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A wind vector simulation model and its application to adequacy assessment

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ABSTRACT

Modelling wind profile is crucial to the adequacy assessment of wind-integrated generation system. This paper characterizes the wind profile as a wind vector that consists of wind speed and direction. A wind vector simulation model is proposed to produce long-term wind vector samples, whilst maintain the probability distribution of actual wind vector as well as its gusty characteristics. Such model is incorporated into sequential simulation process of wind-integrated generation system, while the wake effect is considered with Jensen model. Then, adequacy assessment procedure considering wake effect is developed. Collected wind vector data from four distinctive sites in North Dakota in US are used to verify the proposed model. The wind-integrated IEEE Reliability Test System (IEEE-RTS) is used to demonstrate the application of the proposed model and the procedure to adequacy assessment. The impacts of wake effect, peak load, and wind turbine type on system adequacy are investigated in detail.

1. Introduction

With the accelerated depletion of fossil energy resources and growing awareness of environmental concerns, many countries around the world are trying their best to develop renewable energy resources [1]. Compared to geothermal energy and tidal energy, wind energy is widely distributed, low-cost, and technically mature [2]. In addition, considerable incentive policies have been established in order to develop and utilize wind energy [3]. All these facts have sparked a rapid growth of wind power capacity. By the end of 2016, the global wind power capacity has reached 486.749 GW [4] and expected to achieve 2000 GW in two decades [5].

Nowadays, many countries have established wind-integrated power systems with impressive wind penetration level. For example, the wind-integrated power systems of Denmark, Portugal, Spain, Iceland, and Germany contain 39%, 18%, 16%, 14% and 9% wind penetration level, respectively [6]. Moreover, as the world's most populous country, China has installed largest wind power capacity and set an ambitious goal to reach 250 GW by 2020 [7]. On the other hand, wind generation depends on wind profile, which is highly variable and less predictable. Traditional methods cannot be directly applied to the performance evaluation of wind-integrated power systems. Especially, when it is in the absence of reasonable wind profile model to address these characteristics. For instance, adequacy assessment of wind-integrated power system is a procedure that measures how well the conventional generation and wind generation satisfy the load demand [8]. It provides important indicators for investors and operators to select the best design option and avoid unnecessary economic losses. It is, therefore, challenging and beneficial to study wind profile model and assess the system adequacy status.

The existing wind profile models that utilized in system adequacy assessment can be divided into two categories: analytical models and simulation models. The analytical models aim to represent wind profile with multiple discrete states and their transitive relationship. For example, Leite et al. [9] propose a wind speed Markov chain model. This model obtains discrete wind speed states and their transition rate matrix from the actual wind profile data via K-means clustering technique as well as a frequency & duration approach. Buliding upon [9], Dobakhshari et al. [10] propose a state merging technique to merge the generation states with identical power output. Markov chain of wind farm generation is formed to assess the adequacy of wind-integrated Roy Billiton test system (RBTS). Besides, based on [9], Ghaedi et al. [11] employ fuzzy

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C-means clustering technique to obtain optimal wind speed states, where the reliability status of the key components of wind turbines are considered. Adequacy assessment of wind integrated RBTS and IEEE-RTS (Reliability test system) are conducted. The simulation models aim to produce long-term wind profile samples that maintain the key characteristics of the actual wind profile. Such samples are crucial in the Monte Carlo simulation of a wind-integrated power system because it requires extensive simulation so as to guarantee accurate results. Furthermore, long-term actual wind profile data are usually unavailable. For example, Billinton et al. [12] simulate long-term wind speed samples using autoregressive moving average (ARMA) method. An hourly simulation model of wind-integrated power systems is established and used to assess the adequacy of the wind-integrated RBTS and IEEE-RTS. Thapa et al. [13] propose a conditional wind speed model using the long-term simulated wind speed sample. The adequacy benefit of wind integration is assessed. Bhuiyan et al. [14] propose a sampling technique which produces wind speed samples that follow Weibull probability distribution. And it is used in the adequacy assessment of wind-integrated IEEE-RTS. Nevertheless, among all of these works [9–14], wind direction is not considered in the wind profile model.

