A Day-Ahead Economic Dispatch Method Considering Extreme Scenarios Based on Wind Power Uncertainty Set

Jian Xu, *Member, IEEE*, Bao Wang, Yuanzhang SUN, *Senior Member, IEEE*, Qi XU, Ji Liu, Huiqiu Cao, Haiyan JIANG, Ruobing LEI and Mengjun Shen

***Abstract*—As the intermittency of wind power is getting more concern in the day-ahead economic dispatch, this paper proposes a day-ahead economic dispatch method considering extreme scenarios of wind power by using an uncertainty set. The uncertainty set inspired by robust optimization is used to describe wind power intermittency in this paper. Four extreme scenarios based on the uncertainty set are formed to represent the worst cases of wind power fluctuation. An economic dispatch method considering the costs of both load shedding and wind curtailment is proposed. The economic dispatch model can be easily solved by a quadratic programming method owing to the introduction of four extreme scenarios and the uncertainty set of wind power. Simulation is done on the IEEE 30-bus system and the results verify the effectiveness of the proposed method.**

***Index Terms*—Economic dispatch, extreme scenarios, uncertainty set, wind power.**

I. INTRODUCTION

THE rapid development of wind power integration has posed unprecedented challenges to traditional power systems in recent years [1-5]. As a kind of renewable energy, wind energy has attracted widespread concern and support worldwide [6], which will account for 11% of Chinese entire installation capacity by 2020 [7]. With large-scale wind power integrated into the power system, the economic dispatch (ED) problem is getting more and more complicated. To make the grid functioning within the security limit, strategies are adopted either by increasing the cost or abandoning those wind power. Although forecast precision has been improved [8], due to the intermittency of wind power, forecast error is still an intractable problem for the ED, especially in those extreme scenarios when the spinning reserve cannot compensate for the error.

There are three kinds of methods to solve the noted problem about those extreme conditions in previous literatures: 1) deterministic optimization (DO) method [9], in which integrated wind power is forecasted as a constant value in a dispatch period and the determined proportion of installed wind power capacity is used as reserve capacity to deal with wind power intermittency; 2) stochastic optimization (SO) method [10-15], in which chance constraints exist and integrated wind power is analyzed as an approximate distribution function with a large diversity of forms and parameters; and 3) robust optimization (RO) method [16, 17], in which integrated wind power is described as an uncertainty set.

However, the forecasting error of wind power varies a lot with different prediction level, which means DO method disregarding much detailed numerical characteristics of wind power data. For instance, In [9], an EIPSO algorithm is used to solve the optimal spinning reserve and ED for a wind-thermal power system, in which the output of wind power is approximated by a 3-order polynomial function of wind speed. In [10], a beta distribution function is utilized to describe the uncertainty of wind power, in which the parameters of beta distribution are not accurate as only the mean value and standard deviation of the predicted wind power are used. In [11], with the assumption of normal distributions of wind speed and load forecast errors, the proposed method can convert probabilistic constraints into deterministic inequality constraints and investigate the optimal allocation of generators to satisfy the constraints of the power system. The details on forecast errors are not fully considered in these methods. Thus, the intermittency of wind power can not be adequately described.

Though, the intermittency was taken into consideration in SO method, and being included to generating costs, the whole model became intricate in the meantime. In [12] and [13], probability distributions for wind power forecast error and wind speed are applied in the ED, in which underestimation and overestimation costs are described in the form of integral. In [14], the random nature of wind power is modelled using a Weibull probability distribution function, and chemical reaction optimization can well solve the combined economic and emission dispatch problem. In [15], an ED method considering the uncertainty and correlation of wind power is proposed, where chance constraints exist. The integral form or

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J. XU, Y. SUN, J. Liu, H. Cao, H. JIANG, and M. Shen are with School of Electrical Engineering, Wuhan University, Wuhan, 430072, China.

B. WANG (Corresponding author, e-mail: wangbao2013@whu.edu.cn) is with Guangzhou Power Supply Bureau Co., Ltd., Guangzhou, 510620, China.

