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Short-term wind speed prediction using empirical wavelet transform and Gaussian process regression

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A B S T R A C T

Short-term wind speed forecasting plays a major role in wind energy plant operations and the integration of wind power into traditional grid systems. This paper proposes a hybrid model, which is composed of the EWT (empirical wavelet transform), PACF (partial auto-correlation function) and GPR (Gaussian process regression) method, for short-term wind speed prediction. In this proposed approach, the EWT is employed to extract meaningful information from the wind speed series by designing an appropriate wavelet filter bank, and the GPR simulates the internal uncertainties and dynamic features of the wind speed time-series using inputs identified by the PACF. The hybrid GPR model can offer point predictions and interval estimations of future wind speed. Additionally, this study adopts a moving window approach in the prediction process to deal adequately with the training data set, thereby adapting to the time-varying characteristic of the wind speed. The proposed hybrid model was validated with real mean half-hour wind speed data and hourly wind speed data. The computational results show that the suggested hybrid model favorably improves point wind speed forecasts in comparison with other models and provides satisfactory interval wind speed prediction.

1. Introduction

Along with the rapid development and utilization of wind energy, installed wind capacity is drastically rising, and the global wind industry has boomed in recent years [1]. However, due to the intermittent and stochastic nature of wind sources, the integration of wind power into traditional grid systems poses many challenges to the wind industry, including energy generation planning and turbine maintenance scheduling, and electrical grid system operations, including the management of the variability of wind power generation and interconnection standards [1,2].

To mitigate the aforementioned problems caused by the integration of wind energy into power systems, accurate dynamic wind speed prediction by reliable methods and models is becoming increasingly important and urgently needed. Short-term wind speed prediction is an important, representative and effective way to obtain accurate information, which is instrumental in the planning of economic load dispatch and load increment/decrement decisions made with respect to the management of a significant amount of wind power [3]. Numerous methods and approaches have been proposed in the existing literature, and the proposed models can be grouped into two categories: point forecasting of the wind speed and interval forecasting.

At present, the majority of the models in the literature have focused on point wind speed forecasting. These methods include physical modeling methods NWP (numerical weather prediction), time series models, soft computing approaches and hybrid models. The NWP models carry out predictions for weather conditions, including wind speed, through simulations of fluid dynamics and thermodynamics equations [4,5]. The models generally do well in extrapolating future wind conditions and trends. Time series models are widely used tools in the forecasting field, including short-term wind speed forecasting; examples include ARMA (autoregressive moving average) [6], ARIMA (autoregressive integrated moving average) [7], FARIMA (fractional autoregressive integrated moving average) [8], exponential smoothing techniques [9] and grey predictors [10]. These time series models can yield good forecasts under the conditions for which time series possess linearity.

Soft computing methods possess good capabilities, such as good adaptability and strong generality, and they have been extensively

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used by researchers for wind speed forecasting. Among the soft computing methods, artificial neural networks, including the Elman neural network [11], BPNN (back-propagation neural network) [12,13], recurrent neural networks [14], RBFNN (radial basis function neural network) [15] and multilayer perceptron neural network [16] are among the most extensively used approaches for the prediction of wind speed. SVM (support vector machine) [17–19] is another type of soft computing method. A SVM can be generalized to deal with high number of dimensions, small samples, and complex nonlinear problems.

In recent years, hybrid approaches to wind speed and wind power forecasting have been increasingly investigated to pursue more accurate and stable forecasts. Several types of wind forecasting studies with hybrid models have been presented, including the hierarchical integration of NWP and statistical models and the combination of candidate statistical models and modeling algorithms. In the integration of NWP and statistical models, statistical methods are used to adjust the numerical wind speed predictions to provide significant forecast improvement [5]. The combinations of candidate statistical models and modeling algorithms produce wind speed predictions through integrating individual statistical models by the same or different modeling algorithms; examples include data preprocessing-based approaches [19], parameter optimization based approaches [20] and the weighting-based approaches [21].

