An analysis-forecast system for uncertainty modeling of wind speed: A case study of large-scale wind farms

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HIGHLIGHTS
- An analysis-forecast system for wind speed uncertainty modeling is proposed.
- Recurrence analysis is developed to study the characteristics of wind speed.
- Feature selection is developed to determine optimal system input.
- An improved multi-objective optimizer is first proposed to optimize the system further.
- The proposed system shows a greater advantage over benchmark models considered.

ABSTRACT
The uncertainty analysis and modeling of wind speed, which has an essential influence on wind power systems, is consistently considered a challenging task. However, most investigations thus far were focused mainly on point forecasts, which in reality cannot facilitate quantitative characterization of the endogenous uncertainty involved. An analysis-forecast system that includes an analysis module and a forecast module and can provide appropriate scenarios for the dispatching and scheduling of a power system is devised in this study; this system superior to those presented in previous studies. In order to qualitatively and quantitatively investigate the uncertainty of wind speed, recurrence analysis techniques are effectively developed for application in the analysis module. Furthermore, in order to quantify the uncertainty accurately, a novel architecture aimed at uncertainty mining is devised for the forecast module, where a non-parametric model optimized by an improved multi-objective water cycle algorithm is considered a predictor for producing intervals for each mode component after feature selection. The results of extensive in-depth experiments show that the devised system is not only superior to the considered benchmark models, but also has good potential practical applications in wind power systems.

1. Introduction
In recent years, given its advantages, such as renewability and cleanliness, the comprehensive exploitation and utilization of wind energy has made it extensively socially and economically effective. More importantly, it is self-evident in a comparison of wind energy and conventional energy, which is a significant cause of global warming and atmospheric contamination, that wind power is one of the most promising energy sources available worldwide. Thus, wind energy is a greatly preferred energy resource in many parts of the world [1]. For example, wind power may become the second largest resource for generating electricity in China by 2050 [2]. However, in practice, the efficient and comprehensive development of wind power systems is considerably restricted because of the intrinsic randomness and intermittency of wind speed, which presents a significant challenge in terms of electrical network operation and management, in particular wind power integration (WPI). Accordingly, the effective analysis and accurate forecasting of wind speed not only constitute a challenging task, but are also an emphatic concern for those who make decisions-related to wind farms. It is crucial both to design more appropriate and efficient wind farms and to further determine the nonlinear dynamic pattern of wind speed in order to better manage and minimize the operational risks.

The analysis and investigation of the dynamic characteristics, in
particular the predictability, of nonlinear systems are important for forecast modeling. However, most of the studies in the literature placed emphasis mainly on certain basic statistics, such as the maximum, minimum, average, and standard deviation [3,4]. Further, the Lyapunov exponent, complexity, skewness, kurtosis, and emergence of wind speed were investigated in Ref. [5]. Accurate modeling of wind speed has important practical significance for wind energy development and utilization in many forms, such as wind turbines that convert wind power into kinetic energy and mean flow acoustic engines that convert the mean flow power into acoustic power [10–12]. However, given the complex dynamic pattern of wind speed, the design of an effective and scientific wind speed forecast model (WSFM) is consistently attracting considerable research attention. In general, the mainstream studies of WSFMs can be systematically categorized into those using physics and statistical approaches [13] and artificial intelligence methods. Rich physics models involving wind speed forecasts (WSFs) were systematically introduced in Refs. [14–18]. Technically, these models in general involve computational fluid dynamics in order to simulate the atmosphere based on different grid designs [13]. In contrast to physics models, the alternative WSFMs are based on statistical modeling and machine learning theories, which are convenient for implementing the modeling and simulation of wind speed forecasting because of their accessibility and excellent local prediction ability. In earlier research on WSFMs, the traditional statistical models, which usually consist of an autoregressive moving average model
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