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Wind power forecasting error-based dispatch method for wind farm cluster

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Abstract With the technical development of wind power forecasting, making wind power generation schedule in power systems become an inevitable tendency. This paper proposes a new dispatch method for wind farm (WF) cluster by considering wind power forecasting errors. A probability distribution model of wind power forecasting errors and a mathematic expectation of the power shortage caused by forecasting errors are established. Then, the total mathematic expectation of power shortage from all WFs is minimized. Case study with respect to power dispatch in a WF cluster is conducted using forecasting and actual wind power data within 30 days from sites located at Gansu Province. Compared with the variable proportion method, the power shortage of the WF cluster caused by wind power forecasting errors is reduced. Along with the increment of wind power integrated into power systems, the method positively influences future wind power operation.

Keywords Wind power, Dispatch, Forecasting error, Probabilistic distribution

1 Introduction

Along with the increasing wind power penetration level in power systems, more and more wind farms (WFs) interconnect into the grid with high voltage level. However, wind speed is highly variable and site specific, and wind behaviors are different from that associated with conventional energy sources. Therefore, wind power greatly impacts on power system dispatch [1]. The curtailment of wind power is implemented in existing dispatch methods to insure power system safety, which decreases the utilization rate of wind power.

Researches have been carried out to improve wind power dispatch method from different viewpoints. Nowadays, wind power forecasting is widely used, and more attentions are paid to generation scheduling with wind power forecasting for smoothing wind power variation [2]. The active power control performances of WFs comprised of doubly fed induction generators are analyzed, and a proportional method for allocating active power according to the maximum power of each wind generator is proposed [3–5]. Based on these, an optimization strategy for allocating active power of WF is put forward to realize different optimization objectives using wind power forecasting technology [6–8]. Researches above are aimed to allocate active power in WFs, while few researches pay attention to generation scheduling in WF cluster. In [7], wind power forecasting is helpful for generation scheduling in WF cluster, by comparing dispatch methods using wind power forecasting with other methods.

In the existing dispatch methods, either for a single WF or for WF cluster, wind power forecasting is normally considered to be deterministic. However, due to the uncertainty of wind characteristics and the limitation of forecasting precision, it is difficult to accurately schedule wind power

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generation. Compared with the deterministic methods, probabilistic methods using the probability distribution of wind power forecasting data will be highly focused in the future. A probabilistic load forecasting method based on the statistics characteristic of load forecasting error is proposed for the field of short-term load forecasting [9]. A method is used for evaluating forecasting error of short-term wind power using a set of indices of the error distribution [10]. A strategy is proposed for making generating schedule, by combining day-ahead unit commitment with empirical probability density function of forecasting errors [11, 12]. The probability distribution of wind power forecasting errors is studied in dispatch. However, its application on intraday dispatch for WF cluster still needs further investigation.

A dispatch method using the probability distribution of wind power forecasting errors in WF cluster is proposed. The method takes the probability distribution of wind power forecasting errors into consideration by analyzing historical forecasting data of each WF. Then, active power is allocated for each WF in WF cluster to obtain the minimized total mathematic expectation of wind power shortage in all WFs. Through this method, the power shortage caused by forecasting errors can be minimized, and wind power can be used to participate in generating dispatch more reasonably.

2 Dispatch method for WF cluster considering probability distribution of forecasting errors

2.1 Dispatch framework

As wind power output cannot be adjusted like conventional power output of generators, wind power should track the generating schedule using wind power forecasting when it is considered in the dispatch framework. Besides, wind power should take part in frequency control [13]. The dispatch framework considering wind power is shown in Fig. 1.

The framework includes four modules: regional grid dispatch, wind power dispatch of a WF cluster, WF control, and wind generator control. The former three decide the generating schedule and then the generating schedule is sent to relative control unit and the latter executes the instruction.

