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Reliability assessment of bulk electric systems containing large wind farms

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Abstract

Wind power is an intermittent energy source that behaves quite differently than conventional energy sources. Bulk electric system reliability analysis associated with wind energy conversion systems (WECS) provides an opportunity to investigate the reliability benefits when large-scale wind power is injected at specified locations in a bulk electric system. Connecting the WECS to different locations in a bulk system can have different impacts on the overall system reliability depending on the system topology and conditions. Connecting a large-scale WECS to an area which has weak transmission could create system operating constraints and provide less system benefit than connecting it to an area with stronger transmission. This paper investigates bulk electric system transmission constraints associated with large-scale wind farms. The analyses presented in this paper can be used to determine the maximum WECS installed capacity that can be injected at specified locations in a bulk electric system, and assist system planners to create potential transmission reinforcement schemes to facilitate large-scale WECS additions to the bulk system. A sequential Monte Carlo simulation approach is used as this methodology can facilitate a time series modeling of wind speeds, and also provides accurate frequency and duration assessments. An auto-regressive moving average (ARMA) time series model is used to simulate hourly wind speeds.

Keywords: Bulk electric system (BES); Reliability-based transmission constraints; Wind energy conversion system (WECS); Auto-regressive moving average (ARMA); Sequential Monte Carlo simulation

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1. Introduction

The utilization of the wind to generate electrical energy is increasing rapidly throughout the world. Wind turbine generators can be added and are being added in a wide range of locations in modern electric power systems. These units can be dispersed throughout relatively low voltage networks or in concentrated wind farms located at relatively remote sites with suitable wind regimes. Large wind energy conversion systems (WECS) include both inland and off-shore facilities and are usually connected to the BES by radial transmission lines [1,2]. Wind power, however, behaves quite differently than conventional electric power generating facilities due to its intermittent and diffuse nature. The incorporation of WECS in generation and transmission system reliability studies therefore requires distinctive and applicable modeling and data considerations. Considerable work has been done on the reliability evaluation of conventional generating systems incorporating WECS [3–6]. These studies do not consider the bulk electric system (BES) and focus on the ability of the generating facilities including wind power to meet the overall system load. A comprehensive reliability analysis of a BES considers the ability of the system to satisfy the load requirements at each individual load point in the BES in addition to meeting the overall system load [7]. Relatively little work has been done on the incorporation of WECS in quantitative BES reliability evaluation. This

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paper extends the concepts presented in [8–11] to include the chronological variability of WECS.

Sequential simulation [7–12] is ideally suited to the analysis of intermittent generating sources such as wind power. An advantage of utilizing sequential Monte Carlo simulation in bulk electric system reliability evaluation is that the framework already exists to incorporate the chronological characteristics of wind (diurnal and season wind speeds), load profiles and the chronological transition states of all the components within a system. Sequential simulation can provide realistic and accurate results when considering wind power [13].

This paper examines the reliability impacts when connecting a large-scale WECS at different locations in a bulk electric system. The results show that the impact on the system reliability of a WECS addition is dependent on the location used to connect the WECS to the bulk system. This is related to the system topology and conditions, particularly when there are transmission system limitations. The paper also investigates the maximum amount of wind power that can be absorbed by a system without severely violating the system constraints. The maximum amount can vary when connecting the WECS at different locations. The results are illustrated in this paper by application to the original and to a version of the modified IEEE-RTS [14].

2. Wind energy conversion system

The wind energy conversion system (WECS) model is basically composed of two main parts designated as the wind speed model and the wind turbine generator (WTG) model. These two parts are briefly described as follows.

2.1. Wind speed modeling

An essential requirement in incorporating WECS in power system reliability analysis using sequential Monte Carlo simulation is to realistically simulate the hourly wind speed. Wind speed varies with time and location and at a specific hour is related to the wind speeds of the immediate previous hours. Wind speed models, therefore, have unique characteristics that are dependent on their geographies. The two wind regimes utilized in this paper were modeled using auto-regressive moving average (ARMA) time series models [3]. The general expression for the ARMA(n,m) model is as follows:

$$y_t = \sum_{i=1}^{n} \phi_i y_{t-i} + \alpha_t - \sum_{j=1}^{m} \theta_j \alpha_{t-j} \tag{1}$$

where y_t is the time series value at time t, ϕ_i $(i = 1, 2, \ldots, n)$ and θ_j $(j = 1, 2, \ldots, m)$ are the auto-regressive and moving average parameters respectively, $\{\alpha_t\}$ is a normal white noise process with zero mean and variance of σ_a^2, i.e., $\alpha_t \in NID(0, \sigma_a^2)$, where NID denotes Normally Independent Distributed.

The hourly simulated wind speed SW_t at time t is obtained from the mean speed μ_t, its standard deviation σ_t and the time series y_t as shown in Eq. (2)

$$SW_t = \mu_t + \sigma_t y_t \tag{2}$$

New values of y_t can be calculated using Eq. (1) from current random white noise α_t and previous values of y_{t-i}. Eq. (2) is used to generate the hourly wind speeds incorporating the wind speed time series.

The studies presented in this paper utilize wind speed models and data from two different sites located in the province of Saskatchewan, Canada. This information is designated as Regina and Swift Current data. Table 1 shows the hourly mean wind speed and the standard deviation at the two different sites. Wind speed characteristics differ from one location to another location. The parameters "n" and "m" in the ARMA(n,m) model was developed based on a specific wind farm site. The model could have different time series parameters for a different site. The methodology to select the appropriated ARMA parameters was described in [3]. The ARMA models for the two sites are given in Eqs. (3) and (4). The Regina wind model shown in Eq. (3) was developed and published in [3]. The Swift Current wind model shown in Eq. (4) was developed using the ARMASA Toolbox [15,16] associated with the System Identification Toolbox [17] in the MATLAB Program. Hourly wind speed time data from 1996 to 2003 (8 year series) obtained from Environment Canada were used in the ARMA model development, and hourly wind speed data from 1984–2003 (20 years) at the Swift Current site were used to calculate the hourly mean wind speed and standard deviation. Wind speed data for the two locations used in the study are shown in Table 1.

Regina: ARMA (4, 3):

$$\begin{aligned} y_t = {} & 0.9336 y_{t-1} + 0.4506 y_{t-2} - 0.5545 y_{t-3} + 0.1110 y_{t-4} \\ & + \alpha_t - 0.2033 \alpha_{t-1} - 0.4684 \alpha_{t-2} + 0.2301 \alpha_{t-3} \end{aligned} \tag{3}$$

$$\alpha_t \in NID(0, 0.409423^2)$$

Swift current: ARMA (4, 3):

$$\begin{aligned} y_t = {} & 1.1772 y_{t-1} + 0.1001 y_{t-2} - 0.3572 y_{t-3} + 0.0379 y_{t-4} \\ & + \alpha_t - 0.5030 \alpha_{t-1} - 0.2924 \alpha_{t-2} + 0.1317 \alpha_{t-3} \end{aligned} \tag{4}$$

$$\alpha_t \in NID(0, 0.524760^2)$$

2.2. Wind turbine generator modeling

The power output characteristics of a wind turbine generator (WTG) are quite different from those of conven-

Table 1
Wind speed data at the two different sites

Sites	Regina	Swift current
Mean wind speed (km/h), μ	19.52	19.46
Standard deviation (km/h), σ	10.99	9.70