Applied Energy 225 (2018) 902–911

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

An intelligent framework for short-term multi-step wind speed forecasting based on Functional Networks

Adil Ahmed*, Muhammad Khalid

King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

HIGHLIGHTS

- An intelligent framework for multi-step wind forecasting is presented.
- The proposed Functional Network model is a novel concept in renewable energy.
- Accurate power predictions obtained for long forecast horizons bring economic benefits.

ARTICLE INFO

Keywords:
Functional networks
Multi-step forecasting
Neural functions
Wind energy

ABSTRACT

This paper presents a novel method for the development of multi-step wind forecasting models based on functional network (FN), a modern intelligent paradigm. The basis of FN development is the integration of functional theory with neural networks to produce problem-driven network topologies and optimal neural functions with diversified structures as opposed to conventional neural networks. These advantages of functional networks result in optimum models for accurate wind speed and power forecasting. In this research work, FN forecasting engine is developed using three state-of-the-art multi-step forecasting mechanisms, namely, recursive, direct and hybrid DirRec scheme. A detailed analysis of the developed forecast models is carried out using a real-world case study and notable improvement in forecast accuracy is recorded in terms of standard performance indices. Among the three multi-step schemes, hybrid DirRec gives the best forecast accuracy. The results obtained from a comparative analysis against a benchmark model as well as a classical neural network model validate the efficacy of the FN model. Hence the proposed forecasting schemes can be of immense utility for wind power system operators for devising cost-effective energy management and dispatch strategies by accurately forecasting wind power for long forecast horizons.

1. Introduction

Electricity production through renewable energy is a fast-emerging phenomenon due to its advantages of independency from fossil fuels, reduction in greenhouse emissions and environment preservation. Among these renewables, wind energy is a low cost and highly emphasized resource, but the stochastic nature of wind introduces many difficulties in power generation [1,2]. For example, a fractional error in wind speed forecast leads to a large power output deviation, hence accurate wind speed prediction is substantial for optimal integration of wind power into the main electricity grid [3,4]. A lot of research work is being done in this area and special attention is required in forecasting up to few hours ahead because it has great significance in a microgrid environment based on renewable energy for devising strategies for power dispatch, optimal bidding, system reliability assessment, and optimal utilization of resources [5–8].

Wind speed forecasting has been classified on the basis of prediction horizon by the World Meteorological Organization as well as in literature [9,10]. This includes nowcasting (0–2 h), very-short range (up to 12 h), short range (12–72 h) and so on [10]. The focus of this paper, however, is very-short range forecasting, i.e., up to 6 h ahead. This problem has been tackled from various dimensions in literature; spanning from physics (numerical weather predictions) to mathematics (statistical and probabilistic), spatial correlation models to machine learning or a hybrid of these approaches [11,12].

The physical forecasting models are based on lower atmosphere forecasting and numerical weather predictions (NWPs) [13]. The statistical models are purely mathematical and based on recognizing a relationship or pattern from the acquired historical data [14]. The most popular of them include ARMA, ARIMA, Bayesian model averaging,

* Corresponding author.
E-mail addresses: g201408140@kfupm.edu.sa (A. Ahmed), mkhalid@kfupm.edu.sa (M. Khalid).

https://doi.org/10.1016/j.apenergy.2018.04.101
Received 7 February 2018; Received in revised form 16 April 2018; Accepted 29 April 2018

Grey predictor and other advanced regression models [15–17]. The probabilistic models for wind speed represent it as a suitable probability density function (PDF), generally the Weibull distribution, whose parameters are determined with different approaches [18]. In addition to mathematical models, the spatial correlation models are also very effective as they utilize the inherent relationship among wind properties based on the location of the wind farms [19,20].

Machine learning or intelligent methods are trending nowadays since they generally perform better than other short-term time series prediction models. They have the ability to resourcefully make use of historical data for learning patterns and training the algorithms by finding complex relationships among variables without using tedious mathematics [21]. The most prevalent of the intelligent techniques is an Artificial Neural Network (ANN) model [22,23]. The idea of utilizing ANNs for wind speed prediction was introduced about two decades ago [24], but it can still be seen in very recent works, usually combined with other advanced techniques like wavelet decomposition, fuzzy rule base or evolutionary optimization, to compensate for its deficiencies [25,26]. In addition to ANN, Support Vector Machine (SVM), Extreme Learning Machine (ELM) and hybrid models like Adaptive Neuro Fuzzy Inference System (ANFIS) are more advanced Artificial Intelligence (AI) methods that have been used lately [27,28].

The drawbacks of ANN models such as local minimal point, overfitting problems etc. can be overcome by the advanced hybrid AI models like SVM, ELM and ANFIS, that are reported to show good performance as far as the forecast accuracy is concerned [29,30]. However, the computational requirement of most of these models becomes a hassle, especially if training through an optimization technique is involved [26,31]. Thus, making them practically inapplicable for real applications such as competitive energy markets, where the bidding process is very rapid with a large number of contenders [32,33]. Therefore, in such scenarios, accuracy with swiftness of predictions is required. To fill the research gap, there is a recent trend of proposing and evaluating innovative forecast models based on modern AI schemes such as Deep belief network and Elman neural network and Whale optimization algorithm [26,34,35]. Similarly, this paper proposes the development of a new wind forecast model based on Functional Network.

Functional Networks (FNs) are a generalized advanced form of neural networks introduced by E. Castillo et al. (2012) to overcome many issues present in ANN based models [36]. Since the advent of functional networks, they have been applied to show superior performance as compared to ANNs in many engineering and scientific applications [37]. The applications in which FNs have already been used include nonlinear regression and classification [38], time series modelling and predictions [39], and differential equation modelling like beam stress modelling [36]. Furthermore, it has been used in many practical engineering problems like error prediction of navigation satellite clock [40] and for model parameter predictions in petroleum reservoir applications [41]. A general framework for the utility of functional network models for time-series modelling and prediction is discussed in literature [37,39]. However, it is a novel concept in the field of power systems engineering and to the best of authors' knowledge it has not been applied before to address the problem of multi-step wind forecasting.

In predictive control and dispatch framework for renewable power systems, power forecasting is performed for multi-steps ahead in future [12,42]. Therefore, multi-step forecasting (MSF) of renewable power has been an active area of research recently and can be done through different models. The most important of them are Direct, Recursive, DirRec, MIMO and DIRMIMO [43,44]. Precise MSF help power system owners in planning a profitable strategy for power dispatch, unit commitment and improving their participation in competitive energy markets [45,46]. Furthermore, there is not much work found in literature for MSF as compared to single-step forecasting, hence it is still a domain which demands contribution.

This research work is intended to develop Functional Network models to address the problem of very-short term MSF for wind power. A step-by-step procedure for the development of wind forecast models with the proposed scheme is illustrated for better understanding. Three state-of-the-art MSF mechanisms, namely, recursive, direct, and DirRec are developed for six steps ahead forecasts. A benchmark persistence model for time series is used to evaluate the performance of the FN model with all three techniques, while they are also compared among each other to draw conclusions about their benefits and applicability. Forecast accuracy is gauged on the basis of standard error indices. The efficacy of the proposed FN based approach for wind forecasting is further validated by drafting a comparison with a benchmark naive model and standard ANN model. Wind speed data from a real location is used for all simulations as a case study.

The major novel contributions of the work are as follows:

- This paper introduces an effective forecast model based on Functional Network for the first time in the field of power systems engineering for accurate short-term forecasting of highly intermittent renewable resources.
- This paper improves the prediction performance of state-of-the-art multi-step ahead forecasting models; namely, Recursive, Direct, and DirRec schemes using Functional Networks.

The remainder of this paper is organized as follows. Section 2 states the problem with brief discussion. Section 3 is dedicated to the detailed description of the proposed functional network model for time-series forecasting. In Section 4, the development of MSF schemes are described. The details of the case study are given in Section 5. The sets of results obtained from both MSF analysis and comparative analysis of the model are discussed in Section 6 using tabular and pictorial illustrations. Finally, Section 7 concludes the article.

2. Problem statement

The central problem tackled in this research work is very-short range MSF since it has utmost importance for power producers with renewable energy sources in decentralized power markets [47,48]. The practical issues related to this problem are: forecast accuracy for long horizons; and swiftness of predictions. Dependable prediction of wind power helps wind farm owners in bidding scheme preparation and reliability estimation required for operation planning of a power system [32,49]. For wind speed MSF, particularly very-short range (6 h ahead) forecasts are conducted because of its special significance according to the rules of competitive energy markets in many countries [50].

As already evident from the literature review, this problem is lately addressed via intelligent models or hybrid AI forecasting models [51,52]. These models are reported to be sufficiently accurate, but the major problem is their computational burden. ANN based models have relatively low computational requirement, but advanced AI models based on SVM, ANFIS etc. or hybrid models necessitate excessive computational expenses and take a fair amount of time, particularly when these techniques are combined with evolutionary optimization algorithms [26,53]. To alleviate this issue, a forecast model based on a relatively new concept in AI known as Functional Network is proposed.

Functional Network (FN) has been shown to perform better than ANN for various applications and its computational expense is comparable to ANN and much less than the above mentioned advanced AI models. To validate the proposed FN model, a case study is conducted with six steps ahead predictions using three advanced MSF mechanisms; recursive, direct and DirRec. A comparative analysis has also been presented with standard persistence benchmark model and an ANN model. The significant improvement in forecast accuracy exhibits the effectiveness and applicability of the proposed FN model for the wind forecasting problem in practical situations.

In the light of the above discussion, the aim of this work can be