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Review on probabilistic forecasting of wind power generation

Yao Zhang, Jianxue Wang*, Xifan Wang

School of Electrical Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China

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ABSTRACT

The randomness and intermittence of wind resources is the biggest challenge in the integration of wind power into the power system. Accurate forecasting of wind power generation is an efficient tool to deal with such problem. Conventional wind power forecasting produces a value, or the conditional expectation of wind power output at a time point in the future. However, any prediction involves inherent uncertainty. In recent years, several probabilistic forecasting approaches have been reported in wind power forecasting studies. Compared to currently wide-used point forecasts, probabilistic forecasts could provide additional quantitative information on the uncertainty associated with wind power generation. For decision-makings in the uncertainty environment, probabilistic forecasts are optimal inputs. A review of state-of-the-art methods and new developments in wind power probabilistic forecasting is presented in this paper. Firstly, three different representations of wind power uncertainty are briefly introduced. Then, different forecasting methods are discussed. These methods are classified into three categories in terms of uncertainty representation, i.e. probabilistic forecasts (parametric and non-parametric), risk index forecasts and space-time scenario forecasts. Finally, requirements and the overall framework of the uncertainty forecasting evaluation are summarized. In addition, this article also describes current challenges and future developments associated with wind power probabilistic prediction.

Contents

Abbreviations: WPF, Wind Power Forecasting; PDF, Probability Density Function; CDF, Cumulative Distribution Function; QR, Quantile Regression; KDE, Kernel Density Estimation; ISO, Independent System Operator; RS-AR, Regime-Switching Autoregression; MS-AR, Markov-Chain Regime-Switching Autoregression; AR-GARCH, Autoregression-Generalized Autoregressive with Conditional Heteroscedasticity; CPAR, Conditional Parametric Autoregression; LQR, Local Quantile Regression; SQR, Spline Quantile Regression; QRF, Quantile Regression Forest; BMA, Bayesian Model Averaging; MRI, Meteo-Risk Index; NPRI, Normalized Prediction Risk Index; AI, Artificial Intelligence; NWP, Numerical Weather Prediction; CRPS, Continuous Ranked Probability Score

* Corresponding author. Tel.: +86 29 82668842; fax: +86 29 82665489.
E-mail addresses: zy.3110161019@stu.xjtu.edu.cn (Y. Zhang), jxwang@mail.xjtu.edu.cn (J. Wang), xfwang@mail.xjtu.edu.cn (X. Wang).

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1. Introduction

To protect the environment and reduce consumption of conventional energy resources, the installed capacity of renewable energy, wind power in particular, is ever-growing all over the world. Usually, wind power generation is considered as 'non-dispatchable' due to the randomness and intermittence involved, which brings about a great impact on power system operation in various aspects, e.g. power system stability, ancillary service, and power quality. In this aspect, forecasting wind power output is an efficient tool to tackle these problems and bring more and more wind power into power system. Accurate forecasting of wind power can also provide technical support for wind power trading in electricity market, thus producing significant economic benefit.

The currently-used wind power forecasting (WPF) produces only a conditional expectation of wind power output, and is a deterministic prediction (or spot prediction) in nature. Until now, much research has been carried out for improving the accuracy of these prediction methods, which has been published in other reviews [1,2]. In fact, it is extremely difficult, if not impossible, to get the whole knowledge of future events, especially the capricious atmospheric behavior. Therefore, any prediction approach has its inherent and irreducible uncertainty. Compared with the deterministic forecasting, the approach that provides probabilistic information on future events may offer advantages if it is difficult to achieve the accurate spot forecasting. Recently, uncertainty forecasting or probabilistic forecasting has drawn more and more attention in the development of prediction theory [3]. It has found wide applications in weather prediction [4], risk management in economics and finance [5], epidemiological studies [6]. For example, every quarter, the Bank of England issues probabilistic forecasts of Gross Domestic Product (GDP) and Consumer Price Index (CPI) of future three years on its website [7].

Studies have indicated that WPF was not precise enough and the accuracy of WPF varied with time, resulting in remarkable uncertainty for wind power forecasting. In the last decade, the uncertainty forecasting method has been introduced into the wind power generation, and the theory of wind power uncertainty forecasting has also been established. Unlike the conventional wind power forecasting that usually only produces a single value of future wind power output, the wind power uncertainty forecasting can give much information on uncertainty, and is very useful for power system operation with volatile wind power. Gneiting [8] proposed that for a large family of decision-making problems, the optimal decision was directly related to the quantile of conditional predictive distribution. This generalized conclusion provided a theoretical foundation for the wind power uncertainty forecasting to be applied to power system operation. With the help of stochastic optimization, uncertainty information of wind power output has been used in the decision-making problems related to reserve requirement [9–11], trading strategy of wind power [12–15], unit commitment considering wind power uncertainty [16–18], energy storage sizing [19], and optimal dispatch of wind-hydro power plants [20]. These studies show that the penetration rate of wind power generation has increased substantially after the uncertainty forecasting was applied to the power system operation.

Evaluation of wind power forecasts is also of great importance to both deterministic and probabilistic forecasting methods. In general, evaluating wind power forecasts is made up of four functions: performance assessment, model diagnosis, model selection, and model ranking. There are several criteria for evaluating wind power spot forecasts, e.g. Mean Absolute Error (MAE), Mean Square Error (MSE), and Root Mean Square Error (RMSE) [21]. The evaluation of wind power spot forecasts is on the basis of the discrepancy between predictive and measured values. However, it is more difficult to evaluate wind power uncertainty forecasts because the information on uncertainty (e.g. predictive density) cannot be compared with the measured value directly. As a prominent challenge, the evaluation of wind power uncertainty forecasts has drawn much attention among the researchers in recent years.

This paper gives a detailed review of state-of-the-art methods and new developments in wind power uncertainty forecasting. It is organized as follows. The uncertainty of wind power generation is analyzed briefly in Section 2. A detailed definition of wind power forecasting is also given in this section. In Section 3, we qualitatively investigate the influence of wind power forecasting on electricity price. In order to prove the necessity of uncertainty forecast in wind power generation, a representative example of decision-making problems, i.e. offering strategy of wind power in electricity market, is also described in Section 3. Section 4 deals with three different uncertainty representations of wind power output. They are probabilistic forecasting, risk index, and scenario. In Section 5, based on the mathematical methodologies employed, various techniques of wind power probabilistic forecasting are