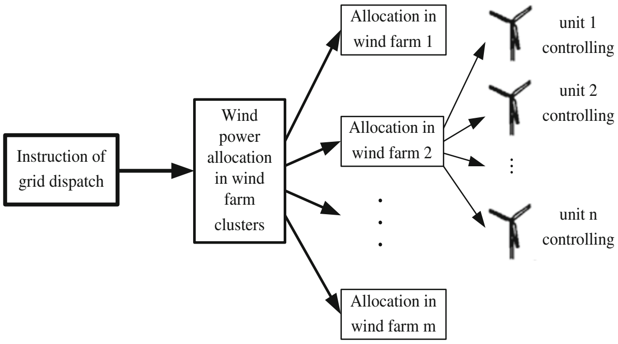


Fig. 1 Dispatch framework with wind power

In conventional power systems, dispatch schedules usually consist of day-ahead generating, daily generating and on-line generating, i.e., every 5 min one time. When wind power is integrated into the power system, correspondingly, short-term wind power forecasting can be utilized to make day-ahead and daily generating schedules, while ultra-short-term wind power forecasting can be utilized to make on-line generating schedule and allocation of active power in WFs.

2.2 Existing dispatch method in WF cluster

The variable proportion method is usually used to allocate WF power output in existing researches. The power output of a WF is allocated according to WF forecasting power shown as

$$P_i^{\text{reg}} = \frac{P_i^{\text{pre}}}{P^{\text{pre}}} P_{\text{D}}^{\text{reg}}, \tag{1}$$

where P_i^{reg} is the active power adjustment of WF i, P_i^{pre} the forecasting power of WF i, P^{pre} the forecasting power of WFs, and $P_{\text{D}}^{\text{reg}}$ the instruction of active power to be allocated in WF cluster.

2.3 Disadvantages of existing method

The forecasting wind power in variable proportion method is usually considered to be deterministic. However, due to the uncertainty of wind characteristic and the limitation of forecasting precision, deterministic methods will generate big errors between forecasting and actual wind power. When the method is used to allocate active power output of a WF, actual active power output of the WF may mismatch the dispatch command. The shortage or excess of active power output of the WF will have to be balanced by reserve generating or load shedding.

2.4 Dispatch method for WF cluster considering probability distribution of forecasting errors

With variable proportion method, the dispatch command is allocated among WFs according to different proportions. However, different WF behaviors make it difficult to achieve the expected objective. Especially, when the wind speed variation is greater, wind generators will be frequently adjusted due to unreasonable power allocation, which will decrease the service life of wind generators and increase the operation expense.

In general, analyzing the variation regularity of forecasting wind power output in a specific time interval is helpful for smoothing the fluctuation of wind power. If the regularity shows a decrease of forecasting power output of a WF, the scheduled power output should not be increased. To the contrary, the scheduled power output of the WF should avoid to be decreased. Besides, if the power output of the WF changes abruptly due to the disturbance of gusty wind, the WF should not be adjusted if possible. Therefore, WF dispatch should satisfy the following principles:

1. If the maximum forecasting power output of WFs cannot satisfy the dispatch command, all WFs should maintain to output their maximum power.
2. If the maximum forecasting power output of WFs is larger than the dispatch command, a reasonable allocation of wind power within the WF cluster should be used to satisfy the command and reduce the power variation.

Based on the principles described above, the calculation procedures are shown in Fig. 2.

The calculation procedures of the proposed method are as follows:

1. Input the historical data of forecasting and actual wind power of each WF.
2. The time series of historical forecasting and actual wind power are defined, and the errors between forecasting and actual wind powers of each WF are calculated.
3. The probability distribution model of wind power forecasting errors is determined by autoregressive moving average (ARMA) time series model.
4. The mathematical expectation E_{err} is calculated by different methods according to the type of historical data, i.e., discrete or continuous.
5. E_{err} is minimized by the genetic algorithm.
6. The power shortage of WF cluster and the utilization of wind power are evaluated.
7. The power allocation schemes of all WFs are decided.

