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Reliability models of wind farms considering wind speed correlation and WTG outage

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ABSTRACT

Wind speed correlation and wind turbine generator (WTG) outage are two factors affecting the reliability model of wind farms, but they are not addressed simultaneously in the existing literature. Meanwhile, WTG outage is reported to be dependent with wind speed to some extent. Therefore, the extended reliability models of wind farms incorporating both of these two factors and the dependency between WTG outage and wind speed are proposed in this paper. To consider the uncertainties and dependencies of wind speed and WTG failure, Copula method is applied to simulate correlated random variables representing for wind speed and the number of failed WTG units. Moreover, the linear apportioning technique is used to create multistate reliability models of wind farms from hourly wind power models. A number of sensitivity analyses on the modified IEEE RTS with wind power are conducted to validate the proposed reliability models for generation adequacy assessment. Case studies show that the generation adequacy indices increase with the correlation of wind speed and WTG forced outage rate (FOR). It is meaningful to point out that the effect of dependency between wind speed and WTG FOR on generation adequacy is minimal when WTG outages are independent, but it will be substantially larger when WTG outages are highly dependent. The proposed multistate reliability models of wind farms provide foundation for the reliability assessment of power systems with wind power integrated.

1. Introduction

Environmental effects of greenhouse gases and the recent energy policies have promoted the development of wind farms as a promising alternative to conventional electric power generation. The intermittent and variable nature of wind speed causes the output power of wind farms to be stochastic and different from those of conventional units. For this reason the reliability evaluation of power systems with wind power integration has received increased attention by power system researchers and engineers in both planning and operation phases [1–4].

Analytical enumeration method, sequential Monte Carlo simulation (MCS), and non-sequential MCS are the three fundamental approaches for power system reliability assessment. Among these three methods, sequential MCS is a commonly used method for evaluating the generation adequacy of a power system associated with wind energy in many works, because sequential MCS is capable of modeling the chronology of wind speed variation as well as demand variation, and it is convenient to incorporate the operation strategies and model the outage of wind turbine generator (WTG) units. However, this method requires a huge volume of historical data and considerable computing time, especially when it is applied to large power systems [5]. It is also not compatible with conventional practices used in power system studies. Therefore, there is a need to develop suitable wind power models that can be easily incorporated in the analytical methods or in non-sequential MCS for generating capacity adequacy assessment. In this context, the wind farms are often modeled as conventional generators with multiple capacity states and corresponding probability reflecting the energy availability at various levels [6,7].

In the process of developing the multistate wind power models, the wind speed correlation of wind farms and the WTG outage are two factors that need to be considered. On one hand, some research works have been conducted to develop reliability models of wind farms incorporating wind speed correlation only, and different types of techniques such as Cholesky decomposition [8], genetic algorithm [2], time-shifting technique [9] and Copula method [10] are used for simulating correlated wind speed. On the other hand,

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some research works only focus on reliability models of wind farms considering WTG outage, and the apportioning method [3] or Markov chain method [4] is used to for modeling WTG outage. Little literature addresses the multistate reliability model of wind farms considering both the wind speed correlation and WTG outage. Additionally, it is reported that in the same wind farm the wind speed and WTG outage may be correlated [11,12]. However, there exist no reliability models of wind farms which consider the correlation between wind speed and WTG outage.

As a complement to the previous works, this paper aims to move toward a comprehensive multistate model which simultaneously considers the dependency between wind speed of two wind farms and the dependency between wind speed and WTG outage into account. The uncertainty of wind speed is represented by Weibull distribution, while the uncertainty of WTG outage is represented by binomial distribution. Copula method is proposed to be used for the simulation of wind speed and the number of failed WTG units of wind farms, which can simultaneously consider the dependency between wind speeds and the dependency between wind speed and WTG outage. The hourly wind power of wind farms can be obtained by combining the wind speed, the relationship between wind speed and output power, and the number of failed WTG units. Then, the linear apportioning technique is used for developing multistate wind power models. Unlike most papers which use Monte Carlo simulation, the analytical method is used in this paper to examine the effects of wind speed correlation and WTG outage on reliability assessment of generation capacity.