On the other hand, wind profile exhibits a gusty characteristic. It means the wind profile maintains at a certain scale for a short period due to the law of inertia. Belu et al. [15] study the wind gusts of western Nevada using meteorological data from four 50-m towers. The results indicate that wind gusts are not likely to exceed 25 m/s. Blackmon et al. [16] analyze the wind gusts under a storm using meteorological data from an instrumented tower. Wind gusts with greater speed and longer duration are frequently observed. The statistics of wind gusts are well discussed in previous works [15,16]. There are, however, relatively few works that focus on the simulation of wind gusty characteristics. Sallis et al. [17] predict the short-term wind gust using a machine-learning algorithm. Multiple factors, i.e., temperature, humidity, and etc., are used in the algorithm to improve the prediction accuracy. Wang et al. [18] investigate the gusty characteristic of wind speed and propose a 2-D wind speed model. This model can produce the wind speed samples that follow Weibull distribution and maintain the gusty characteristics. The existing simulation models of wind gust [17,18] have not incorporated the wind direction of the wind gust.

Wake effect is a phenomenon that the upstream wind turbine generator (WTG) will reduce the wind speed for the downstream WTG due to the law of energy conservation. Such physical effect typically creates 5%–15% losses of total wind generation [19], which should be sufficiently considered in adequacy assessment. Miao et al. [20] propose a Markovian wind farm generation model that incorporates wake effect in adequacy assessment of wind-integrated generation system. The wind-integrated RBTS system and collected wind data from four distinctive sites are used to investigate the impact of wake effect on system adequacy. The results indicate that ignorance of wake effect will lead to underestimation of system adequacy. And this underestimation gets worse if the layout of wind farm is dense. Yang et al. [21] propose an optimal layout scheme for a wind farm using particle swarm optimization algorithm. Simulation results of wind-integrated RBTS system indicate that reducing wake effect will improve the wind energy production and system adequacy. Han et al. [22,23] employ the Jensen model for the calculation of wake speed. Long-term actual wind speed and direction data are used in the Monte Carlo simulation of wind-integrated IEEE-RTS. The impacts of wake effect and other various factors on system adequacy are investigated. Long-term actual wind profile data, however, are not always available due to various technical difficulties.

Through extensive literature review, it is found that few works simulate wind profile considering wind direction and its gusty characteristics. This may disables the consideration of wake effect when assessing the adequacy of wind-integrated generation system. Underestimated system adequacy may misleads planers and result in sub-optimal planning. Hence, the research presented in this work goes further than that found in the literature, and introduces a new wind vector model for the simulation of wind profile considering wind direction and its gusty characteristics. This model defines the wind speed and direction as the wind vector, which is capable of producing long-term wind vector sample. Such sample can maintain the probability distribution of actual wind profile data, while preserving gusty characteristic. Then, combining this model with Jensen model and Monte Carlo simulation approach, an adequacy assessment procedure for wind-integrated power system considering the wake effect is proposed. It consists three major steps to build the proposed wind vector simulation model. First, the actual wind profile data are classified into multiple wind vector scales using Beaufort wind speed scale and cardinal wind direction scale. The duration time of each wind vector scale is represented with a proper probability distribution and such distribution is estimated from classification results. Second, the wind speed probability distribution and wind direction probability distribution are estimated from actual wind profile data. Then, wind vector probability distribution is obtained with a copula function. Third, the probability distribution of wind vector scale is obtained based on a conditional approach. Finally, the wind vector samples are produced by sampling the probability distributions in previous steps. The main contributions of this paper are suggested as follows.

- A wind vector simulation model is proposed. This model can produce long-term wind vector sample that follows the probability distribution of actual wind profile data and maintain the gusty characteristics.
- The proposed model is validated using actual wind profile data collected at four different sites in North Dakota, US. The results demonstrate its accuracy and applicability.
- An adequacy assessment procedure for wind-integrated power system considering the wake effect is proposed. The impacts of wake effect, peak load, and WTG type on system adequacy are also addressed in detail.

The rest of this paper is organized as follows. Section 2 describes wind gusty characteristic with actual wind profile data. The wind vector simulation model and its sampling algorithm are introduced in Section 3. In Section 4, adequacy assessment procedure considering the wake effect is presented. Case studies are discussed in Section 5, followed by conclusions in Section 6.

2. Gusty characteristic of wind vector

Fig. 1 denotes the observed wind speed and direction at time t as v_t and θ_t, respectively. At time t, the observed wind vector is represented as $\boldsymbol{w}_t = (v_t, \theta_t)$, which is a red directional vector as shown in Fig. 1, where v_t is the length of such vector, θ_t is the angle between wind vector and green directional vector. Denote the green directional vector as the reference direction (0°). Then θ_t varies from 0° to 360°, if wind vector deviates from green direction vector in a clockwise direction.

To demonstrate the wind gusty characteristic, the hourly wind vector data between 01/01/2006 to 12/31/2015 at Bowbells, North Dakota, USA are collected from North Dakota Agricultural Weather Network (NDAWN) [24]. According to the data description of NDAWN, the wind speed and direction of hourly wind vector are the averages of all individual measured values during the hour. The