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Smart deep learning based wind speed prediction model using wavelet packet decomposition, convolutional neural network and convolutional long short term memory network

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ABSTRACT

High precision and reliable wind speed forecasting is important for the management of the wind power. This paper develops a novel wind speed prediction model based on the WPD (*Wavelet Packet Decomposition*), CNN (*Convolutional Neural Network*) and CNNLSTM (*Convolutional Long Short Term Memory Network*). In the proposed WPD-CNNLSTM-CNN model, the WPD is employed to decompose the original wind speed time series into a number of sub-layers; the CNN with 1D convolution operator is used to forecast the obtained high-frequency sub-layers; and the CNNLSTM is adopted to complete the forecasting of the low-frequency sub-layer. To verify and compare the prediction performance of the proposed model, eight models are used. According to the results of four experimental tests, it can be observed that: (1) the proposed model is robust and effective in predicting the 1D wind speed time series, besides, among the involved eight models, the proposed model can perform best in wind speed 1-step to 3-step predictions; (2) when the wind speed experiences sudden change, the proposed model can have better prediction performance than the other involved models.

1. Introduction

Along with the development of the world economy, the energy demand has become one of the most important topics in the world. The past years have witnessed the phenomenon that there are some prevalent problems in the conventional resources, for example, the energy scarcity and environmental pollution. In order to overcome these problems, renewable energy is needed. In recent years, wind energy, as a significant and promising renewable energy, has been developed rapidly [1]. However, the high penetration of the wind power can bring challenges to the stability of the power system operation [2]. The wind power generation is strongly related with the inputting wind speed. Accurate wind speed predictions can benefit the management of the wind power and help reduce the unexpected effects on the power system [3]. If the multi-step high-accuracy wind speed forecasted values can be obtained, it is good for the power dispatching department to control the wind power systems scientifically. So the wind speed forecasting technique is desired in the wind power engineering. Nevertheless, due to the inherently intermittent of the wind, it is difficult to predict the wind speed accurately. Therefore, the wind speed forecasting has attracted much attention of the scholars.

Over the past few years, various wind speed prediction models have been developed. These models can be classified into three types based on the time horizons: the short-term prediction models, medium-term prediction models and long-term prediction models [4]. Generally, in order to establish the wind speed prediction models, various methods can be used. These methods can be classified into two types: the prediction methods and optimization methods. The prediction methods are used as the predictors, and they mainly include the physical methods, conventional machine learning methods, and deep learning methods. The optimization methods are used to improve the prediction performance of the predictors, and they mainly contain the signal processing methods and parameters optimization methods [5].

The physical methods predict the wind speed by using the physical parameters, such as the ambient temperature, atmospheric pressure and terrain conditions [6]. These methods are often suitable for the mid-long term and large-scale areas wind speed forecasting. The NWP (*Numerical Weather Prediction*) and CFD (*Computational Fluid Dynamics*) are the key technologies in these methods [7]. Recently, some valuable wind speed models based on the physical methods have been proposed. Wang et al. [8] presented an extreme wind speed non-stationary model based on the NWP. Galanis et al. [9] presented a hybrid wind speed

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prediction model by combining the Bayesian model, nonlinear Kalman filter, and NWP. Allen et al. [10] investigated a BLS (*Boundary Layer Scaling*) method for long-term wind speed forecasting.

The conventional machine learning methods predict the wind speed by using single data or multiple data. These methods are often suitable for the wind speed data which has a clear trend. The technologies of these methods mainly comprise of the persistence methods, time series methods, grey methods, Kalman methods, ANN (*Artificial Neural Networks*) methods and SVM (*Support Vector Machine*) methods. Various effective wind speed prediction models have been presented in the literature based on these technologies. Kiplangat et al. [11] demonstrated a hybrid wind speed prediction model based on the linear time series methods. Maatallah et al. [12] carried out a wind speed forecasting model by using the Hammerstein method and Autoregressive method. Akçay et al. [13] built a Kalman filter based model for wind speed forecasting. Mi et al. [14] predicted the wind speed based on the ARMA (*Auto-Regressive Moving Average*) and ELM (*Extreme Learning Machine*). Zhang et al. [15] investigated the ANN-based models and SVM based models for wind speed forecasting. Sun et al. [16] successfully introduced the RELM (*Regularized Extreme Learning Machine*) into wind speed forecasting. Shrivastava et al. [17] executed a wind speed intervals prediction model based on the SVM. Liu et al. [18] conducted a comparative study on ANN-based models for wind speed forecasting. Feng et al. [19] developed a short-term wind speed prediction model, which exploited the ensemble algorithm for combing the ANN, SVM, GBM (*Gradient Boosting Machine*) and RF (*Random Forest*).

The deep learning methods are the new branch of the machine learning methods. With the booming development of the data science, deep learning methods have been widely used in solving classification and regression problems [20]. According to the literature [21], compared with the shallow methods, the deep learning methods can have better performance in extracting the hidden natural structures and inherent abstract features of the data. Accordingly, the deep learning methods can be the promising methods in wind speed forecasting field. Recently, some deep learning methods, such as the DBN (*Deep Belief Network*) and LSTM (*Long Short Term Memory*), have been applied for establishing the wind speed prediction models. Wang et al. [22] put forward a DBN based wind speed prediction models, and their case studies verified the proposed model was accurate and stable. Hu et al. [23] successfully designed an efficient wind speed model based on the DBN and transfer learning. Liu et al. [24] put up with the LSTM based model for wind speed forecasting, and the proposed model could obtain satisfactory prediction performance.

