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A new method to adequate assessment of wind farms' power output

Saeed Zolfaghari, Gholam H. Riahy *, Mehrdad Abedi

Electrical Engineering Department, Amirkabir University of Technology, Tehran, Iran

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ABSTRACT

This paper presents a novel probabilistic technique so as to estimate the power output of wind farms (WFs). At first, the power output of each wind turbine (WT) is calculated using power probability distribution functions (PPDFs). These PPDFs are acquired from the actual data of an installed WT measured in a particular time horizon, which involves WT's wind speed and its corresponding power output. In the next step, using the calculated PPDFs and assigning Poisson distribution as statistical spatial distribution for wind speed over the WF, the power output of WF is computed in a probabilistic manner. It has been demonstrated that the probability distribution function (PDF) of a WF's power output as well as its capacity factor (CF) can be calculated accurately utilizing the proposed approach. The outcome could have a substantial effect on conducting several power system studies such as reliability evaluation, power system expansion planning and so on. To verify the outperformance of the proposed method, the actual measured data of Manjil WF in Iran has been used as a real case study. The obtained results confirm the accuracy of the proposed method as a more precise approach compared to the conventional ones.

1. Introduction

Wind energy, which is growing more quickly among the other renewable resources, is a clean energy resource which requires no fuel and hence, does not cause environmental pollution. The main disadvantage of the wind energy is its erratic nature and hence, intermittent power production. By a swift penetration of the wind farms (WFs), secure operation of the power systems has been affected due to the probabilistic nature of these resources [1].

In the context of integrated power systems with WFs, there have been conducted versatile research works. To determine the wind power of a WF, three steps should be considered.

The first step is to model the wind speed. There are a lot of methods for wind speed estimation in the literature. Two widely used approaches are applying an appropriate distribution to wind speed such as Weibull [2] and also time series method [3]. However, there are other techniques to model the wind speed such as k-nearest neighbor classification [4], methods based on neural network [5] and models based on weather conditions [6]. In Ref. [7], different methods of wind speed estimation has been surveyed.

The next step is to calculate the power output of the wind turbine (WT). One of the methods, which is used widely in various studies, is the application of the WT's power curve. Power curve is a mathematical function given by the manufacturer, which relates WT's wind speed with its power output. Thus, by taking the wind speed values and power curve into account, WT's power output values can be achieved precisely. This approach is broadly used in many research fields of power systems including wind energy resources such as WT and WF modeling [8–10], reliability evaluation in the presence of wind energy [11–13], optimal power flow considering the stochastic nature of the WFs [14,15], power system expansion planning integrated with wind power resources [16,17], determining the optimal capacity of wind energy in power systems [18], defining spinning reserve in power system with the penetration of WFs [19] and hybrid power systems including wind energy [20,21].

It should be noted that to match the power output of a WT with its constructive power curve in all wind speed values, the following conditions should be met [22]:

1. The wind speed should be horizontal and uniform across the face of the WT.
2. The vertical profile of the wind speed should be equal to the corresponding value at the time of WT's calibration.
3. The air density should be equal to the density of air at the time of WT's calibration.

It is not always possible to satisfy all of these conditions during the operation of a WT. Thus, for different environmental conditions

* Corresponding author. Tel.: +98 9121337238.
E-mail addresses: s.zolfaghari@aut.ac.ir (S. Zolfaghari), gholam@aut.ac.ir (G.H. Riahy), abedi@aut.ac.ir (M. Abedi).

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such as air density or ambient temperature, WT would produce different power outputs for one specific wind speed value. Consequently, it can be easily deduced that utilizing the power curve concept and devoting one value as WT's power output for a given wind speed value, would definitely leads to errors in estimating the power output of the WT.

In addition to utilization of power curve, there are also a lot of researches in which the forecasting methods have been used to calculate the power output of WTs. These methods can be divided into two main groups, which include deterministic [23,24] and probabilistic approaches [25–28].

Ref. [23] proposes a method which identifies forecast regimes at the meteorological station near to the WF and fits an uncertain predictive model for each regime. Taylor et al. [24] used deterministic power curve to predict the probability distribution function (PDF) of WF's power output.

In contrast with deterministic methods, [25] models the uncertainty in the wind speed and its direction using a bivariate VARMA-GARCH model. Also, to model the stochastic nature of the relationship between the wind power and two mentioned independent variables, conditional Kernel density estimation has been used. Ref. [26] presents a non-parametric approach to model the actual wind power curve of a WF. Kernel density estimation (KDE) method has been used in [27] to probabilistic estimation of WF's power output. Also, [28] proposes a method based on wavelet neural network (WNN) to forecast wind power, which uses Morlet wavelets as activation functions in the hidden layer. As it can be seen, the forecasting methods does not use WT's power curve which results in better estimation of the WT's power output.