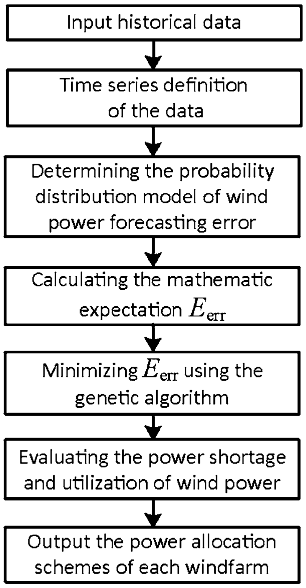


Fig. 2 Calculation procedure of the proposed method

3 Probability distribution model of wind power forecasting error

In general, the random variation of wind may generate errors between forecasting and actual values of wind speed. The errors can either be positive or negative. If the actual wind speed is larger than the forecasting one, positive errors occur, which makes WF power output exceed the dispatch command. Otherwise, negative errors occur, and WF power output will not satisfy the dispatch command.

In deterministic methods, the forecasting wind speed is considered to be accurate, and it can directly calculate WF power output. Since it is difficult for WF power output to track dispatch command, a probability method could be used to give accurate distribution characteristics of wind power forecasting errors. In addition, a statistic method is used to establish discrete probability distribution model, which reflects the regularity of wind power forecasting errors.

The historical data of forecasting and actual wind power are two basic parts of probability distribution model of wind power forecasting errors. The wind power forecasting errors at a specific time are related to the error of previous time. $\{P_{at}\}$ is defined as the time series of the historical data of the WF actual power output, and p_{ai} are samples of $\{P_{at}\}$. $\{P_{ft}\}$ is defined as the time series of the historical data of the WF forecasting power output, and p_{fi} are samples of $\{P_{fi}\}$. So the absolute error e_i between the forecasting and actual power output of WF i is calculated as

$$e_i = p_{fi} - p_{ai}. \tag{2}$$

The relative error e_{ri} between the forecasting and actual power output of WF i is calculated as

$$e_{ri} = \left(p_{fi} - p_{ai}\right)/p_{ai}. \tag{3}$$

Due to the random variation of wind speed, WF power output may reduce to zero. The denominator of Eq. (3) p_{ai} is zero and the relative error e_{ri} is large, thus the relative error is insignificance. So, the absolute error is used to establish probability distribution model of wind power forecasting errors.

The wind power forecasting errors described by the absolute error e_i can be simulated by ARMA time series model. The general expression of ARMA time series model is

$$\begin{aligned} e_i = {} & a_1 \times e_{i-1} + a_2 \times e_{i-2} + \cdots + a_n \times e_{i-n} + \varepsilon_i - b_1 \\ & \times \varepsilon_{i-1} - b_2 \times \varepsilon_{i-2} + \cdots + b_m \times \varepsilon_{i-m}, \end{aligned} \tag{4}$$

where e_i are the time series values at time i, a_i ($i = 1, 2, 3, \ldots, n$), b_j ($j = 1, 2, 3, \ldots, m$) the autoregressive and moving average parameters of the model, respectively, $\{\varepsilon_i\}$ is a normal white noise process with zero mean and a variance of σ^2.

The wind power forecasting error $\{E_i\}$ at time i is obtained from the mean wind power forecasting error μ_i, standard deviation σ and the time series value e_i are

$$E_i = \mu_i + \sigma_i e_i. \tag{5}$$

Equations (2)–(5) give the model of wind power forecasting errors. Then, the distribution characteristic of wind power forecasting errors can be obtained by the model, and the probability distribution model of wind power forecasting errors will be given.

An appropriate window width h is important for analyzing wind power forecasting errors, where h represents the window width in wind power forecasting error statistics, i.e., the window is equally divided into n parts and the width of all parts is h. When the window width h is smaller, the probability distribution model of wind power forecasting errors is more accurate and complicated. However, it may take more time to operate the dispatch algorithms. So an appropriate window width h should be chosen considering the requirements for the accuracy and calculating speed of algorithms.

After the window width h is chosen, the window number W for analyzing wind power forecasting error e_i can be calculated as

$$W = \mathrm{int}(e_i/h). \tag{6}$$

In Eq. (6), int(x) is a rounding function. So the window of e_i can be described as $[hW, h(W+1))$, and its probability in the window is described by

$$p(W) = m_{\mathrm{W}}/M. \tag{7}$$

where m_{W} represents the number of samples in the window $[hW, h(W+1))$ and M the total number of samples.

