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Variogram time-series analysis of wind speed

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A B S T R A C T

Fluctuations of wind-power production are a significant hindrance to its high penetration in power systems. System operators have to provide complementary power and relevant control strategies to smooth out the fluctuations when large-scale wind power ones is injected into the grid. To better smooth the fluctuations, the change rate of the wind speed is a critical piece of information. In this study, the variogram function is introduced to measure the change rate of the wind speed. Based on the variogram time-series, some statistical analyses are conducted. These results contribute to a better understanding of the characteristics of the change rate of the wind speed, such as the chronological variation pattern of the change rate on a day, whether the future change rate can be forecasted, and whether there is a relationship between the change rate and wind speed.

1. Introduction

A twofold significant challenge for humanity in the 21th century is energy depletion and environmental pollution. An effective solution to tackle these challenges is to develop renewable energy vigorously for power generation. Due to the superiorities of clean and renewable energy, wind power has become the most prominent potential and competitive renewable energy. However, because of the random fluctuations of wind, the wind power output is variable and uncontrollable, which brings huge threat to power systems with large-scale wind power integration. To ensure the security and stability of power systems, reserve capacity must be supplied to smooth the fluctuations of wind power. An important premise to smooth the fluctuations is by mastering the wind power output information accurately in advance. Wind speed is the main driving factor of wind power; therefore, wind speed prediction has become a hot topic for study.

The prediction methods can be divided into physical and statistical ones [1]. The physical prediction method, namely Numerical Weather Prediction (NWP), is based on a series of mathematical and physical equations to obtain wind speed prediction using computer power [2]. There are lots of famous NWP models, including the UK Meteorological Office mesoscale (MESO) model [3], the Danish Meteorological HIRLAM model [4], the Regional Atmospheric Modeling System (RAMS) model [5], the Weather Research and Forecasting Model (WRF) [6] and so on. The physical prediction method has the advantages in long-term wind speed prediction, but the grid resolution of NWP is not fine enough. So it is usually applied in large-area weather prediction and has poor prediction performance in a local wind farm when the time horizon is short [7]. Different from NWP, the statistical prediction method is widely applied and performs well in local and short-term wind speed predictions [8]. The statistical prediction method uses statistical models to mining the potential relationship of wind speed data at different times. Thus wind speed predictions can be obtained from historical wind speed data [9,10]. In earlier times, the time-series analysis model [11], the autoregressive moving average model (ARMA) [12], [13], the grey model method [14,15,16], and so on were introduced for wind speed prediction. With the development of artificial intelligence, more methods were introduced, including the Kalman filter [17], the fuzzy logic methods [18], the artificial neural network [19,20], the support vector regression (SVR) [21,22], the deep neural network [23].

The wind speed prediction can offer information about the wind power variation, which contributes to schedule the reserve capacity and control strategies to smooth out the fluctuation out.

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Nevertheless, the response speeds of complementary power and wind power are different. In general, the fluctuation rate of wind power is faster, the complementary power must respond to the change rate of wind power quickly to smooth the fluctuation out. Therefore, in the process of fluctuation smoothing, the change rate is another critical factor that must be taken into account. If the regulation speed of complementary power cannot keep up with the change rate of wind power, it is still unable to achieve the effect of smoothing, even if enough capacity of complementary power is supplied. Some scholars have noted this problem and conducted some related research. Banunavayanan et al. [24] proposed a concept of wind ramp (a sudden increase and a rapid decrease of power output) [25] rate: the power changes from minute to minute and its unit is MW min^{-1}. Lee and Baldick [26] researched the ramp rate of wind power output and designed a battery system to limit it. Hwang et al. [27] used an exponential smoothing method and ARIMA to predict the wind power ramp rate. Zheng et al. [28] utilized multivariate time-series models to build wind power ramp rate prediction models. In general, the research of ramp rate has been focused mostly on special events in the process of wind power change. However, to the best of the authors' knowledge, there is little literature on the research of the instantaneous change rate of wind power.

Therefore, the present paper conducts research on the instantaneous change rate of wind power output. The variogram function is a popular tool that reflects the variation degree of a variable in a certain direction within a certain distance. The method using variogram for analyzing the spatio-temporal process that evolves in space and time is of great interest in many areas of application, including medicine [29,30], environmental science [31], biology [32], image analysis [33] and so on. Therefore, in this paper, a variogram function is introduced to measure the change rate of wind speed. After obtaining the variogram time-series, some important properties of wind speed change are obtained.

This paper is organized as follows: Section 2 states the variogram function; sections 3 presents the calculation results of wind speed variogram and some statistical properties of wind speed change; Section 4 discusses the results; and Section 5 deploys the conclusions.

