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Fuzzy copula model for wind speed correlation and its application in wind curtailment evaluation

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ABSTRACT

Wind parks always produce diverse percentages of their nominal power at the same time, leading to a concern about correlation between wind speeds. The assessments of wind speed correlation have been particularly focused on probabilistic modeling of aleatory uncertainty. However, poor historical data, imprecise parameter estimation and incomplete knowledge of wind speeds lead to another type of uncertainty, possibilistic uncertainty, which requires an explicit analysis. Therefore, a fuzzy copula model is firstly proposed to express the possibilistic uncertainty of wind speed correlation. The advantage of the proposed model is that the copula parameters can be interval numbers, triangular or trapezoidal fuzzy numbers based on the wind speed data and subjective judgment of decision makers. For estimating copula parameters, a complete decision rule and interval estimation method is developed based on cumulative probability and probability distributions of correlated wind speeds. The effectiveness of the proposed model is validated by the application in wind curtailment evaluation while a method is developed to evaluate and quantify wind curtailment in a hybrid power system involving different types of generation. The results demonstrate that the proposed model and method are capable of describing the possibilistic uncertainty and evaluating its effect on wind curtailment. Compared with previous research, the proposed model develops a new universal parameter estimation method and selection rule to provide more interval results, by calculating the membership function of copula parameters and wind curtailment. System planners and operators can apply the fuzzy results to various topics like reserve capacity evaluation or real-time dispatch depending on their level of risk tolerance.

1. Introduction

Wind energy has achieved great development around the world due to its excellent environmental and social benefits. However, wind power generation behave quite differently from conventional generating units because of the uncertainty, uncontrollability and low capacity factor of the wind resource. It is essential to identify the potential wind resource in a region in order to integrate wind power economically and reliably. In general, wind equipment are installed and kept in multiple sites of interest. Meanwhile, wind speed correlation is widely observed between different wind farms due to the atmospheric and topographical relationship. Therefore, the determination of a model for wind speed correlation is essential in the management of wind power generation planning [1].

Considerable work had been devoted to the modeling of wind speed correlation. Some models describe the wind speed correlation from the point view of wind flow mechanism, considering area topography, distance of wind farm sites and space–time correlation [2,3]. Meteorological and geographic data are necessary for these models. More models simulate correlated wind speeds according to the correlation coefficient like Nataf transformation [4] and vector autoregression (VAR) model [5,6]. Nataf transformation generate correlated normal distribution vector through multiplying an independent normal distribution random vector by a Cholesky decomposed factor of a given covariance matrix. VAR is a vector model used to describe the linear correlation among several time series. Each endogenous variable is denoted as a linear weighted sum of their past values. The shortage of Nataf transformation and VAR model is that they can only deal with linear correlation while nonlinear correlation represents wind speeds more reasonably. Therefore, copula based model [7,8] are investigated in recent years. Copula separates marginal probability distribution function (PDF) and dependence of multivariate variables while it depicts correlation between various variables by joint

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probability distribution. However, all these wind models depend greatly on the historical data, while the data are unfortunately incomplete or very limited [9] in many cases. In addition, obtaining accurate parameters in a probabilistic model is not an easy task even if data are supplied. Different statistical methods generate different results of parameter estimation [7,8,10,11]. This results in another type of uncertainty in wind speed correlation model, possibilistic uncertainty. The assessment of possibilistic uncertainty of wind speed correlation is lagging.

This research aims to model possibilistic uncertainty of wind speed correlation and investigate its effect on power systems. As an example, the application of the proposed model in wind curtailment evaluation is conducted in our work. With the increasing penetration of wind power, wind curtailment is a natural choice to deal with the system stability [12], transmission system congestion [13] and cost-effective integration [14] in many places. The wind speed correlation affects wind curtailment significantly because variability of wind speed is a main problem for power system to integrate wind power and the wind speed correlation has a direct effect on wind variability. Theoretically, negative wind speed correlation will smooth out the variability of wind power and positive wind speed correlation will enhance it. From the point view of power system operation, wind curtailment was always evaluated by studying optimal power generation scheduling of a hybrid power system integrating wind energy and conventional energy sources or energy storages. Unit commitment based model was applied to discover suitable operational strategies of generation units and maximize wind energy integration [15–17]. For power system planning, the aim is to minimize wind curtailment considering the balance of economy, reliability and social benefit [13,14,18,19]. However, up to now no studies about the relation between wind curtailment and wind speed correlation can be found in the published literature.