According to the theory of probability statistics, when the number of samples is large enough, empirical distribution of frequency function which represents event occurrence, is almost the same as the overall distribution density. Therefore, empirical distribution can be used to replace the probability density [9].

4 Objective function

All schedules are used to minimize the mathematic expectation E_{err} between the forecasting and actual wind power to reduce power shortage of WFs caused by wind power forecasting errors. In this paper, only the uncertainty of wind power is taken into consideration, and it is characterized by the probability distribution model of wind power forecasting errors described in Sect. 2.

According to the theory of probability statistics, mathematic expectation is the average value of a set of variables. If variables are discrete, mathematic expectation is the sum of the product of variables and their probability. If variables are continuous, mathematic expectation is the integration of the product of variables and their probability density.

The samples of wind power are discrete. However, in Eq. (6), the errors in each window are continuous. So, the probability of wind power forecasting errors can be calculated as

$$p_{\mathrm{real}} = p(\mathrm{int}((P_{\mathrm{forecast}\_n} - P_{\mathrm{real}\_n})/h)), \tag{8}$$

where P_{forecast_n} represents forecasting power output of WF n, and P_{real_n} the actual power output of WF n.

If $P_{\mathrm{real}\_n} < P_{\mathrm{dispatch}\_n}$, the power shortage of WF n is calculated by

$$P_{\mathrm{short}\_n} = P_{\mathrm{dispatch}\_n} - P_{\mathrm{real}\_n}. \tag{9}$$

Using the probability p_{real}, mathematic expectation E_{err} can be evaluated as follows.

1. Using the probability distribution model of wind power forecasting errors, window number W_n is determined as

$$W_n = \mathrm{int}(P_{\mathrm{short}\_n}/h). \tag{10}$$

Wind power forecasting errors of WF n is divided into W_n windows, i.e., $[0, h]$, $[h, 2h]$, …, $[h(W_n - 2), h(W_n - 1)]$, $[h(W_n - 1), P_{\mathrm{short}\_n}]$.

2. Mathematic expectation in each window E_{ni} is calculated as

$$E_{ni} = \int_{ha}^{h(a+1)} \frac{p(a)}{h} \cdot \left(P_{\mathrm{dispatch}\_n} - P\right) \mathrm{d}P. \tag{11}$$

3. Total mathematic expectation E_{err_n} of WF n is calculated by

$$E_{\mathrm{err}\_n} = E_{0\_n} + \sum_{a=0}^{W_{0\_n}-1} E_{ni}, \tag{12}$$

$$E_{0\_n} = \int_{h(W_{0\_n}-1)}^{P_{\mathrm{dispatch}\_n}} \frac{p_{\mathrm{real}}}{h} \cdot \left(P_{\mathrm{dispatch}\_n} - P\right) \mathrm{d}P. \tag{13}$$

4. Mathematic expectation E_{err} can be calculated by summing up E_{err_n} of all WFs, and it should be minimized as

$$E_{\mathrm{err}} = \sum E_{\mathrm{err}\_n} \to \min. \tag{14}$$

Besides, power allocation of each WF should satisfy the dispatch command:

$$P_{\text{dispatch\_all}} = \sum P_{\text{dispatch\_}n}, \tag{15}$$

$$P_{\text{dispatch\_}n} < P_{\text{ava}}, \tag{16}$$

where $P_{\text{dispatch\_all}}$ represents the dispatch command and P_{ava} the available power output of WF n.

A genetic algorithm is used to obtain power allocation schemes of each WF by minimizing the objective function described in Eq. (14). In order to observe the influences of the proposed method on the precision of power allocation in WF cluster, the power shortage of WF cluster is calculated as

$$\eta = \frac{P_{\Sigma}^{\text{ref}} - P_{\Sigma}}{P_{\Sigma}} \times 100\ \%, \tag{17}$$

where P_{Σ}^{ref} represents total power command of WF cluster, P_{Σ} the actual power output of WF cluster, and η the ratio of power shortage.

