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New methods to assess wind resources in terms of wind speed, load, power and direction

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Abstract

The 2-parameter Weibull distribution is widely used, accepted, and recommended as probability law to describe and evaluate the wind speed frequency, which is especially useful for assessing wind resources. In this study, six popular parameter estimation methods are reviewed and compared with a new method that we call Modified Energy Pattern Factor (MEPF) method. The advantage of MEPF is that it is free from binning, linear least square problems or iterative procedures. All methods are compared via a thorough Monte Carlo simulation study with sample sizes varying from 100 to 100,000. The results indicate that the MEPF is a suitable alternative and comparable with the relatively best estimator of the Weibull parameters at each sample size. Consequently, we have used the MEPF to estimate the Weibull parameters of wind data from three regions in India, and we explain how to use these insights for the calculation and prediction of wind energy production. In particular, for harnessing the wind energy, both wind speed and direction are important. For the wind direction assessment, we have compared the conventional von Mises distribution to the new 4-parameter Kato-Jones distribution, and found that the latter approach provides better results.

Introduction

Wind resources assessment includes the estimation of the wind load density as well as the wind power density, as both are equivalently important for the installation of the wind farm. The wind load density helps assessing the fatigue failure of both turbine tower and turbine blades. Natural wind flow can cause fatigue failure of the slender structures, which occurs due to the periodic vortex shedding. If the frequency of the periodic vortex shedding matches with the natural frequency of the structure, significant crosswind vibration will cause damage to the structure as well as the turbine blades. The wind power density helps in the conversion of kinetic energy of the wind into a useful form of energy production. It enables the selection of potential sites for the installation of the wind farm and the selection of a suitable wind turbine for a given site. Therefore, a correct assessment of these two aspects of wind is significantly important. In the literature, the 2-parameter Weibull distribution is a widely accepted and recommended model for describing the wind regime (at a given site). A particularly salient feature of the Weibull distribution is that if the wind speed follows the Weibull distribution with shape parameters k and scale parameter s, the load and power density also follow the same distribution with shape parameter $k/2$ and $k/3$ respectively, and scale parameters s^2 and s^3 respectively [1,2].

Several authors [[3], [4], [5], [6], [7], [8], [9]] discussed various methods to estimate the Weibull parameters. These methods are the Least Squares Method (LSM) also known as Graphical Method, the Empirical Method (EM), the Method of Moments (MOM), the Power Density Method (PDM) also known as Energy Pattern Factor Method, the Maximum Likelihood Method (MLM) and the Modified Maximum Likelihood Method (MMLM). Seguro and Lambert [7] compared MLM, MMLM and LSM on basis of a sample of size 72 and concluded that MLM is the best estimation method for the Weibull parameters based on the criterion of total energy output. They also found the MMLM and MLM to be more accurate than the LSM regardless of the bin size. However, Cook [10] discarded the claim made by Seguro and Lambert [7] and concluded that LSM is equally good as MLM for estimating the Weibull parameters. Akdag and Dinler [11] proposed a newer method, the PDM, and compared it to LSM, MLM and MOM. The sample data size taken for the analysis is less than 100,000. They stated that the PDM is an adequate method to estimate the Weibull parameters and that it might have better suitability than other methods. Jowder [12] compared the Empirical and Graphical Methods by taking monthly and annual wind speed data and determined the wind power density at 10, 30, and 60 m heights in the Kingdom of Bahrain. He found that the EM provides more accurate prediction of average wind speed and power density than the Graphical Method. Chang [1] checked the accuracy of all the methods mentioned above on the basis of simulated as well as observed data with sample size 10,000. He found that MLM performs best on both simulated as well as observed data and LSM performed poorly based on the criteria of root mean squared error and the Kolmogorov-Smirnov test. However, the simulated data taken for the comparison had variation in seed values, and an average value of the parameters was taken for the analysis. Akdag and Guler [13] proposed a novel energy pattern factor for estimating the 2-parameter Weibull distribution. However, this method is only a simplification of the PDM or Energy pattern factor method (E_{pf}) with pre-determined coefficient. Wrapping up, from all the methods discussed in the literature to estimate the parameters of the 2-parameter Weibull distribution, not a single method stands out as being the universally accepted best one.