As a main contribution, this paper proposes a fuzzy copula model to propagate the possibilistic uncertainty of wind speed correlation. In this model, distribution of multivariate wind speeds is described by a copula function and the copula parameters can be interval numbers, triangular or trapezoidal fuzzy numbers. A complete decision rule and interval estimation method is proposed to determine the format of copula parameters based on cumulative probability and probability distributions of correlated wind speeds. Furthermore, this work develops a Monte Carlo simulation based method to quantify wind curtailment in a hybrid power. Compared with previous research, the proposed model develops a universal parameter estimation method and judgment rule to provide interval results by calculating the membership function of copula parameters and wind curtailment. These fuzzy results are available in further study like reserve capacity evaluation or real-time dispatch depending on the level of risk tolerance. The effectiveness of the proposed method is validated by its application to a real-life power grid case.

The rest of this paper is structured as follows: Section 2 gives the details of wind speed fuzzy copula model and parameter estimation method. The system model and sequential Monte Carlo method for wind curtailment are presented in Section 3. Section 4 summarizes the steps of wind curtailment evaluation process considering the fuzzy copula model. In Section 5, the proposed model is applied on a real-life power grid and the results are discussed. Finally, some conclusions are drawn in Section 6.

2. Fuzzy copula model for wind speeds

This article mainly studies the wind speed model and the power output can be obtained from the power output curve as shown in Ref. [8]. To describe the uncertainty of wind speed correlation, the fuzzy copula model is introduced in this section.

2.1. Fuzzy copula model

A common n-dimensional copula is a multivariate cumulative distribution function (CDF) C with the following properties [20]:

1. C is defined on $I^n = [0,1]^n$;
2. C is n-dimensional bounded and monotonically increasing;
3. C has n one-dimensional margins C_k, $k = 1,2, \ldots,n$, where $C_k(u_k) = C(1, \ldots 1, u_k, 1, \ldots, 1) = u_k$, $0 \le u_k \le 1$.

Let $X = [X_1, X_2, \ldots, X_n]$ represent the wind speed variables in n wind farms with continuous marginal CDFs $F_1, F_2, \ldots, F_n$ and H denote the joint CDF of n-dimensional wind speed variables. Sklar's theorem states that there uniquely exists an n-dimensional copula C such that for X in R_n, H can be expressed using the following form

$$H(x_1, x_2, \ldots, x_n) = C(F_1(x_1), F_2(x_2), \ldots, F_n(x_n), \theta) \quad (1)$$

where θ are the parameters of copula.

For wind speeds, joint distribution is just an assumption compensated for our incomplete understanding of the 'real' wind speeds. Meanwhile, the question of parameter estimation can hardly be answered with absolute certitude. Although the estimation of copula model is widely studied, it is difficult to obtain accurate estimation. Different estimations are achieved using different methods [7,8,10,11]. Moreover, sometimes historical data are insufficient or contain numerical errors [21]. In these cases, possibility theory can be used and it is more reasonable to represent the copula parameters by interval numbers or fuzzy numbers instead of crisp values [22,23]. An interval is a set of real numbers with the property that any number that lies between two numbers in the set is also included in the set. Based on the decomposition theorem, a fuzzy set can be represented by the union of many α-cut intervals, weighted by their value α [24]. The fuzzy number is an generalization of a regular, real number in the sense that it does not refer to one single value but rather to a connected set of possible values, where each possible value has its own weight between 0 and 1. This weight is called the membership function. The interval number is a special format of fuzzy number.

To recognize the possibilistic uncertainty of wind speed correlation, which was ignored in the previous research, a fuzzy copula model is proposed in our work. In the proposed model, the joint probability distribution of wind speeds is expressed as copula, whose parameters are interval numbers or fuzzy numbers. An example of wind fuzzy copula model is illustrated in Fig. 1 (Gaussian copula). We can see that for certain wind speeds, the probability density is an interval, providing more information than the regular copula model. Here, $\tilde{A} = (a_{\min}, a_L, a_U, a_{\max})$ represents the fuzzy trapezoidal number as shown in Fig. 2(b).

2.2. Parameter estimation

The central problem in fuzzy copula model is parameter estimation. General strategy of choosing copula and estimating parameter is to pre-select several copulas of wind speeds, estimate dependence parameters of each copula and then pick out the best one based on some criterion [7,8]. It is not available for the proposed model because the unknown variables are fuzzy copula parameters. No research has focused on estimating the membership function of copula parameters. A new estimation method is in urgent need.

The results of our estimation strongly depend on the shape of the membership function of these parameters. Less regular