The rest of this paper is organized as follows. First, the uncertainties and dependencies in wind power reliability modeling are presented in Section 2. Then, Copula method is introduced in Section 3 for the simulation of correlated multivariate random variables, which include the wind speed and the number of failed WTG units of wind farms. The reliability models considering wind speed correlation, WTG outage, and the correlation of wind speed and WTG outage are proposed in Section 4, and the application of the proposed models in generation adequacy assessment is introduced in Section 5. A series of sensitivity analyses are conducted on the IEEE reliability test system (RTS) with wind power to validate the proposed reliability models in Section 6. Final conclusions are provided in Section 7.

2. Uncertainties and dependencies in modeling wind power reliability

2.1. Uncertainty of wind speed

Wind speed is a key factor that affects the output power of all WTG units, and its intermittent and stochastic characteristics can be simulated by the auto-regressive and moving average (ARMA) time series model [2,7,13] or Weibull distribution model [14–16]. In this paper, the Weibull distribution is used to simulate the hourly wind speed of wind farms. The wind velocity is treated as a random variable following Weibull distribution and its probability density function is given by:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

where c is the scaling factor and k is the shape factor. Then, the equivalent cumulative probability function is

$$F(v) = \int_0^v f(v)dv = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2}$$

2.2. Uncertainty of WTG outage

A WTG may be out of service due to forced outages and then each WTG can be represented by a two-state model (up or down state). Consider a wind farm consisting of m identical WTG units. Further assume that each WTG unit has a forced outage rate of λ and the outages of WTG units are independent. Then, the number of failed WTG units is a random variable following Binomial distribution [16]. The probability p_k that k WTG units are on forced outage at any point in time can be given by

$$p_k = \binom{m}{k} \lambda^k (1-\lambda)^{m-k} \quad (k = 0, 1, 2, .., m) \tag{3}$$

2.3. Dependencies among wind speed and WTG outage

With the development of wind power generation, large-scale wind power is often integrated into power systems at different wind sites. Influenced by similar meteorological conditions, wind speeds in adjacent wind farms are often dependent which calls the need to incorporate the wind speed correlation among wind farms. Moreover, WTG failure is reported to be dependent with wind speed in the same wind site [11,17] and WTG forced outage rate (FOR) increases at higher wind speed [18,19]. When a wind farm is composed of identical WTG units, it is reasonable to assume that the higher the wind speed, the larger the number of WTG units may fail simultaneously, i.e., the number of failed WTG units is positively related to the wind speed at the same time in the same wind site. It is easy to understand that this correlation may weaken the effect of wind power on adequacy of generation system and there is a need to incorporate this correlation in the wind power reliability model.

In short, when the wind speed and the number of failed WTG units are considered for modeling wind power of wind farms, both the uncertainties of these two variables and dependencies among these two variables need to be considered. Fortunately, the marginal distributions of wind speed and the number of failed WTG units have already been given in the discussion above. As long as the correlation coefficients among wind speed and the number of failed WTG units are specified, Copula method can be used to simulate these two dependent random variables.

3. Copula method for simulating related random variables

As a powerful tool to analyze the dependence relationship among random variables, Copula method was rapidly developed and widely applied in power systems [10,20–22]. Copula is a function that characterizes dependencies among variables and presents an approach to create distributions that model correlated multivariate data. The detailed information of Copula has been presented in [23]. In contrast to the conventional methods to estimate the joint distribution of multivariate variables, with the Copula method it is allowed to start with marginal distributions of different types. The application of Copulas to simulate related wind speed and the number of failed WTG units include the following steps:

(1) Calculate the Weibull parameters of wind speed at different wind sites and obtain the marginal distributions of wind speed, according to the historical wind speed data.
(2) Calculate the correlation coefficients of random variables from historical data of wind speed and WTG units. There are various types of dependence measurement methods for random variables, such as Pearson's linear correlation coefficient, Spearman's rank correlation coefficient, Kendall's rank correlation coefficient, and Tail dependence coefficient. Different correlation coefficients measure different dependence relationship