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Ensemble methods for wind and solar power forecasting—A state-of-the-art review

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ABSTRACT

This paper reviews state-of-the-art on wind speed/power forecasting and solar irradiance forecasting with ensemble methods. The ensemble forecasting methods are grouped into two main categories: competitive ensemble forecasting and cooperative ensemble forecasting. The competitive ensemble forecasting is further categorized based on data diversity and parameter diversity. The cooperative ensemble forecasting is divided according to pre-processing and post-processing. Typical articles are discussed according to each category and their characteristics are highlighted. We also conduct comparisons based on reported results and comparisons based on simulations conducted by us. Suggestions for future research include ensemble of different paradigms and inter-category ensemble methods among others.

Contents

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Nomenclature

Abbreviations

AdaBoost	adaptive boosting
ANN	artificial neural network
ANFIS	adaptive neuro-fuzzy inference system
ARIMA	autoregressive integrated moving average
ARMA	autoregressive moving average
ARTMAP	predictive adaptive resonance theory
BP	backpropagation
CI	computational intelligence
CSP	concentrated solar power
CVNN	complex-valued neural network
DWT	discrete wavelet transform
ECMWF	European Center for Medium-Range Weather Forecasting
EMD	empirical mode decomposition
EnKF	ensemble Kalman filter
FNN	fuzzy neural network
GARCH	generalized autoregressive conditional heteroscedasticity
GHI	global horizontal irradiation
kNN	k-nearest neighbors
MLP	multi-layer perceptron
NWP	numerical weather prediction
NECP	National center for environmental prediction
NDBC	National data buoy center
NSRDB	National solar radiation data base
PR	pattern recognition
PRNN	pipelined recurrent neural network
PV	photo-voltaic
RNN	recurrent neural network
RBPN	recurrent backpropagation network
RVNN	real-valued neural network
SMA	seasonal moving average
SVM	support vector machine
SVC	support vector classification
SVR	support vector regression
TSI	total satellite image

Error measures

NMSE	normalized mean square error
NMAE	normalized mean absolute error
RMSE	root mean square error
MRE	mean relative error
MAE	mean absolute error
MSE	mean square error
MAPE	mean absolute percentage error
MASE	mean absolute scaled error

1. Introduction

Renewable/sustainable energy sources, such as wind energy, solar energy, wave energy and tidal energy, draw increasing attention of researchers due to the shortage and their adverse impacts on the environment of fossil fuel. Renewable energy is abundant and environmentally-friendly. However, the cost of using renewable energy is still high because it is difficult to be integrated into the power grid either temporally or spatially. Among various renewable energy sources, wind and solar are two most commonly used sources. This paper focuses on these two types of renewable energy sources.

Consumable electricity has a unique feature: consuming while producing with little or no storage. Conventional electricity power is generated according to the demand from residential, industrial and commercial customers. The primary problem of introducing renewable energy into the power grid is the unpredictability such as intermittent nature of wind speed, and furthermore for a wind farm, different wind turbines generate different amount of power based on the wind direction and location within the wind farm [1]. Solar irradiance is affected by cloud cover, haze effect and solar elevation angle. Although the solar elevation angle is analytically determinant, the cloud cover and haze effect are stochastic [2].

The unpredictability causes a large fluctuation in the power outputs and in order to smooth the fluctuation, large amount of battery storage or power reserve capacity is required, which is costly. By improving the forecasting accuracy, these reserves can be reduced. In addition, accurate wind speed/power forecasting and solar irradiance forecasting can improve the energy conversion efficiency, reduce the risk caused by system overloading and extreme weather conditions, and can improve the unit commitment optimization [3–5].

The objective of this paper is to review some of the recently published articles on ensemble wind speed/power and solar irradiance forecasting with a clear categorization. The details of the ensemble forecasting methods with examples will be discussed in the paper as well. The strengths and weaknesses of each approach are also identified. The comparisons of the results presented in the literature and the experimental comparisons based on our own simulations are discussed. In addition, promising future research directions are also recommended.

The remaining of this paper is organized as follows: Section 2 discusses the ensemble forecasting methodologies on wind speed/power and solar irradiance forecasting; Section 3 reviews state-of-the-art ensemble forecasting methods; Section 4 compares the reviewed ensemble forecasting methods with numerical examples and Section 5 concludes the paper and proposes some future research directions.

2. Ensemble forecasting methodologies

This section gives a brief introduction on wind speed/power forecasting and solar irradiance forecasting followed by the introduction of ensemble forecasting methodologies.

2.1. Wind speed/power forecasting

Wind is bulk, directed movement of air. Wind power is generated by propelling a turbine to rotate, which converts the mechanical power to electrical power. The conversion from wind speed to wind power is shown as [3]

$$P = \frac{1}{2}\rho A C_p(\lambda, \beta) v^3 \tag{1}$$

where ρ is the air density, A is the area of the turbine when rotating, $C_p(\lambda, \beta)$ is the efficiency which is affected by two parameters: tip speed ratio λ and blade pitch β, and v is the up-wind speed. If the wind turbine is placed in a wind farm, wake effect should also be considered.

In the literature [6,7], wind power forecasting and wind speed forecasting are considered equivalent if a proper wind speed to wind power conversion equation such as (1) is available. Therefore, wind speed and wind power forecasting is equivalently discussed in the paper.