The final step is to calculate the WF's power output. Considering the WTs of a WF to be identical, a simple way to get the WF's power output at each time is to multiply one WT's power output value at that time to the number of existent WTs in the WF. In this case, it is assumed that the wind has the same speed in all parts of the WF at any time and as a result, all WTs in the WF have equal power output values in each time. Whereas the meteorological parameters such as the wind speed or the wind direction at various locations of a WF are not the same at any time. Hence, the power output of all WTs would not be identical too. Therefore, it is not always true to represent the power output of a WF by the multiplication of one WT's power output to the number of existent units and this is what has been neglected in all above studies. In other words, the meteorological input data of all mentioned models belongs to one point, inside or outside of the WF which is used for all WTs installed in the WF, while it is clear that the wind speed/direction values at different parts of a WF are not the same. Of course several studies have also been conducted to investigate the influential factors affecting the wind speed distribution in a WF [29–32].

Contemplating the above discussion, this paper organizes a new probabilistic method to calculate the WF's power output, which contains two basic steps. At the first step, getting access to the historical real data of an installed unit of WT in a specific time interval, involving the chronological wind speed data and its corresponding power output, the power probability distribution functions (PPDFs) are defined for different wind speed sets. Using these PPDFs, the PDF of WT's power output at any specific period could be calculated.

The second step is established based on the fact that the wind speed values in distinct places of a certain WF differ from each other at any time. To do so, this paper suggests that it could be considered a statistical spatial distribution for the wind speed over the WF which could be effectively highlighted by applying an appropriate distribution function. This is similar to wind speed's temporal distribution modeling by applying an appropriate PDF like Weibull.

In this way, wind speed differences over the place could be also considered to predict WF's power output more efficiently. Herein the Poisson distribution function has been used in modeling the stated distribution. Consequently, by extracting the wind speed values for one specific WT's location, the Monte Carlo simulation (MCS) method is effectively deployed to obtain the wind speed values in other installation sites of WTs in the studied WF. By this procedure, the power output of all WTs and consequently, the WF's power output can be easily calculated.

To verify the effectiveness of the proposed method, the actual measured data of Manjil WF in Iran has been considered. Then, different numerical studies have been devised to investigate the performance of the proposed approach in estimating the power output of a single unit of WT and aggregation of them as a WF. The obtained results are encouraging which puts forward this approach as an effective solution for wind energy studies.

The remainder of this paper is organized as follows. The second section talks about the calculation method of the PDF for a random variable such as the wind speed. In the third section, impracticability of the power curve utilization of WTs in power systems studies is shown. In fourth section, it is suggested to use Poisson distribution for modeling the wind speed with respect to the location rather than assuming the same wind speed in all locations of a WF. In the fifth section, the proposed method to model the WF's power output is thoroughly addressed. The sixth section covers the numerical studies raised for assessing the validity of the proposed method. Eventually, the concluding remarks are discussed in the last section.

2. Calculating the PDF for a random variable

Let assume that the measured values of a random variable such as wind speed in a certain time interval is denoted by X. Using these values and choosing an appropriate amount such as N, there could be $N + 1$ sets which measured values of X lie within as shown in Fig. 1.

In Fig. 1, I_i and $\overline{X_i}$ are the interval and the center assigned to the ith set which could be calculated through Eqs. (1)–(4).

$$D = X_{max} - X_{min} \tag{1}$$

$$\delta = \frac{X_{max} - X_{min}}{N} \tag{2}$$

$$\overline{X}_i = X_{min} + i \times \delta; \;\; i = 0, 1, 2, \ldots, N \tag{3}$$

$$I_i = \left(\overline{X}_i - \frac{\delta}{2}, \overline{X}_i + \frac{\delta}{2}\right); \;\; i = 0, 1, 2, \ldots, N \tag{4}$$

In Eq. (1), D, X_{min}, and X_{max} show the domain, minimum, and maximum values of the random variable respectively. It should be noted that the value of each interval i.e. $|I_i|$ is equal to δ which is calculated in Eq. (2). However the value of intervals $|I_0|$ and $|I_N|$ equals to $\delta/2$ actually, because there are not any real data in intervals $\left(\overline{X_0} - \frac{\delta}{2}, \overline{X_0}\right)$ and $\left(\overline{X_N}, \overline{X_N} + \frac{\delta}{2}\right)$. Using this splitting strategy, the data near to the minimum and maximum values of X does not loosed.

If the number of occurrences of the ith set equals to N_i, its probability can be calculated as:

$$Prob(X \in I_i) = \frac{N_i}{\sum_{i=0}^{N} N_i} \tag{5}$$

where $Prob$ = Probability.

By this way, the probability of occurrence for each set is easily calculated. This is worth noting that the PDF for the random variable X would contains $N + 1$ sets.