Researchers proposed the aforementioned models for point or deterministic wind speed or power forecasts. For optimal management of wind power production and distribution, it is also important to obtain information on the uncertainty of potential future events in addition to single-valued predictions. Information about the uncertainty of projections can be conveyed by prediction intervals in a practical and visual way [23]. Interval predictions of wind speed can meet the needs of various applications, including power system operations [24,25] where risks and uncertainties must be quantified. For this reason, researchers have conducted considerable research in interval wind speed or power prediction considering uncertain information. The approaches proposed in the literature include probability-distribution functions [26,27] Bayesian theory and structural break modeling [28], copula estimator [29], fuzzy inference [22], Bayesian model averaging model [30].

To provide satisfactory and reliable point forecasts and interval estimations for future wind speeds, this paper proposes a hybrid forecasting approach using hybrid prediction. The proposed hybrid constructor incorporates the EWT (empirical wavelet transform), PACF (partial autocorrelation function) and GPR (Gaussian process regression) method, which performs the distribution prediction of the future wind speed. The prediction intervals, quantiles and single-valued predictions can be inferred from the obtained predictive set of forecasts depending upon the specific interest. The developed hybrid method is examined using mean half-hour wind speed data and hourly wind speed data. The simulation results reveal that the hybrid forecasting method outperformed other popular algorithms.

The remainder of this paper is organized as follows. Section 2 discusses the contributions of the proposed model. Section 3 introduces the required individual models and describes the developed hybrid model. In Section 4, the wind speed predictions and advantages of the developed strategy are analyzed and discussed through comparisons with other benchmark models. Finally, the study's conclusions are presented in Section 5.

2. Contribution

As mentioned in Section 1, hybrid approaches utilize the advantages of each individual model and combine them through the same or different modeling algorithms, thereby generating more accurate and reliable wind speed predictions, to some extent.

Based on the aforementioned forecasting methodology, this article integrates two already existing models and algorithms for wind speed forecasting. The main contributions of this study with respect to those offered by other studies in the same area of research can be summarized as follows:

(1) The hybrid approach is proposed not only to generate point and interval wind speed forecasts but also to tackle the characteristics of wind speed series. The proposed approach extracts meaningful information from a short-term wind speed series to eliminate disturbing factors, tackles the uncertainties in the wind speed series with the latent function, and then models the behavior of the wind speed. Finally, the hybrid approach provides the uncertainty associated with the future wind speed.

(2) In the pretreatment of the short-term wind speed series, the WT (wavelet transform) or EMD (empirical mode decomposition) techniques are commonly used to eliminate noise in the time series. However, the WT lacks the ability of self-adaptive data processing and the wavelet basis and parameters need to be specified beforehand, while the EMD is sensitive to noise and sampling and lacks mathematical theory. The EWT method remedies the drawbacks of the aforementioned decomposition methodologies to some extent. It can adaptively represent the processed signal by automatically generating the adaptive wavelet and then decomposing the signal into a finite number of modes.

(3) GPR is employed to generate probabilistic wind speed forecasts. GPR is a principled and practical probabilistic approach, which is advantageous in the interpretation of model predictions. It possesses very good adaptability and strong generality to deal with high dimensions and small samples in complex nonlinear problems. Compared with neural networks and SVM, GPR is easy to implement, self-adaptive to enable superior parameter estimation, and flexible enough to make nonparametric inferences.

(4) The GPR is based on Bayesian inference that solves this issue by incorporating prior domain knowledge of wind speed characteristics and by specifying prior distributions for the model parameters. In addition, a Bayesian forecasting model can produce a predictive sample of the wind speeds. The predictive sample provides more information than a classical point forecast, including credible intervals and quantile.

(5) Wind speed is characteristically time-varying, which should be exhibited by the wind speed forecasting model. Thus, this study employs a moving window method in these prediction processes, which allows the proposed hybrid model to adaptively respond to wind speed changes and to better reflect the actual forecasting environment.

3. The hybrid EWT-GPR model

The hybrid constructor composed of the EWT and GPR model is proposed for point wind speed forecasting as well as interval estimation. In the suggested hybrid model, the EWT is employed to extract different modes from the wind speed series by designing an appropriate wavelet filter bank, and the GPR model performs the forecasting task with the appropriate input determined by the PACF. To adapt quickly to the dynamic features of the wind speed time-series, a moving window approach is adopted. Both the point and interval wind speed forecast can be inferred from the predictive probability distribution of the future wind speed obtained by