Q. XU is with Electric Power Research Institute of Guangdong Power Grid Co., Ltd., Guangzhou, 510080, China.

R. LEI is with Suzhou Power Supply Bureau Co., Ltd., Suzhou, 215000, China.

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chance constraints make the solving process of these methods complicated.

Instead of describing the statistic property of wind power, the RO method attempt to deal the uncertainty of wind fluctuation with some extreme scenarios. In [16], a game theory model for the robust ED with wind power and plug-in electric vehicles is proposed, in which the worst case of wind power output is considered. In [17], a robust interval wind power optimization method for look-ahead power dispatch is proposed. The solution may be excessively conservative by using these methods. To avoid an excessively conservative solution, the parameter г (between 0 and T) is introduced to represent the degree of conservatism, while the appropriate г is hard to determine to balance conservatism and robustness of the solution [18]. In [19, 20], the wind power output extreme scenarios are obtained by Monte Carlo sampling with the appropriate г, while the random sampling may lead to the results unique.

In this paper, a day-ahead economic dispatch method considering extreme scenarios based on wind power uncertainty set is proposed. An appropriate uncertainty set is utilized to describe the intermittency of wind power and the extreme scenarios are obtained to represent the worst wind power output. The proposed method calculates average operating costs by considering the four possible extreme scenarios of wind power. The methods of this work are briefly summarized as follows:

1) The intermittency of wind power is adequately described by using detailed information on forecast errors with forecast bins. The proposed method allocates appropriate reserve capacity to deal with wind power intermittency under the premise of system safety. Utilizing an appropriate uncertainty set, the proposed method requires minimal information on the detailed distribution model and corresponding parameters of wind power forecast errors.

2) The four extreme scenarios are selected to represent the worse wind power output scenarios, which can avoid an excessively conservative solution by considering the worst wind power output and can avoid the randomness by Monte Carlo sampling of various wind power output scenarios. Based on the extreme scenarios and uncertainty set of wind power, and with the introduction of variables and constraints for load shedding and wind curtailment, the optimization ED model with uncertainty is transformed into a deterministic optimization ED model. The transformed ED model is easy to implement without complex derivation and procedures.

The remaining of this paper is organized as follows. In Section II, the uncertainty set and four extreme scenarios of wind power are described. The economic dispatch formulation considering extreme scenarios based on wind power uncertainty set is established in Section III. The modified IEEE 30-bus system is used for case study to evaluate the proposed method in Section IV. The conclusions are drawn in Section V.

II. Description of Wind Power

A. Wind Power Uncertainty

An appropriate wind power uncertainty set is important for the proposed method. A too big set will make the results too conservative and a too small set can hardly include almost all wind power scenarios, which may cause serious load shedding or wind curtailment. Thus, the forecast bins [21] are introduced to determine the appropriate uncertainty set.

First, the data of wind power forecasts and corresponding measurements are normalized varying within [0, 1]. The standard interval is divided into 20 bins equally to ensure adequate data in each forecast bin. For each bin, the forecast error of each wind power forecast data can be calculated by

$$P_{w,t}^{error} = (P_{w,t}^{actual} - P_{w,t}^{fcst}) / P_{w,t}^{fcst} \tag{1}$$

where $P_{w,t}^{error}$, $P_{w,t}^{actual}$ and $P_{w,t}^{fcst}$ are the forecast error, actual value and forecast value of wind power at t, respectively.

The empirical cumulative distribution function (ECDF) of wind power forecast errors in each bin can be obtained by counting the probability density histogram (PDH) [13]. For each day-ahead forecast value, the 0.05-quantile $\alpha_{0.05}$ and 0.95-quantile $\alpha_{0.95}$ of the corresponding wind power forecast error distribution can be obtained according to the corresponding ECDF of each bin. The minimum and maximum of the possible wind power at t, denoted as $P_{\min,t}^{Wind}$ and $P_{\max,t}^{Wind}$ respectively, can be expressed as

$$\begin{cases} P_{\min,t}^{Wind} = (1 - \alpha_{0.05}) \cdot P_{w,t}^{fcst} \\ P_{\max,t}^{Wind} = (1 + \alpha_{0.95}) \cdot P_{w,t}^{fcst} \end{cases} \tag{2}$$

