to low turbulence and vice versa. Moreover, when shear and turbulence are introduced and combined in the wind field, a suboptimal aerodynamic performance over parts of the blades will reduce the power output compared to the ideal case for the same kinetic energy potential [63].

A considerable body of literature has attempted to characterize and modelling the effect of wind turbulence on wind turbine's performance. In [67], it was observed that, there are usually two methods to get the wind speed fluctuation in different time scales. One method is using the wind speed models, such as the four-component composite model [68], mean value and turbulence composite model [69], stochastic differential equations based continuous wind speed model [70], and the Weibull distribution-based model [71,72]; the other method is through the wind speed forecast [73-77]. Another relevant contribution concerning procedure to characterize and modelling the effect of wind turbulence can be found in [66]. The authors pointed out that the IEC6400-12-2 standard mandates designers to use a *Normal Turbulence Model* (NTM) that describes turbulence and turbulence intensity and includes the effects of varying wind speed and varying direction [78]. The *Normal Turbulence Model* (NTM) states that the expected standard deviation of longitudinal wind speed can be estimated using data collected from open terrain sites [78]. IEC 6400-12-2 defines a ‘characteristic turbulence intensity, *I*, as the 90th percentile of turbulence intensity measurements binned with respect to wind speed [47]. For each wind speed bin, the 90th percentile value of turbulence intensity is obtained by taking the mean *I* value in the bin plus *1.28* standard deviations of *I* from the mean, thus assuming a Gaussian distribution for turbulence intensity values.

Concerning the subject of turbulence modelling, the IEC standard 61400-1 [47] recommends the use of either Mann's uniform shear model [79], or the Kaimal model [80] for defining turbulence spectra in three dimensions. In the IEC standard, the values of the parameters of the Mann model are chosen such that the resulting spectra in longitudinal, transverse horizontal and transverse vertical directions (denoted *u*, *v* and *w*, respectively) represent the best possible match to the corresponding spectra of the Kaimal model [66]. The length scale increases linearly with height up to *60 m*, but above that height remains constant. However, measurements have shown that spectral characteristics corresponding to this set of parameters rarely occur in practice [81,82]. Furthermore, wind turbine load modelling requires input of a three-dimensional air flow field that realistically reflects natural turbulent wind conditions [66]. The properties of the wind field model depend on the spectral and spatial coherence properties used to generate it. In the atmospheric boundary layer, the wind turbulence spectral density definition considers the correlation in the time domain of the different component of the wind velocity. The cross power spectral density function describes the correlation between velocities at two different points *i* and *j* in space at different time points in the frequency domain. The wind turbulence spectral density definition contains the auto and cross spectral density functions for the along-wind, lateral and vertical turbulence components *u*, *v* and *w* [83]. Besides, a coherence function is defined. The coherence function describes the relation between the auto and cross power spectral density functions and is defined as the absolute value of the cross power spectral density function. The spectral density functions are the Fourier transforms of the correlation functions. A commonly used theoretical model for the correlation functions is a turbulence model for isotropic turbulence [84-86]. There are many other definitions for auto spectral density functions. An overview to the commonly used auto spectral density functions in wind engineering can be found in [87, 88].

Moreover, during the last years there has been an increasing trend towards the installation of wind turbines in non-open terrain, such as in urban areas, above forests and in mountainous regions [89]. Since, many of these non-open sites are often characterised by highly turbulent wind flow, the interest on improve the understanding and modelling approach of turbulence phenomena has grown, as well. Gontier et al. [90] used the Kaimal, von Karman and Mann turbulence models suggested in the IEC guidelines as well as the Friedrich-Kleinhans model as a non-Gaussian turbulence model to compare fatigue loads of wind turbines.

In [91] a comparison of turbine blade load statistics for inflow turbulence fields based on the open terrain standard Kaimal spectra, was presented. The authors show that for extreme, high turbulent intensity winds, the measured spectra predict isolated loading events around twice the magnitude of loads predicted by use of the standard IEC61400-2 spectra. In the same way, in [92], the analysis of turbulence intensity based on wind speed data in onshore wind farms was presented. In this study, the results show that the *Normal Turbulence Model* overestimates the turbulence intensity. The authors purposed an improved time-varying turbulence intensity model developed according to the daily periodicity, which shows better performance than the *Normal Turbulence Model*. Furthermore, in [83] the wind turbulence parameters from three dimensional full-scale measurements at 344 m high guyed mast was presented. The estimated turbulence parameters such as integral time scales and standard deviations of all three turbulence components from more than 2500 10-min. time series were presented. The authors demonstrated that the estimated auto spectral density functions of all three turbulence components were in a good agreement with the von Karman [84] and Dryden [86] models. Additionally, the effects of normal and extreme turbulence spectral parameters on wind turbine loads was studied in [66]. The authors investigate the effect of variation turbulence spectral parameters of the commonly used Mann turbulence model on the magnitude of the obtained design loads. While, Burlibas and Ceanga [93] presented a rotational wind speed turbulence modelling. Using the correlation technique based on von Karman fixed point spectrum model, the authors analyses how the power spectral density changes when the system operating point moves through different operating regions of the power-wind speed characteristic.

5. CONCLUSION

As wind power is increasing its presence within the energy sector, an accurate modelling and assessment of wind power resource is crucial for successful design and operation of any wind energy conversion system. Therefore, the paper has presented an overview of different approaches used for modelling of turbulence on wind turbine assessment. Multiples driving factors have an impact on the accuracy assessment and prediction of wind energy production. Turbulence and wind shear are complex characteristic of wind, meanwhile can provide indications about the behavior of wind itself. A crucial step becomes to guarantee an adequate understanding of the effects of wind variability, atmospheric stability and turbulence on production. Hence, a comprehensive review of the research works carried out in this area have been examined. The preliminary assessment gives the basic idea that actual wind data and statistic approach plays an important role in wind resource assessment. The short term as well as long term data analysis both, ranging from one year to ten years with 10 min step interval measurements have been recommended by majority of authors in the literature. In addition, the various models like statistical models, applied to determine wind speed distribution, directional distribution, frequency distribution, and annual energy yield reported in literature have been presented in this review. However, several authors have pointed out the necessity of validation for each model using measured data, so that the uncertainties associated with quality of data, instrumentation sensors, wind flow models, and wind parameter estimation process can be reduced.

Despite that during the las years an attend to take into account turbulence intensity, the effects of shear and atmospheric stability within the current IEC standard, 61400-12 concerning wind turbine performance assessment have been considered, several authors have highlighted that the standard approach is not fully able to reflect the variability of an actual wind field. In this work a variety of PDFs that have been proposed in the scientific literature related to describe wind speed frequency distributions have been compiled. Accordingly, the extensive collection of probabilistic distribution functions (PDFs) constitutes a valuable catalogue for the practitioner. In general, in a wide group of studied cases, the Weibull distribution of two parameters presents a series of advantages with respect to other PDFs analysed. Even though that the Weibull distribution presents advantages such as: i) its flexibility; (ii) the dependence on only two parameters; (iii) the simplicity of the estimation of its parameters, independently of the method used, certainly, the Weibull distribution is not able to represent wind regimes with high percentages of null wind speeds, high turbulence or bimodal distributions, etc. In the same way, the mixture distributions of two Weibull distributions or a Weibull distribution and a normal truncated distribution are particularly suitable for bimodal wind regimes and even unimodal cases, due to the flexibility on the determination of the statistics parameters.

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