Applied Energy 104 (2013) 42–49

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Continuous wind speed models based on stochastic differential equations

Rafael Zárate-Miñano [a], Marian Anghel [b], Federico Milano [c,*]

[a] University of Castilla-La Mancha, Almadén, Spain
[b] Los Alamos National Laboratory, Los Alamos, NM, USA
[c] University of Castilla-La Mancha, Ciudad Real, Spain

HIGHLIGHTS

- We propose two procedures to build wind speed models based on stochastic differential equations.
- The starting point of both procedures is a SDE defining an Ornstein–Uhlenbeck process.
- Proposed models show statistical properties similar to available wind speed measures.
- Proposed models can generate wind speed trajectories ranging from few minutes to several hours.
- Developed models can be coupled with wind generator models for power system dynamic studies.

ARTICLE INFO

Article history:
Received 24 April 2012
Received in revised form 8 October 2012
Accepted 24 October 2012

Keywords:
Stochastic differential equations
Dynamic analysis
Wind speed
Weibull distribution
Ornstein–Uhlenbeck process
Memoryless transformation

ABSTRACT

This paper proposes two general procedures to develop wind speed models based on stochastic differential equations. Models are intended to generate wind speed trajectories with statistical properties similar to those observed in the wind speed historical data available for a particular location. The developed models are parsimonious in the sense that they only use the information about the marginal distribution and the autocorrelation observed in the wind speed data. Since these models are continuous, they can be used to simulate wind speed trajectories at different time scales. However, their ability to reproduce the statistical properties of the wind speed is limited to a time frame of hours since diurnal and seasonal effects are not considered. The developed models can be embedded into dynamic wind turbine models to perform dynamic studies. Statistical properties of wind speed data from two real-world locations with significantly different characteristics are used to test the developed models.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

The power production of a wind power plant is affected by the statistical characteristics of the wind speed at its location. Due to the volatile and uncontrollable nature of this energy source, the power output of wind generators is a fluctuating signal. As a consequence, from the network perspective, wind power can be viewed as a source of stochastic perturbations coming from the generation side. These perturbations can affect the power quality and they must be taken into account in power system dynamic studies. The uncertainty in the power production of wind power plants has also economic implications since this kind of generation cannot be dispatched in a conventional way. To deal with these issues, careful studies have to be performed in which the appropriate representation of the wind variability represents a key modeling aspect. This paper is devoted to the development of mathematical models able to reproduce the wind speed behavior.

The wind speed at a specific location is characterized by its statistical properties. Through the analysis of recorded historical data, the marginal distribution of the wind speed can be estimated. Several probability distributions have been proposed to describe the wind speed behavior (e.g., [1–6]). From the studies reported in the literature, it can be concluded that the type of probability distribution depends on the particular location. For long time scales, the two-parameter Weibull distribution has shown a good fit to the observed wind speed empirical distribution in many locations around the world [2]. However, for wind speed fluctuations in time scales shorter than 10 min, turbulent effects take place, and the Weibull distribution is not considered a good fit [4,7].

Another characteristic observed from the wind speed data is that wind speed is an autocorrelated (two-point time-correlated) variable. The autocorrelation function of the wind speed is usually characterized by an exponential decay in the range of hours.

* Corresponding author.
E-mail address: Federico.Milano@uclm.es (F. Milano).

0306-2619/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2012.10.064

Outside this time frame, non-stationary phenomena related to diurnal and seasonal effects can be observed [8–11].

Therefore, wind speed models have to reproduce the statistical properties discussed above in order to provide reliable results in wind power studies.

Wind speed models are of interests in dynamic studies and control of wind turbines (e.g., [12–16]), in generating capacity reliability evaluation (e.g., [17–19]), and in power system economics and operation (e.g., [20–22]). Techniques used in these areas include wind speed trajectories generation, wind speed forecasting, Monte Carlo simulation and wind speed scenarios. These techniques can accommodate different wind speed models. In this regard, reference [23] reports the state of the art of wind speed models used in power system dynamic analysis, whereas [24] provides a bibliographical survey on wind speed forecasting methods and models. Reference [25] uses Monte Carlo simulations to compare the performance of different wind speed models in the context of reliability evaluation of power systems. Finally, a general methodology to generate wind speed scenarios is proposed in [26].

Among the wind speed models used in different research fields, discrete models used in time-series analysis are the most common. These models are based on Box–Jenkins methods and include Auto-Regressive (AR), Moving Average (MA), Auto-Regressive Moving Average (ARMA), and Auto-Regressive Integrated Moving Average (ARIMA) models. The ability of these models to reproduce the statistical properties of the wind speed for a particular site depends on the wind speed data available and on the time frame of interest [24]. Other models include four-component composite model [27], models based on filters and wind power spectral density [12], and Markov chain models [28]. Recently, wind speed fluctuation models constructed from the solution of the stationary Fokker–Plank equation have been proposed in [29].