Consequently, the wind power uncertainty set, denoted as D, can be expressed as

$$P_{w,t} \in D = \left\{ P_{w,t} : P_{\min,t}^{Wind} \le P_{w,t} \le P_{\max,t}^{Wind}, \forall t \in T \right\} \tag{3}$$

where $P_{w,t}$ is the possible wind power and T is the time point set during one dispatch period.

The uncertainty set D is described as a parallelotope perturbation set, which makes it easy to solve linear optimization problems and quadratic problems [22, 23]. Moreover, the parallelotope perturbation set is easy to obtain extreme scenarios for the economic dispatch model.

B. Extreme Scenarios of Wind Power

From the perspective of probability theory, the probability of any single scenario is almost zero. However, for the actual wind power output, the worst scenario could cause wind curtailment or load shedding, and may even result in system instability. In other words, a little probability event (worst scenario) may have great impact on system security. For a power system with high security requirement, it is necessary to consider the worst scenario of wind power output.

In this paper, four extreme scenarios with physical meaning are introduced to avoid excessive conservatism of the solution. As the uncertainty set is obtained in the previous section, two kinds of wind power fluctuation are employed to depict the extreme scenarios. The first kind is the extreme wind power output, which means the entire wind power is either minimum or maximum. The other one is the extreme wind power ramping, which represents the wind power fluctuates between the minimum and maximum of the wind power uncertainty set. The four extreme scenarios can be expressed as

$$\begin{cases} P_{w,t}^{worse1} = P_{\max,t}^{Wind}, \forall t \in T \\ P_{w,t}^{worse2} = P_{\min,t}^{Wind}, \forall t \in T \\ P_{w,t}^{worse3} = h_t^{+} \cdot P_{\max,t}^{Wind} + h_t^{-} \cdot P_{\min,t}^{Wind}, \forall t \in T \\ P_{w,t}^{worse4} = h_t^{-} \cdot P_{\max,t}^{Wind} + h_t^{+} \cdot P_{\min,t}^{Wind}, \forall t \in T \end{cases} \quad (4)$$

Where $P_{w,t}^{worse1}$ and $P_{w,t}^{worse2}$ are the extreme wind power output scenarios. $P_{w,t}^{worse3}$ and $P_{w,t}^{worse4}$ are extreme wind power ramping scenarios. When t is odd, h^{+}_{t}=1, h^{-}_{t}=0. When t is even, h^{+}_{t}=0, h^{-}_{t}=1.

The extreme maximum output scenario and the extreme minimum output scenario are opposite, and the extreme ramping scenarios of wind power also share those totally opposite tendency. By considering both kinds of opposite extreme scenarios, the solution can avoid excessive conservatism but still maintain robustness and can also avoid being conservative for ED.

III. DAY-AHEAD ECONOMIC DISPATCH MODEL

A. Objective Function

The objective function of this model is to minimize total costs, which contains fuel costs and average penalty costs for extreme scenarios. That is,

$$\begin{aligned} \min F = & \sum_{t=1}^{T}\sum_{i=1}^{I}\left(a_i P_{i,t}^2 + b_i P_{i,t} + c_i\right)\cdot I_{i,t} \\ & + \frac{1}{S}\cdot\sum_{t=1}^{T}\sum_{s=1}^{S}\left(\alpha \cdot P_{s,t}^{Wcut} + \beta \cdot P_{s,t}^{Dcut}\right) \end{aligned} \quad (5)$$

where a_i, b_i and c_i are the fuel cost parameters. $I_{i,t}$ and $P_{i,t}$ represent the unit state and schedule of the generator i at t, respectively. α and β represent the penalty coefficient for wind curtailment and load shedding, respectively. $P_{s,t}^{Wcut}$ and $P_{s,t}^{Dcut}$ represent wind curtailment and load shedding at t for the extreme scenario s, respectively. I and S are the number of thermal generators and extreme scenarios, respectively.

