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Evaluating wind power density models and their statistical properties

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ABSTRACT

Information about the wind power df(density function) is very important when measuring the wind energy potential for a specific area. Usually, the wind power df provides knowledge about the mean power, which is an indicator of the energy potential. However, the mean power does not describe well the characteristics of power density. Thus, by knowing information about other statistical properties, such as standard deviation, skewness and kurtosis, better insight about the characteristics and properties of power density can be obtained. This study proposes a method to derive a wind power density model and its statistical properties particularly from well-known dfs, namely, the Weibull, Gamma and Inverse Gamma dfs. Applying the method of transformation and Monte Carlo integration has been discussed to address the difficulty of finding the different statistical properties of power density. In addition, an application of the proposed method is demonstrated by a case study that involves wind speed data from several stations in Malaysia.

1. Introduction

Currently, wind energy has become an important alternative source of energy because it is cost-effective and readily available. In addition to its low cost and its availability everywhere in the world, wind energy also provides advantages with its low, local and manageable impact on the environment. These advantages exist specifically because the process involved in generating the electricity from wind turbines does not release carbon dioxide. These advantages have allowed wind energy to be among the potential alternatives for renewable clean energy; thus, wind energy could substitute for fossil-fuel-based energy sources, which contaminate the lower layers of the troposphere [1]. In addition, wind energy does not pose a transportation problem, and its utilization does not require advanced technology [2]. In fact, investment into wind energy will provide benefits in terms of employment, research, economic activity and energy independence in the electricity sector [3]. In developed countries such as Germany, USA and Spain, the use of wind energy has gained recognition, and currently, it is gaining more and more advanced implementation. In addition, Asia, China and India have also actively enhanced and expanded the use of wind energy applications [4]. Thus, to take advantage of this freely available energy source, a large amount of research has been conducted toward the development of an accurate and reliable wind energy assessment model using many different approaches [5].

An effective utilization of wind energy requires detailed knowledge of wind characteristics in a specific area. The characteristics of wind speed can be explained by using a wind speed density function. The wind speed density function is important in determining the selection of suitable sites for a wind generator, designing the wind farm, designing the power generator, determining the dominant direction of the wind and evaluating the management operations of the wind power conversion system [6,7]. Thus, it can be concluded that the information regarding the wind speed density function is very important for assessing the capacity and the potential performance of wind energy in a specific area. A wind speed density function is usually described by its pdf (probability density function). Then, the energy density E in term of W/m^2 for a specific wind site and a wind turbine can be obtained by using the power curve and the probability density function of wind speed [8]. Morgan et al. [9] and Carta et al. [10] stated that engineering practice has identified the mean of the wind energy that

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can be produced by a wind turbine associated with the probability distribution function of wind speed which can be calculated as follows:

$$\overline{P}_w = \int_0^\infty P_w(x)f(x)dx \quad (1)$$

where $\overline{P}_w$ is the mean power that is produced, x is the value for the wind speed random variable X, $f(x)$ is a pdf for the wind speed, and$P_w(x)$ is a turbine power curve. The uncertainties in the wind power estimation when using Equation (1) depend on the pdf for wind speed, $f(x)$. This relationship occurs because the value of the turbine power curve can usually be determined accurately. Thus, the selection of the 'good' wind speed pdf can provide a more precise estimation and a better result for the analysis of wind energy potential. In fact, the mean of the wind power $\overline{P}_w$, described by Equation (1) can also be known as a first-moment of the wind speed density function corresponding to the turbine power curve$P_w(x)$.

The turbine power curve mentioned in Equation (1) defined wind power as a proportion of the cube of wind speed X. Instead of the wind speed, the power curve of a wind turbine also depends on the value of constant air density, ρ_k and the area of the airstream that has been measured at a perpendicular plane to wind speed direction, A [11,12]. Thus, the wind power equation, based on the criteria of the power curve, can be written as follows:

$$P_W(X) = \frac{1}{2}A\rho_k X^3 \quad (2)$$

Equation (2) provides the power of the wind that flows at the speed of X through a blade sweep area A. This equation has been used to compute the availability of the wind power in a specific area. To be more precise, we must consider Betz's law in the power coefficientC_p, which is used in windmills after considering several factors in the process of generating power [11]. Thus, the complete wind power equation is:

$$P_{C_p}(X) = \frac{1}{2}A\rho_k X^3 C_p(\lambda, \beta) \quad (3)$$

where $C_p(\lambda,\beta)$ is the power coefficient value (which complies with Betz' law and the type of wind turbine that is used). However, the calculation involved in Equation (3) must be performed by involving several engineering aspects, such as the parameter of the rotational speed of a wind turbine, the turbine blade's angle of attack, the pitch angle etc. [13]. Thus, in this study, I attempt to provide a theoretical approach to the estimation of wind power using Equations (1) and (2). The researchers who are involved with the real application of wind power generators (using Equation (3)) can easily make modifications to our approach in order to meet the requirements of their study.

