Electrical Power and Energy Systems 55 (2014) 100–107

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Statistical distribution for wind power forecast error and its application to determine optimal size of energy storage system

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ARTICLE INFO

Article history:
Received 9 April 2013
Received in revised form 30 August 2013
Accepted 3 September 2013

Keywords:
Wind energy
Forecast error
Statistical analysis
Energy storage system (ESS)
Probabilistic method
Optimal size of ESS

ABSTRACT

Accurate wind power forecast is an important tool for wind farm to participate in day-ahead or hours-ahead energy markets. However, forecast errors with any methodology are so large that they cannot be neglected. The forecast error needs to be analyzed individually for single wind farm to estimate the impact of this error on trading wind energy in electricity market. Although forecast error is always assumed as normal distribution, it can be demonstrated that it is not proper with a simple statistical analysis. In this paper, a mixed distribution is proposed based on laplace and normal distribution to model forecast errors associated with persistence forecast for single wind farm over multiple timescales. Then the proposed distribution is used to estimate the penalties for prediction errors in the electricity market. Energy storage system (ESS) can smooth the wind power output and make wind power more "dispatchable". A probabilistic method is proposed to determine optimal size of ESS for wind farm in electricity markets. The results indicate that the proposed distribution and probabilistic method is efficient to find optimal size of ESS.

1. Introduction

In recent years, with rapid development of wind power industry, the increased impact of wind power on power system should be taken into consideration [1]. Wind power can reduce the operating cost of system and emissions, but the imperfect prediction has negative effects on wind farm in electricity market. Although forecast problem has drawn a great deal of attention all over the world in recent years and lots of methodologies have been proposed such as simplistic persistence forecast model, statistical method and numerical weather prediction [2,3], forecast accuracy is far from satisfactoriness. When wind power participates in short-term markets, it cannot be treated as conventional generation because of its high forecast errors [4–6]. Moreover, the inaccuracy of forecast would cause additional cost as much as 10% of total generator energy incomes [4].

In order to deal with imperfect wind power prediction [7,8], system operators (SO) may increase spinning or supplemental reserve level. ESS is a prior option because it has amounts of advantages [9]. Furthermore, ESS can increase the predictability of wind power and reduce the cost of the requirements associated with spinning reserve by effective control [10]. Literatures [11–15] apply deterministic method to determine optimal ESS size. However, the characteristic of wind generation is so intermittent and stochastic that probabilistic method is more suitable for optimal sizing of ESS problem than deterministic method. Literature [16] proposed a probabilistic method based on spectral analysis of wind and solar resources combined with daily load demand and a function of the desired remaining forecast uncertainty to obtain ESS size and unserved energy. Literature [17] optimized size of ESS with unsevered energy below a well-defined limit by investigating the probability density function of the forecast errors and state of charge (SOC). Literature [18] use forecast error pdf to optimize the rated ESS power on the basis of energy rejection limit.

Probability density function (pdf) of wind power forecast can provide valid information to estimate impact of this error on trading wind energy and optimize size of ESS. Literature [19] proposed a scenario-based stochastic programming framework based on probability distribution functions of uncertain variables to model the random nature of wind forecast errors in dynamic economic emission dispatch (DEED) problem. Literature [20] use conditional value-at-risk (CVaR) methodology to estimate the risk based on probability distribution function of forecast error. Literature [21] estimates the uninstructed deviations in market based on pdf of forecast error. Wind power forecast error is usually assumed as Normal distribution [7,10,22–23]. In [24], the Gaussian distribution for wind speed prediction error combined with power curve of the wind energy conversion system is used to model power prediction error. Literature [25] estimates the aggregated power output distribution from wind farms based on Monte Carlo

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http://dx.doi.org/10.1016/j.ijepes.2013.09.003

simulation. However, the Normal assumption has been changed in a few work and weighted beta distribution together with mixed distribution are proposed by researchers as more suitable distributions [18,21].

In summary, the kurtosis of the pdf is variable form 3 to above 6 at different forecast horizon and it cannot be easy to use only one distribution to describe wind power forecast error. Furthermore, the economic benefit and cost of ESS should be taken into account in the problem of determining optimal rated ESS power by using probabilistic method. Therefore, this paper focus on the problem of finding a suitable probability density function to model forecast error and establishing a probabilistic method to find optimal ESS size.

This paper is organized as follows: In Section 2, persistence method to forecast wind power and how to calculate the forecast error with persistence method are illustrated. In Section 3, some proposed distributions are discussed and those distributions are demonstrated as inappropriate to describe the forecast error over multiple timescales. In Section 4, a novel mixed distribution based on the laplace and normal distribution is proposed to model the wind power error. In Section 5, a probabilistic method is established to find the optimal rated capacity and power of ESS.