B. Constraints

Aiming to minimize the total costs of the day-ahead generation dispatch, the presented model considers four extreme scenarios as the worst cases to better weight security and economy. In the day-ahead ED model, following constraints are included.

1) Active power balance constraints for dispatched wind power and four extreme scenarios are expressed as:

$$\sum_{i=1}^{I} P_{i,t} + P_{dis,t}^{Wind} = \sum_{b=1}^{N} P_{b,t} \quad \forall t \quad (6)$$

$$\sum_{i=1}^{I} P_{i,t} + P_{s,t}^{Wind} - P_{s,t}^{Wcut} = \sum_{b=1}^{N} P_{b,t} - P_{s,t}^{Dcut} \quad \forall s, \forall t \quad (7)$$

where $P_{dis,t}^{Wind}$ is the dispatched wind power at t. $P_{b,t}$ is the load of the bus b at t. $P_{s,t}^{Wind}$ is the extreme wind power for the extreme scenario s at t. N is the number of buses.

2) The generation output constraint is expressed as:

$$P_{i\min} \cdot I_{i,t} \le P_{i,t} \le P_{i\max} \cdot I_{i,t} \quad \forall i, \forall t \quad (8)$$

where $P_{i\min}$ and $P_{i\max}$ are the minimum output and maximum output of the generator i, respectively.

3) The ramping rate limit constraints are expressed as:

$$\begin{cases} P_{i,t} - P_{i,t-1} \le P_{i\max} \cdot \left(2 - I_{i,t-1} - I_{i,t}\right) + R_i \cdot \left(1 + I_{i,t-1} - I_{i,t}\right) \\ P_{i,t-1} - P_{i,t} \le P_{i\max} \cdot \left(2 - I_{i,t-1} - I_{i,t}\right) + U_i \cdot \left(1 - I_{i,t-1} + I_{i,t}\right) \end{cases} \forall i, \forall t \quad (9)$$

where R_i and U_i are the upward and downward ramping rate of the generator i, respectively.

4) Adequate spinning reserve capacity is required to keep power balance as actual intra-day wind power fluctuates within the uncertainty set D. The constraints can be expressed as:

$$\begin{cases} R_{i,t}^{up} \le \left(P_{i\max} - P_{i,t}\right)\cdot I_{i,t} \\ R_{i,t}^{up} \le R_i \cdot I_{i,t} \\ R_{i,t}^{down} \le \left(P_{i,t} - P_{i\min}\right)\cdot I_{i,t} \\ R_{i,t}^{down} \le U_i \cdot I_{i,t} \\ P_{\max,t}^{Wind} - P_{dis,t}^{Wind} \le \sum_{i=1}^{I} R_{i,t}^{down} \\ P_{dis,t}^{Wind} - P_{\min,t}^{Wind} \le \sum_{i=1}^{I} R_{i,t}^{up} \end{cases} \forall i, \forall t \quad (10)$$

where $R_{i,t}^{up}$ and $R_{i,t}^{down}$ are the upward and downward spinning reserve capacity of the generator i at t, respectively.

5) Transmission capacity constraints of the lines for the optimal dispatched wind power and four extreme scenarios are expressed as:

$$\underline{P_{ij}} \le \sum_{i=1}^{N_{Bg}} k_{mn} \cdot P_{i,t} - \sum_{d=1}^{N_{Bd}} k_{md} \cdot P_{Dd} \le \overline{P_{ij}} \quad \forall t \quad (11)$$

$$\underline{P_{ij}} \le \sum_{i=1}^{N_{Bg}} k_{mn} \cdot P_{i,t} - \sum_{d=1}^{N_{Bd}} k_{md} \cdot P_{Dd,s} \le \overline{P_{ij}} \quad \forall s, \forall t \quad (12)$$

where k_{mn} and k_{md} are the distribution factors of the transmission lines [24]. $P_{Dd,s}$ represents the net load at the load bus d under the extreme scenario s of wind power. P_{Dd} represents the net load at the load bus d for the dispatched wind power. Wind power is treated as a negative load. $\underline{P_{ij}}$ and $\overline{P_{ij}}$ represent the lower and upper power flow limit of the transmission line ij. N_{Bg} and N_{Bd} represent the number of generator buses and the net load buses, respectively.