Based on the wind power equations discussed above, it can be concluded that the probability density function of the wind speed is very important in determining and evaluating wind energy potential. In fact, the Weibull pdf is among the most popular statistical distributions in the field of wind energy applications. For example, the Weibull pdf has been used widely in modeling and the assessment of wind energy potential for particular areas for examples,see [14–25]. The information from the Weibull pdf can be used to estimate the wind power corresponding to the wind turbine capacity factor see [26–30]. In addition to this, the Weibull pdf has also been used as an estimation model to evaluate the wind power performance system [31,32] and the failure model for the wind turbine [33]. However, not all of the wind regimes can be modeled using the Weibull distribution. For example, Jaramillo & Borja [34] have shown that the mixture in the Weibull pdf can provide a better result in modeling the wind regime than using a bimodal distribution. Brano et al. [35] have found that the Burr distribution is among the best pdf models for wind regime in the urban area of Palermo, Italy. Safari [36] has found that the Gamma distribution can also be used to model the wind-regime data in Rwanda. Morgan et al. [9] compare 14 different wind speed pdfs to determine the best model for offshore wind speed calculations in North America. The results of their study conclude that the Lognormal, Kappa, Bimodal Weibull and Wakeby pdfs can perform better for modeling wind speed compared with the Weibull pdf. Zhou et al. [37] evaluated 9 wind speed pdf models to describe the data of wind speed in several sites within the North Dakota region. Based on the goodness-of-fit assessment, they found that different sites have different suitable pdf models for wind speed data. Carta et al. [38] provided a comprehensive review of the wind speed pdf in wind energy applications. Overall, they have determined that 11 of the wind speed pdf models have been used by most of the researchers all over the world for modeling and assessing wind energy potential. Masseran et al. [39] used 9 different wind speed pdf models to describe the variability of the wind regime in the Malaysian regions by working with 67 wind station sites. Based on their analysis, they found that the Gamma, Weibull and Inverse Gamma pdfs provide a good, fitted model to the data. Chang [40] estimates the wind energy potential in Taiwan using six different probability density functions, namely; Weibull, mixture Gamma-Weibull, mixture Normal, mixture Normal-Weibull, Mixture Weibull and MEP(maximum entropy principle distribution). The results of the study indicate that the unimodal distribution of wind speed data does not provide a significant differential between the fitted of each pdfs. However, if the wind speed data is bimodal, the mixture pdfs and MEP pdf can provide better characterizations of wind speed than the Weibull pdf. Usta & Kantar [41] analyze two flexible families of pdfs for estimation of the wind speed distributions. The families of pdfs being proposed include the STD (skewed t-distribution) and skewed generalized error distribution (SGED). Their results found that the STD and SGED can provide better results than the Weibull with a two- or three-parameter distribution. Apart from that, there are many research studies that have performed analysis regarding wind energy by considering several probability densities simultaneously to provide more accurate results for wind energy calculation and estimation.

2. Deriving the wind power density using the transformation method for random variables

As mentioned above, the wind power estimation can be described by Equations (1)–(3). Thus, to determine the theoretical wind power density function, a method of transformation for random variables is needed. The transformation method is a technique that is commonly used in statistical analysis to derive the pdf for the function of a random variable,$h(X)$. As is mentioned above, X is a random variable for wind speed data. Then, let $P = h(X)$ be a function of the random variable X, while the pdf for X is$f_X(x)$. Because the value for the wind speed data is always greater than zero, the function of $h(x)$ is always a monotonic function. Then, by using the transformation method, the pdf for P can be derived by

$$f_P(p) = \begin{cases} f_X\left(h^{-1}(p)\right)\left|\dfrac{d\left[h^{-1}(p)\right]}{dp}\right|, & p \in P \\ 0 \quad , & \text{otherwise} \end{cases} \quad (4)$$