2. Persistence for forecasting wind power

Nowadays, although a considerable variety of forecast methods have been proposed for wind power prediction all over the world, persistence method still plays an important role in short-term markets [1]. Persistence method, which is the simplest method of all, can perform nearly equally well as other advanced models in short-term horizons. Therefore, we analyze the wind power forecast error associated with persistence method.

The persistence method is based on the assumption that atmosphere is "quasi-stationary" in a few hours. Therefore, wind power could be supposed to change slowly enough so that measured power in previous k time steps can be used as forecast power k time steps ahead. The persistence forecast model can be written as expression 1:

$$P(t+k|t) = P(t) \tag{1}$$

$P(t+k|t)$ donates wind power forecast value for time $t+k$ made at original time t, k is the prediction horizon. $P(t)$ donates the measured average power for time t over an interval of length T. The prediction error ε can be calculated as following expression:

$$\varepsilon(t+k|t) = P(t+k) - P(t+k|t) \tag{2}$$

To understand persistence method well, the measured wind power and forecast over a 10 min interval are depicted in Fig. 1.

3. Evaluating existing possible distribution

The data analyzed in this study is from two geographically dispersed wind farms located in Inner Mongolia and Sinkiang, respectively. Two datasets are named as dataset A and dataset B. Dataset A contains two-year time series of 10 min measured average wind speed and wind power from 40 wind generators in wind farm A, each rated 1.5 MW, with around 1.5 million values were available for statistical analysis. In dataset B, 10 min mean values were measured form 30 wind generators in wind farm B, each rated 1.5 MW. Two datasets correspond to years 2008 and 2009.

3.1. Normal distribution model

The pdf of wind power forecast error is always assumed as normal distribution with parameters calculated by the following equations:

$$\mu_e = \frac{1}{n}\sum_{i=1}^{n} e_i \tag{3}$$

$$\sigma_e^2 = \frac{1}{n}\sum_{i=1}^{n} (e_i - \mu_e)^2 \tag{4}$$

Fig. 2 shows the pdf of 1 h forecast error and corresponding normal fit, using dataset A. It can be shown that normal distribution cannot fit the shape of the forecast error pdf.

3.2. Mixed distribution model based on laplace

Through analyze the distribution of wind speeds with the power curve of a wind turbine, wind power is always zero when wind speed is below cut-in speed or above cut-out speed, and is at its rated power between rated speed and cut-out speed [21]. A case may happen that wind power stays at its rated power when the wind speed varies between rated speed and cut-out speed. So its easy to know that forecast error could be equal to zero over an extended period of time which happens in a high probability. The situation would be similar for wind speed high enough or low enough that wind turbine generates no power. Therefore, the forecast error converges in the peak. A mixed distribution based on laplace distribution and Dirac delta function is proposed to fit pdf of forecast error:

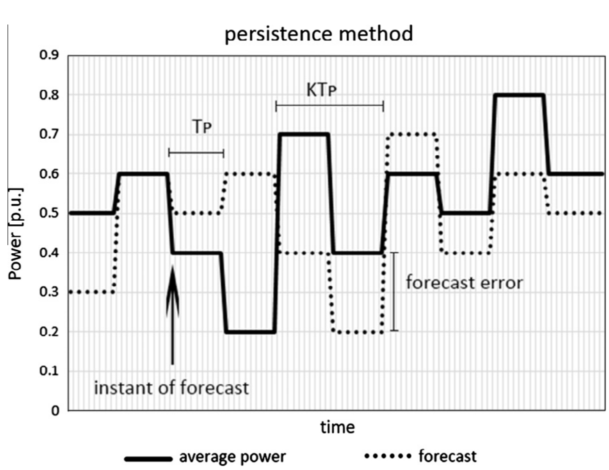

Fig. 1. Persistence method.

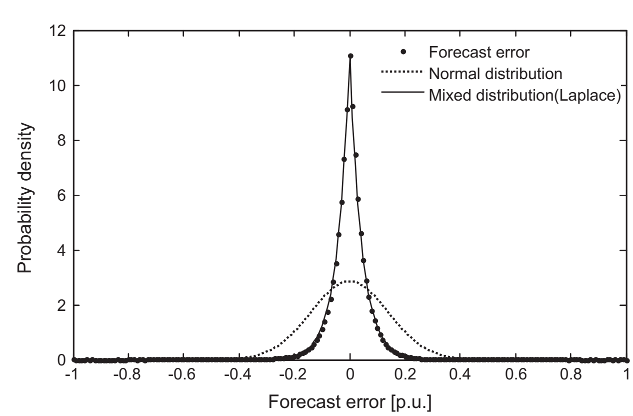

Fig. 2. Comparison of a histogram of 1-h forecast error with normal and mixed distribution based on laplace, using dataset A.