In this paper, two continuous wind speed models based on stochastic differential equations (SDEs) are developed. The starting point of the development of both models is a SDE defining an Ornstein–Uhlenbeck process. This process can be considered as the continuous-time equivalent of the discrete-time AR process of order one, AR (1), [30]. The developed models are intended to generate wind speed trajectories with similar statistical properties to those observed in the wind speed data available at a particular location. The developed models take into account the marginal distribution and the autocorrelation function of the wind speed. To illustrate the proposed procedures, the two-parameter Weibull distribution is used in the development of the models. However, it is important to note that the proposed methodology is not limited to the Weibull distribution and other probability distributions can be used.

Therefore, the developed models provide autocorrelated Weibull distributed wind speed trajectories. As they are continuous models, they can in principle be used to generate wind speed trajectories at any time scale. However, since the models strive to reproduce the observed exponential autocorrelation feature, their ability to reproduce the wind speed behavior is expected to be acceptable only in the time frame where the wind speed remains exponentially autocorrelated, typically for a few hours. Furthermore, the developed models can be used to perform short term dynamic studies. In these studies, the inclusion of autocorrelations into wind speed trajectories is critical.

For simulation purposes, each developed model can be used as an independent "block" that generates wind speed trajectories. Another possibility in the context of dynamic simulations is to merge the equations of the wind speed model within the differential equations of the wind generator.

The remainder of the paper is organized as follows. Section 2 briefly introduces SDEs and provides the main theoretical methods used for developing the wind speed models. Section 3 describes the developed models and their properties. Section 4 discusses the generation of wind speed trajectories and illustrates their statistical properties through numerical simulations. Finally, Section 5 provides relevant conclusions.

2. Brief outline on stochastic differential equations and stochastic calculus

Stochastic differential equations (SDEs) are widely used to model stochastic phenomena in several fields of science, engineering and finance (see, for example, [31,32]). This section defines SDEs and provides the relevant stochastic calculus background that will be used to build our wind models. The interested reader can find theoretical background on SDEs and stochastic calculus in [33–37].

2.1. Definition of stochastic differential equations

A one-dimensional stochastic differential equation has the general form

$$\begin{aligned} dy(t) &= a[y(t),t]dt + b[y(t),t]dW(t), \quad t \in [0,T], \\ y(0) &= y_0, \end{aligned} \tag{1}$$

where $a[y(t),t]$ and $b[y(t),t]$ are the drift and the diffusion terms of the SDE, respectively, and $W(t)$ represents a standard Wiener process. This kind of equation can be viewed as an ordinary differential equation where an additional term is included to model the stochastic dynamical behavior related to variable $y(t)$. The standard Wiener process $(W(t), t \in [0,+\infty))$ is a non-stationary diffusion process with the following characteristics [34]:

- $W(0) = 0$, with probability 1.
- The function $t \mapsto W(t)$ is almost surely continuous.
- For $0 \leqslant t_i < t_{i+1} \leqslant T$, the random variable defined by the increments $\Delta W_i = W(t_{i+1}) - W(t_i)$ is Gaussian distributed with mean zero and variance $h = t_{i+1} - t_i$, i.e., $\Delta W_i \sim \mathcal{N}(0,h)$.
- For $0 \leqslant t_i < t_{i+1} < t_{i+2} \leqslant T$, the non-overlapping increments $\Delta W_i = W(t_{i+1}) - W(t_i)$ and $\Delta W_{i+1} = W(t_{i+2}) - W(t_{i+1})$ are independent.

Therefore, a standard Wiener process describes a continuous Gaussian process whose sample paths (increments) are of unbounded variation [36]. Another characteristic of the Wiener process is that $W(t)$ is nowhere differentiable. Therefore, despite the fact that the differential formulation is widely used in the literature (and it will be used throughout this paper), in a strictly mathematical sense Eq. (1) is not fully correct. Actually, the only correct formulation for (1) is its equivalent integral form

$$y(t) = y(0) + \int_0^t a[y(s),s]ds + \int_0^t b[y(s),s]dW(s), \quad t \in [0,T], \tag{2}$$

where the first integral is an ordinary Riemann–Stieltjes integral and the second one is a stochastic integral. Due to the unbounded variation of the sample paths of the Wiener process, stochastic integrals cannot be interpreted as Riemann–Stieltjes integrals. In this regard, there are mainly two different interpretations of stochastic integrals: the Itô's and the Stratonovich's approaches. In order to exploit the advantages of the Itô's calculus, in this paper stochastic integrals will be interpreted in the Itô's sense.

In the general case, SDEs have to be solved numerically. Numerical methods for SDE can show two types of convergence: strong and weak. Strong convergence refers to the goodness of the approximation when the focus is on the process trajectories themselves. On the other hand, weak convergence refers to the goodness of the approximation of the moments of the solutions to the

Download English Version:

https://daneshyari.com/en/article/6693268

Download Persian Version:

https://daneshyari.com/article/6693268

Daneshyari.com