A common method for Weibull parameter estimation used in industries is the Wind Atlas Analysis and Application Program (WAsP) developed by the Department of Wind Energy at the Denmark Technical University earlier known as Riso National Laboratory of Denmark. Various researchers compared this tool with statistical methods. For instance, Bagiorgas et al. [14] compared the WAsP algorithm used in the WindoGrapher software with four statistical methods to estimate Weibull parameters, namely LSM, MOM, MLM and an alternative maximum likelihood method. They found that the MOM and MLM produce the same results as far as the shape parameter is concerned, while for the scale parameter all the methods produce almost identical results. Bénédicte [15] compared MLM and MOM (based on the first and third moments) to the WAsP method based on the error in production of real wind farms. They found that the MOM strongly agrees with the WAsP method in estimating the Weibull parameters. Furthermore, the WAsP was employed to simulate the wind climate by reverse modeling using wind data [16,17]. However, the methods employed by them to estimate the Weibull parameters for the wind energy potential are respectively the MOM and LSM. WAsP programming is also commonly employed for wind energy resources assessment [[18], [19], [20]].

Besides wind speed, assessing the wind direction plays an equally important role for harnessing the wind energy potential at a given site. Firstly, it helps in establishing a desirable zone for the installation of the wind farms; secondly, it has a significant impact on the installation of the overhead transmission lines. Therefore, it is futile to study wind power at a particular site without considering the analysis of wind direction. The analysis of wind direction requires the use of particular statistical models, namely distributions on the circle. Indeed, a direction in the plane has no length, hence all observations can be considered to have length 1 and to lie on the same circle. Razali et al. [21] compared different circular distribution models for wind direction analyses, namely the von Mises distribution, the generalized von Mises distribution and the wrapped Cauchy distribution (see Chapter 2 of [22] for a description of circular distributions). They stated that the von Mises distribution fits the data better compared to the other distributions. Thus, the researchers concluded that the 2-parameter von Mises distribution is the most suitable distribution for wind direction analysis. Recently, Kato and Jones [23] proposed a new 4-parameter distribution for circular data which is much more versatile than the von Mises distribution. It enjoys numerous good properties such as, for example, unimodality, simple parameter interpretability as location, concentration, skewness, and kurtosis parameters, a wide range of circular skewness and kurtosis, and straightforward parameter estimation methods. Moreover, it includes a number of attractive sub-models such as the wrapped Cauchy and cardioid distributions.

In the present paper, we follow two main goals. First, we propose a new Modified Energy Pattern Factor (MEPF) method to estimate the parameters of the 2-parameter Weibull distribution. This MEPF method has the additional advantage that it does not require binning and solving a least squares problem or iterative procedures. The performance of the MEPF is compared with the available six aforementioned methods, namely LSM, EM, MOM, PDM, MLM, and MMLM. This comparison will be based on simulated data of varying sample size from 100 to 100,000 for a fixed seed value. We then use the well-performing MEPF to estimate the Weibull parameters for real wind data from three sites in India. These estimated parameters are then extrapolated to the three different heights of 30, 60 and 90 m. From these extrapolated Weibull parameters, the mean wind load, wind power density and capacity factor curves are estimated. The design rated speed of wind turbine is evaluated based on the maximum capacity factor. Our second goal is to compare the 4-parameter Kato-Jones distribution with the widely used 2-parameter von Mises distribution for modeling wind direction data.

The paper is organized as follows. Section 2 describes the wind data that we shall analyze. The various mathematical methods used in the present paper are presented in Section 3, while Section 4 contains both a simulation study to compare the various Weibull estimation methods to our new MEPF method and a detailed analysis of the wind data at the three sites in India in terms of wind speed, load, power and direction, hereby comparing the Kato-Jones model to the von Mises model. The final Section 5 provides the overall conclusion.