And the utilization ratio of wind power is calculated as

$$\lambda = \frac{P_{\Sigma}}{P_{\Sigma}^{\text{actual}}} \times 100\ \%, \tag{18}$$

where $P_{\Sigma}^{\text{actual}}$ represents forecasting available power output of WF cluster and λ the utilization ratio.

5 Case study

5.1 Data

Case study with respect to power dispatch of WF cluster has been conducted using forecasting and actual wind power data within 30 days obtained from WF sites at Gansu Province. The WF cluster is comprised of four WFs: the capacities of wind farms 1 (WF1) and 3 (WF3) are 200 MW, while wind farms 2 (WF2) and 4 (WF4) are 150 MW. The data are divided into two sets: (1) containing data in the former 29 days, which are used to evaluate the probability distribution of wind power forecasting errors; (2) containing data in the last day, which are used to verify the proposed method.

Figure 3 shows the total power output of the WF cluster.

The historical forecasting and actual power output of each WF is shown in Figs. 4, 5, 6, and 7. It can be seen that actual power output of all WFs deviates from forecasting values with different frequencies and magnitudes, which may result in power output shortage or WF cluster excess.

Then probability distributions of wind power forecasting errors of all WFs are analyzed using the model presented in Sect. 3. The probability distributions of each WF are shown in Fig. 8.

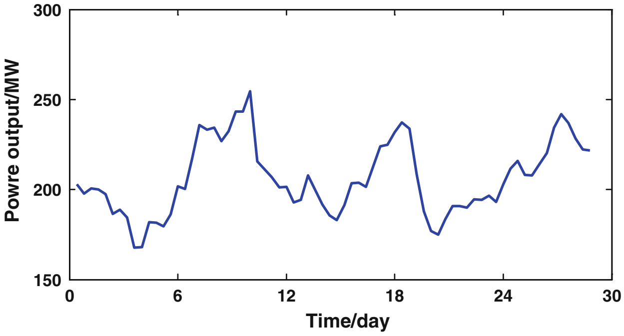


Fig. 3 Total power output of the wind farm cluster in Gansu Province in 30 days

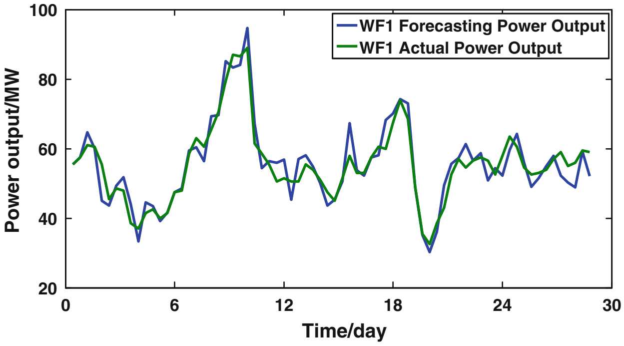


Fig. 4 Forecasting and actual power output of wind farm 1

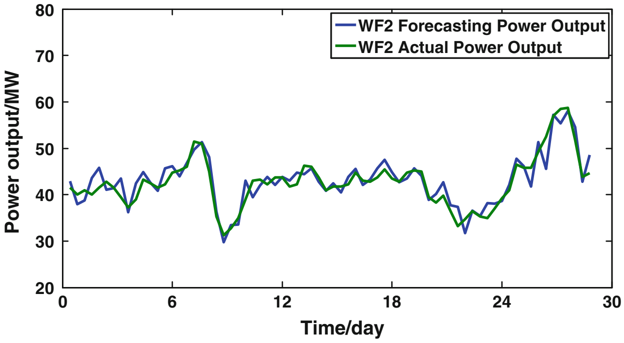


Fig. 5 Forecasting and actual power output of wind farm 2

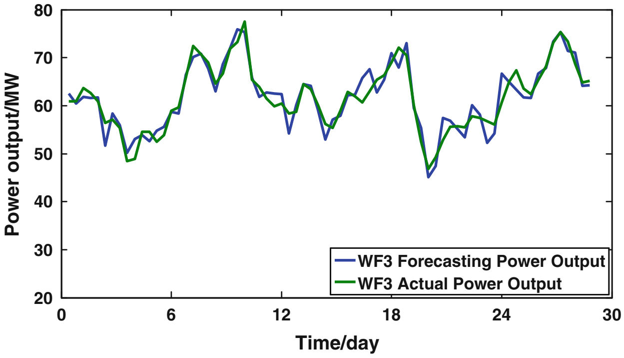


Fig. 6 Forecasting and actual power output of wind farm 3

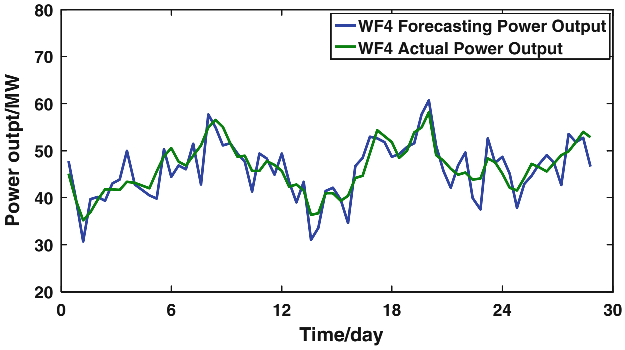


Fig. 7 Forecasting and actual power output of wind farm 4

Figure 8 shows that the probability distributions of forecasting errors are approximate to normal distribution in all WFs. However, all actual distributions shown in Fig. 8 are irregular due to wind power curtailment. By analyzing the forecasting errors, the standard variances of each probability distribution can be obtained, i.e., 15.36, 4.54, 5.09, and 10.37 for WF1, WF2, WF3, WF4, respectively. Table 1 shows other concrete data.

5.2 Analysis results

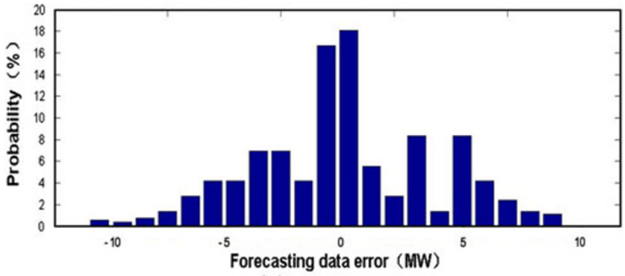
5.2.1 *Comparison with different confidences*

The proposed method is verified in four cases considering different confidences of wind power forecasting. The confidences are selected as 99, 90, 60, and 15 %. Table 2 shows power shortage of the WF cluster at different confidence levels.

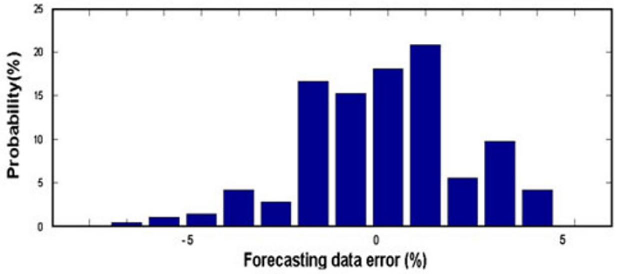
Table 2 shows that:

1. Compared with variable proportion method, power shortage ratio is reduced by the proposed method. Therefore, considering the confidence of wind power forecasting and the probability distribution of forecasting errors, power output of WF cluster can better track the dispatch command.
2. Along with the increasing confidence of wind power forecasting, the differences of power shortage decrement between the two methods are reduced. In general, high confidence implies high forecasting precision. So the generating schedules of the WF cluster made by both methods can well track the dispatch command when forecasting confidence is high enough. To the contrary, the generating schedule made by the proposed method will lead to less power shortage.

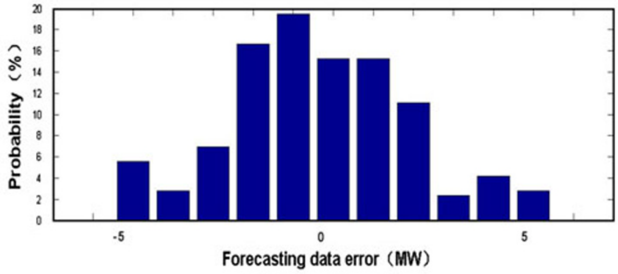
5.2.2 *Comparison of different standard variances*



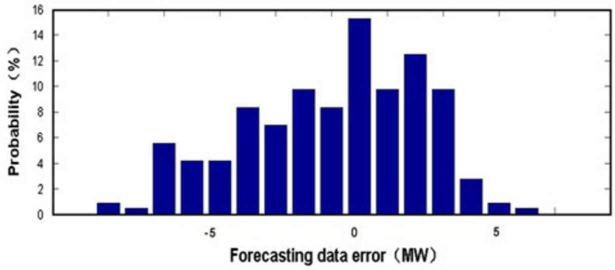
(a) Wind farm 1



(b) Wind farm 2



(c) Wind farm 3



(d) Wind farm 4

Fig. 8 Probability distribution model of wind power forecasting error

Table 1 Historical data statistics of wind power forecasting errors

WFs	Upper limit (MW)	Lower limit (MW)	Average (MW)	Standard variance
WF1	−10.5646	9.2405	0.1856	15.3636
WF2	−6.9831	4.3248	0.3600	4.5385
WF3	−4.7411	5.9401	0.0268	5.0887
WF4	−8.3135	6.5533	−0.4100	10.3668

Assuming that the confidence of wind power forecasting is 60 %, the effectiveness of the proposed method is analyzed by comparing power shortage ratios of different WFs. The probability distributions of wind power forecasting errors in different WFs are shown in Fig. 8. The

Table 2 Power shortage in different confidences

Confidence (%)	15	60	90	99
Shortage ratio by variable proportion method	3.09	1.15	0.31	0
Shortage ratio by proposed method	2.35	0.68	0.11	0
Decrement of shortage	0.74	0.47	0.20	0
Wind power utilization by variable proportion method	81.09	89.90	94.52	97.83
Wind power utilization by proposed method	81.09	89.93	94.60	98.01

Table 3 Calculation results of power shortage ratio in different wind farms (%)

WFs	Shortage ratio by variable proportion method	Shortage ratio by proposed method	Decrement of shortage
WF1	1.69	1.18	0.51
WF2	0.95	0.88	0.07
WF3	0.65	0.40	0.25
WF4	1.10	0.11	0.99

standard variances of probability distributions are given in Table 1. Table 3 shows power shortage of the WF cluster with variable proportion method and the proposed method, respectively.

Table 3 shows that:

(1) Power shortage ratio by the proposed method is smaller than variable proportion method.
(2) If the installation capacity of WFs increases, the power shortage ratio of WFs increases, for instance in WF1 and WF4, when the standard variances of wind power forecasting errors are the same.
(3) Large standard variances can increase power shortage of a WF. Thus, the effectiveness of the proposed method is more obvious when the standard variance of the probability distribution of wind power forecasting errors is large. The power shortage reduction is compared between WF1 and WF3, which have the same installation capacity. The power shortage reduction of WF1 is 0.51 %, while that of WF3 is 0.25 %. Similarly, power shortage reduction of WF4 is 0.99 %, while that of WF2 is 0.07 %.

6 Conclusion

With increasing penetration level of wind power, wind power forecasting errors in grid dispatch are important to balance the power fluctuation caused by wind variations. This paper focuses on the study of grid dispatch method with large-scale wind power. A wind power forecasting error-based dispatch method of WF cluster is proposed. By comparing the variable proportion method, the results show that the proposed method can accurately allocate active power in WF cluster considering probability distribution of wind power forecasting errors. Using the method, power shortage of WF cluster can be obviously reduced. Therefore, the method can assist power system operators to make reasonable generating schedules.

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