2. Methodology

By ensuring that the balance between generation and load is the primary rule of power system operation, the traditional generation units, such as thermal power generation, hydroelectricity and nuclear power, are relatively stable. Therefore, the generation side is relatively controllable. However, the generation side becomes unstable when large-scale wind power integration takes place because of the wind power fluctuations. To ensure the security and stability of the power system, scheduling plans and control strategies must be taken to smooth the fluctuations of wind power. It is well known that the operation control in the power system is realized by sampling control, i.e., each control process is realized in an individual time interval. As shown in Fig. 1, the control processes of EDC (Economic Dispatch Control) and AGC (Automatic Generation Control) are discrete, and the sampling periods of EDC and AGC are 15 min and 15 s, respectively. Suppose the current sampling time is t and the corresponding wind power is P_1; the next sampling time is $t+\Delta t$ and the corresponding wind power is P_2. Then the fluctuation range ΔP in the future time Δt can be given as $\Delta P = P_2 - P_1$. According to the load demand and the wind power fluctuation range in the future time Δt, control instructions are given by the power system to balance the difference between generation and load. As illustrated by the example of a thermal power unit, the thermal power unit adjusts its output on the basis of control instructions to smooth out the fluctuations of wind power. Upon completing the regulation in the current sampling interval, the operation control process goes to the next sampling interval.

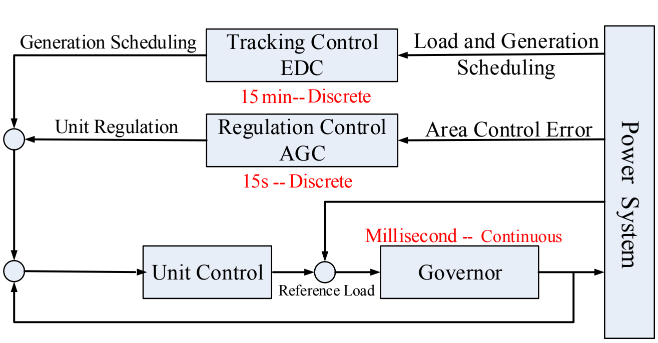

Fig. 1. Diagrammatic sketch of the Automatic Generation Control.

Nevertheless, the load regulation rate of the thermal power unit dP/dt is limited by the Generation Rate Constraints (GRC) of the unit. For a thermal power unit, the regulation rate is limited to 2%–5% of the rated capacity per minute. If the regulation rate of the thermal unit cannot keep up with the fluctuation rate of the wind power, it is impossible to smooth the fluctuations in a more efficient way. Therefore, the change rate of the wind power must be taken into account. As mentioned above, the control process is realized by the sampling control. Spontaneously, what we are concerned with is the change rate of the specific time interval, namely the change rate between two sampling points. We need to search an effective tool to measure the change rate of the wind power between the two sampling points. The variogram function is just a useful tool to research the change degree under specific distance. So a variogram function is employed in this paper to measure the change rate of the wind power.

Suppose that the random variable $Z(x)$ represents the value of a parameter at the location x. Let x and $x+\Delta x$ denote a pair of points that are separated by lag Δx. Then the semivariogram is given by Refs. [33,34]

$$\gamma(x,\Delta x) = \frac{1}{2}Var[Z(x) - Z(x+\Delta x)] \tag{1}$$

In practice, researchers call $\gamma(x, \Delta x)$ as variogram directly. The variogram function can be used to tackle both spatial and temporal problems [35].

It is difficult to get the variogram value in engineering applications, so the empirical variogram is taken instead [34,36,37].

$$\gamma^{*}(x,\Delta x) = \frac{1}{2N(\Delta x)}\sum_{i=1}^{N(\Delta x)}[Z(x_i) - Z(x_i+\Delta x)]^2 \tag{2}$$

where $N(\Delta x)$ is the total number of data pairs.

As can be seen from Equation (2), the variogram function reflects the variation degree of the spatial or temporal variable in a certain direction within a certain distance.

Since wind speed is the main driving force of wind power, the change rate of wind speed is studied firstly, which may roughly reflect the change rate of the wind power in some extent. Suppose $\{v(t)\}$ is the wind speed time-series, then the variogram of the wind speed $\gamma(t\ ,\ \Delta t)$ is:

$$\gamma(t,\Delta t) = \frac{1}{2N(\Delta t)}\sum_{i=1}^{N(\Delta t)}[v(t_i) - v(t_i+\Delta t)]^2 \tag{3}$$