Section snippets

Geographical condition and observation period

The Indian Meteorological Department (IMD), Pune, recorded the long-term hourly mean wind speed data in km/h at 10 m height above the ground level with a dyne pressure tube anemograph. The wind direction data have been recorded on three hourly average bases with a 16-point compass. The observation period for which the wind speed data are available varies in each station. In the scope of this study, the sites selected are Calcutta (42809), Ahmedabad (42647) and Trivandrum (43371). Calcutta is…

The mathematical models

This section contains all mathematical formulae used in the present paper. We start by describing the existing methods to estimate the Weibull parameters plus our new MEPF method (Section 3.1), then we explain how to extrapolate the estimated parameters to different heights (Section 3.2) and how to calculate the resulting energy production (Section 3.3). In Section 3.4 we define the probabilistic models used to fit the wind direction, while Sections 3.5 Random variable generation of the Weibull …

Comparison of different methods to estimate the Weibull parameters based on simulated data

The best way to see which estimation method works best in which circumstances consists in simulating data from a Weibull distribution, as we then know the true values of the shape and scale parameters and can compare the estimates to these true values. Therefore, we have considered various simulation scenarios with sample sizes varying between 100 and 100,000. In each case, the Weibull parameters were estimated using the seven different methods described in Section 3.1, namely LSM, EM, MOM,…

Conclusion

In this paper, the proposed Modified Energy Pattern Factor Method is compared to six different Weibull parameter estimation methods proposed in the literature. Our simulation study revealed that the MEPF is a suitable alternative to these methods, and it clearly outperforms in terms of precision and simplicity its antecedent, the Power Density Method of Akdag and Dinler [11]. Compared to the other methods MEPF has the advantage that it is robust, efficient in calculation, free from binning…

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> *Citation Excerpt :*
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> …Consequently, since the hub height value of 90 m is closer to 100 m than to 20 m, for further analysis in this paper, the Hellman exponential law technique is to be used to extrapolate wind data values to the hub height of the NREL 5 MW wind turbine. According to Gugliani et al. [44] and Aghbalou et al. [45], the description of the wind speeds in a determined location is of great significance, since an accurate description of this probability function can derive in an optimal design of the wind turbines and a better estimation of the electrical energy generated by a wind turbine or a wind farm. In probability theory and statistics, the Weibull distribution is a continuous description of a random phenomenon in terms of the probability of events.…

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Comparison of different statistical methods used to estimate Weibull parameters for wind speed contribution in nearby an offshore site, Republic of Korea

2021, Energy Reports

> *Citation Excerpt :*
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> …The analysis methods varied among the stations, in accordance with variation in the wind speed values, location, height, measurement period, data size, and etc, therefore, data obtained at one site were not applicable to the other sites (Tiam Kapen et al., 2020). To choose the most frequent used estimations methods for this study, we reviewed all Weibull Parameter methods and statistical analysis methods used previously (Garcia et al., 1998; Ayodele et al., 2012; Ahmed and Mahammed, 2012; Tiam Kapen et al., 2020; Sathyajith, 2016; Azad et al., 2014; Kang et al., 2018; Ouahabi et al., 2020; Guarienti et al., 2020; Saxena and Rao, 2015; Kumar and Gaddada, 2015; Costa Rocha et al., 2012; Hove et al., 2014; Elie Bertrand et al., 2020; Werapun et al., 2015; Gugliani et al., 2018; Akdağ and Güler, 2015; Akdağ and Dinler, 2009; Chaurasiya et al., 2018b,a; Khahro et al., 2014; Kidmo et al., 2015; Ihaddadene et al., 2016; Indhumathy et al., 2014; Bilir et al., 2015; Mohammadi et al., 2016; Jamil, 1994; Justus et al., 1978; Carneiro et al., 2016; Chang, 2011; Ali et al., 2018; Adaramola et al., 2014; Akgül et al., 2016; Jowder, 2009; Arslan et al., 2014; Stevens and Smulders, 1979; Scerri and Farrugia, 1996; Saleh, 2012; Shoaib et al., 2017; Hulio et al., 2019). As shown in Fig. 1, there are 16 methods.…

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