The signal processing methods can effectively enhance the performance of the wind speed prediction models. Ordinarily, these methods can be used for data denoising, data transformation and data feature extraction. In the last years, these methods have been widely applied in wind speed forecasting. Sun et al. [25] adopted the PSR (*Phase Space Reconstruction*) as the input vectors selection method of the wind speed prediction model. Tascikaraoglu et al. [26] employed the WT (*Wavelet Transform*) for decomposing the raw wind speed data into more stationary components. Wang et al. [27] applied the WPT (*Wavelet Packet Transform*) and PSR for wind speed data feature extraction. Liu et al. [28] proposed a wind speed prediction model based on the WPD and FEEMD (*Fast Ensemble Empirical Mode Decomposition*). Hu et al. [29] used the EWT (*Empirical Wavelet Transform*) for extracting the significant information of the wind speed data. Jiang et al. [30] developed an EEMD based wind speed prediction model. Yu et al. [31] analyzed the performance of three wind speed prediction models, in which the EMD (*Empirical Mode Decomposition*), EEMD (*Ensemble Empirical Mode Decomposition*) and CEEMDAN (*Complete Ensemble Empirical Mode Decomposition with Adaptive Noise*) were exploited as the decomposition methods, while the SSA (*Singular Spectrum Analysis*) was exploited to further handle the highest frequency data. Yu et al. [32] designed a hybrid decomposition method for wind speed forecasting by combining the WT and SSA. Peng et al. [33] exploited the CEEMDAN and VMD (*Variational Mode Decomposition*) for processing the non-linearity of the wind speed data.

The parameters optimization methods consist of many technologies and can be used for optimizing the hyperparameters of the single prediction model and the weight parameters of the multiple prediction models. These methods have attracted extensive attention for they can improve the accuracy and stability of the wind speed prediction models. Xiao et al. [34] established a wind speed prediction model and utilized the improved BA (*Bat Algorithm*) and CG (*Conjugate Gradient*) for optimizing the initial weights of the GRNN (*General Regression Neural Network*). Zheng et al. [35] combined the PSO (*Particle Swarm Optimization*) and GSA (*Gravitational Search Algorithm*) for optimizing the weights and bias of the ORELM (*Outlier Robust Extreme Learning Machine*). Zhang et al. [36] used the CLSFPA (*Flower Pollination Algorithm with Chaotic Local Search*) for optimizing the weight parameters of the combined model. Jiang et al. [37] adopted the CS (*Cuckoo Search*) algorithm for tuning the parameters of the v-SVM. Zhao et al. [38] employed the CS algorithm for optimizing the fuzzy clustering.

In this study, a novel wind speed prediction model is proposed based on the WPD, CNN and CNNLSTM. The WPD has been proved to be one of the most effective data decomposing algorithms in the field of wind speed prediction. Both of the CNN and CNNLSTM are the mainstream neural networks in the field of deep learning. The originality of the study is to investigate the combination performance of the WPD and the CNN and CNNLSTM in the wind speed multi-step prediction. The detailed framework of the study is explained as follows: (a) The WPD is employed to decompose the original wind speed time series into a number of sub-layers. The purpose of executing the WPD decomposition is to decrease the non-stationarity of the original wind speed data and also to provide more sub-layer wind speed data for the deep learning prediction; (b) The CNN is used to complete the forecasting of the high-frequency sub-layers; (c) The CNNLSTM is adopted to complete the forecasting of the low-frequency sub-layer. The reason to use the CNN and CNNLSTM for the forecasting computation is to utilize their nonlinear processing capacity to obtain satisfactory wind speed forecasting results.

The main contributions of this study are demonstrated as follows: (a) A novel wind speed prediction model is proposed by combing the WPD, CNN and CNNLSTM; (b) The real performance of the CNN algorithm in the WPD based high-frequency wind speed sub-layers has not been studied before; (c) The real performance the CNNLSTM in the WPD based low-frequency wind speed sub-layers has also not been investigated before; and (d) the proposed hybrid model will be compared fully with other eight single or hybrid wind speed forecasting models. The involved comparing models include the ARIMA model, SVM model, WPD-BP model, WPD-GRNN model, WPD-Elman model, WPD-ELM model, WPD-CEEMDAN-RBF model and WPD-CNNLSTM-CNN model. The significant difference of the study to others is to only use the deep learning neural networks in the wavelet decomposing framework to realize the multi-step wind speed forecasting computation. The study will provide a useful reference how to combine the data decomposition algorithm and the deep learning algorithm for the wind speed multi-step prediction.

The contents of this study are arranged as follows. In Section 2, the framework of the proposed model and the principle of the necessary individual methods are presented. In Section 3, the proposed model and contrast models are applied in the experimental data; besides, the comparison and discussion of the prediction results are also provided. In Section 4, the paper is concluded.

2. The WPD-CNNLSTM-CNN model

2.1. The entire process of the proposed model

The framework of the WPD-CNNLSTM-CNN model is depicted in Fig. 1, and the entire process is described in detail as follows: