Applied Energy 190 (2017) 291–305

Contents lists available at ScienceDirect

Applied Energy

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

Electricity price forecasting by a hybrid model, combining wavelet transform, ARMA and kernel-based extreme learning machine methods

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HIGHLIGHTS

- Propose a new hybrid model for day-ahead electricity price forecasting.
- Analyze complex features of prices series by wavelet transform and stationarity test.
- The proposed model has linear and nonlinear prediction abilities.
- Three real electricity markets data are used to assess the forecasting performance.
- Improve the prediction accuracy of electricity price forecasting.

ARTICLE INFO

Article history:
Received 14 February 2016
Received in revised form 19 November 2016
Accepted 27 December 2016
Available online 6 January 2017

Keywords:
Electricity price forecasting
ARMA
KELM
Wavelet transform
SAPSO

ABSTRACT

Electricity prices have rather complex features such as high volatility, high frequency, nonlinearity, mean reversion and non-stationarity that make forecasting very difficult. However, accurate electricity price forecasting is essential to market traders, retailers, and generation companies. To improve prediction accuracy using each model's unique features, this paper proposes a hybrid approach that combines the wavelet transform, the kernel extreme learning machine (KELM) based on self-adapting particle swarm optimization and an auto regressive moving average (ARMA). Self-adaptive particle swarm optimization (SAPSO) is adopted to search for the optimal kernel parameters of the KELM. After testing the wavelet decomposition components, stationary series as new input sets are predicted by the ARMA model and non-stationary series are predicted by the SAPSO-KELM model. The performance of the proposed method is evaluated by using electricity price data from the Pennsylvania-New Jersey-Maryland (PJM), Australian and Spanish markets. The experimental results show that the developed method has more accurate prediction, better generality and practicability than individual methods and other hybrid methods.

1. Introduction

In deregulated and competitive electricity markets, electricity price forecasting has become a very valuable tool for all market participants. Producers and consumers can use prediction information to adjust their production schedule and select the best bidding strategy to maximize their respective benefits. For managers of markets, the forecasting ensures healthy, stable and orderly operation of the power market. High-quality electricity price forecasting also has a very important role in power investment decisions and transmission expansion. However, accurate electricity price forecasting is a rather complex task because electricity prices have many exclusive features, such as high frequency, high volatility, nonlinearity, multiple seasonality, mean reversion, the calendar effect and price spikes [1,2].

In the recent years, many researchers have proposed different approaches to predict electricity prices. Some recently published papers and literature reviews can be found in [3–5]. According to [4], electricity price forecasting methods can be broadly summarized in five categories: multi-agent models, fundamental methods, reduced-form models, statistical approaches and computational intelligence techniques. Among the different methods, two widely used approaches are statistical approaches and computational intelligence. Statistical approaches such as exponential smoothing, auto regression (AR), moving average (MA), autoregressive moving average (ARMA), autoregressive integrated moving average (ARIMA), ARMA with exogenous variables (ARMAX) and generalized

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http://dx.doi.org/10.1016/j.apenergy.2016.12.130
0306-2619/

autoregressive conditional heteroskedastic (GARCH) methods use a mathematical combination of the previous electricity prices to predict the current electricity prices. However, statistical approaches are often criticized for their limited ability to capture the non-linear behavior of electricity prices and rapid changes in the price signal [2]. Recent computational intelligence methods have attracted considerable attention from many researchers. These methods can approximate any multivariate function to a desired degree of accuracy by adjusting weightings during online updates and can capture the complex, dynamic and non-linear features of electricity prices. Thus, the computational intelligence method has higher prediction accuracy than statistical approaches. Many authors have reported their work in electricity price forecasting using various computational intelligence methods such as artificial neural networks (ANNs), feed-forward neural networks, recurrent neural networks, fuzzy neural networks and support vector machines [6–13].

Although computational intelligence methods can process multivariable and non-linear problems, the selection of network structure and parameters is mainly dependent on experience. Furthermore, for the ANNs method, because the functional relationships among price series vary with time, some features captured by the ANNs method may lose their value as time changes [3]. Some other drawbacks associated with the ANNs method are fast convergence speed, excessive tunable parameters, slow learning rate, high possibility of entrapment in local minima, long computational time, and over-tuning [14]. These limitations often misrepresent parts of the non-linear input–output relationship and lead to unsatisfactory prediction accuracy. A new learning algorithm called the extreme learning machine (ELM) based on a single-hidden-layer feed-forward neural network (SLFN) was proposed [15]. This algorithm randomly generates the connection weight between the input and hidden layers and the threshold of neurons in the hidden layer, and parameters do not need to be adjusted during the training process. Unlike other neural network algorithms, the output matrix is obtained by minimizing the squared loss function of the least squares solution, a process that requires no iterations and greatly reduces the network parameter settling time. The ELM has been successfully applied to various prediction applications such as load, price, wind power, computer sales and bankrupt [16–27]. In kernel-based ELM (KELM), the kernel matrix replaces the randomness matrix of ELM. This method uses the kernel function to map the training samples into a high-dimensional space for training. In KELM, if the penalty factor and the kernel parameter are determinant, the output of the KELM is also fixed. Therefore, the KELM avoids the random fluctuations of the ELM. In [28], optimal kernel parameters can improve the stability and generalization of the KELM.

In newly deregulated electricity markets, uncontrollable and unpredictable contingencies increase the complexity of accurate price prediction. A single prediction model does not meet the needs of all market participants in terms of error and accuracy. The hybrid method is a better option in that it effectively combines linear and nonlinear modeling capabilities and is thus able to capture different patterns in the electricity price series data and improve the forecasting accuracy. The wavelet transform (WT) is a data preprocessing method that provides useful decomposition information in terms of time and frequency, making this method suitable for the analysis of non-stationary signals such as price series. The WT method in combination with other forecasting techniques, such as statistical models and neural network models, has been proposed in the literature for forecasting electricity prices. Tan et al. [29] proposed a novel price forecasting method based on the WT combined with the ARIMA and GARCH models. Mandal et al. [30] presented a novel hybrid technique based on the WT, the firefly (FF) algorithm, and a fuzzy ARTMAP (FA) network to forecast day-ahead electricity prices in the Ontario market. In [31], Zhang et al. presented a new method that included the WT, CLSSVM and EGARCH, and their model was applied to the marginal price (LMP) of the PJM market and market clearing price (MCP) of the Spanish market. Shayeghi and Ghasemi [32] suggested a hybrid methodology that combined the WT, the Gravitational Search Algorithm and LSSVM to predict Iran's, Ontario's and Spain's price markets. The author of [33] developed a hybrid method based on wavelet and ELM to improve the forecasting accuracy. Shafie-Khah et al. [34] presented a hybrid method based on WT, ARIMA and RBFNN; the proposed method was examined with respect to the electricity market of mainland Spain. Nguyen et al. [35] presented a forecasting model combining the WT with fixed and adaptive machine learning/time series models. Voronin and Partanen [36] used ARIMA, WT and neural networks techniques to forecast demand and price forecasting in the Nordic Power Pool. In two recent papers, Abedinia and Amjady [37] adopted a hybrid approach based on the WT, ARIMA and radial basis function neural networks to predict electricity prices in mainland Spain. Zhang et al. [38] proposed a novel hybrid method using a generalized regression neural network (GRNN) combined with the WT and a generalized GARCH model to forecast Spanish electricity prices.

Real electricity price data are nonlinear and non-stationary. Therefore, in an effective electricity price forecasting model, nonlinear and linear predictions must both be considered. After using wavelet transform, the decomposed series have more stable variances than the original series and can thus be more accurately forecasted. The ARMA is frequently applied in linear and stationary time series because of its high performance and robustness [39]. The KELM has many advantages, such as time efficiency, nonlinear capacity, and good generalization performance. Because the kernel parameters affect the generalization ability of the KELM, the KELM based on self-adapting particle swarm optimization (SAPSO-KELM) method is developed in this paper. The SAPSO-KELM is more stable and more effective than the KELM due to the optimization of its parameters by SAPSO. The integration of the WT with the ARMA and the SAPSO-KELM should be investigated to form a hybrid approach for better price forecasting. To the best of the author's knowledge, the integration of these three technologies has not been tried or applied to electricity price forecasting before. Therefore, this paper proposes a new hybrid method based on a combination of the WT, the ARMA, and the SAPSO-KELM models. The WT is used to decompose the electricity price series into stationary and volatility series. The stationary series are predicted by ARMA, whereas the non-stationary series are forecasted by the SAPSO-KELM model. The forecasted values generated separately by ARMA and SAPSO-KELM are combined so that the final predicted electricity price is generated. To illustrate the performance of the proposed model, price forecasts in the Pennsylvania-New Jersey-Maryland (PJM), the Australian and the Spanish electricity markets are calculated and compared with those obtained using the ARMA model, the KELM model, and other hybrid models, including combined models reported in the literature.

The remainder of this paper is organized as follows. Section 2 introduces the fundamental theories of the proposed method. Section 3 describes the proposed hybrid approach in detail. In Section 4, three case studies and prediction results are given. The conclusions are presented in Section 5.

2. Methodologies

In this section, we present the methodologies used for electricity price forecasting.