6) Load shedding constraints for four extreme scenarios are expressed as:

$$\begin{cases} (P_{d,t} - \sum_{i=1}^{I} P_{i,t}) - P_{s,t}^{Wind} \le P_{s,t}^{Dcut} \\ 0 \le P_{s,t}^{Dcut} \le \gamma \cdot P_{d,t} \end{cases} \quad \forall s, \forall t \quad (13)$$

where $P_{d,t}$ is the total load of the system at t. γ is the maximum allowable load shedding percentage.

7) Wind curtailment constraints for four extreme scenarios are expressed as

$$\begin{cases} P_{s,t}^{Wind} - (P_{d,t} - \sum_{i=1}^{I} P_{i,t}) \le P_{s,t}^{Wcut} \\ 0 \le P_{s,t}^{Wcut} \le P_{s,t}^{Wind} \end{cases} \quad \forall s, \forall t \quad (14)$$

8) The dispatched wind power and extreme wind power scenarios should be limited within the uncertainty set. The wind

power constraints can be expressed as

$$P_{s,t}^{Wind}, P_{dis,t}^{Wind} \in D \quad \forall s, \forall t \tag{15}$$

Overvalued and undervalued penalty costs of wind power can be easily calculated by adopting above mentioned constraints. If the actual wind power is greater than the dispatched wind power, which means the wind power is undervalued, the wind power needs to be curtailed. According to (14), $P_{s,t}^{W\text{cut}}$ should be no less than the part of the undervalued wind power. Also, due to the restriction of (13), $P_{s,t}^{D\text{cut}}$ should not be smaller than zero. In order to minimize the total costs, $P_{s,t}^{W\text{cut}}$ and $P_{s,t}^{D\text{cut}}$ should be equal to the undervalued part of the forecast wind power and zero, respectively. The penalty coefficient α of wind curtailment should be smaller than the penalty coefficient β of load shedding. Similarly, if the actual wind power is smaller than the dispatched wind power, which means the wind power is overvalued, $P_{s,t}^{D\text{cut}}$ and $P_{s,t}^{W\text{cut}}$ should be equal to the overvalued part of the forecast wind power and zero, respectively. Actually, the costs of load shedding are spent for the system upward spinning reserve, which is used to maintain active power balance and avoid load shedding.

C. *Solution of the Model*

The proposed day-ahead economic dispatch model can be expressed by (5)-(15). The process of solving the proposed model is described as below.

Step 1) Normalize the history data of wind power forecasts and corresponding measurements varying within [0, 1]. Divide the standard interval into 20 bins with 0.05p.u. bin width to ensure adequate data in each forecast bin. The wind power data pairs [*measured*, *forecast*] are sorted by forecast values and assigned to matching forecast power bins.

Step 2) In each bin, calculate the forecast error of each wind power history data by (1) and obtain the ECDF of wind power forecast error by counting the probability density histogram (PDH). Then, obtain the 0.05-quantile $\alpha_{0.05}$ and 0.95-quantile $\alpha_{0.95}$ of the corresponding wind power forecast error distribution in each bin.

Step 3) Based on the day-ahead wind power forecast curve, calculate the minimum and maximum of possible wind power at different time by (2). Then, obtain the day-ahead wind power uncertainty set *D* by (3).

Step 4) Obtain four extreme scenarios of wind power fluctuations by (4). The boundary of the uncertainty set, as well as the extreme output scenarios, is described by the upper and lower bound of wind power. The extreme wind power ramping scenarios are built by setting wind power fluctuating between the minimum and maximum of possible wind power in sequence.

Step 5) Input parameters of the generators, transmission lines and forecast system load. With the introduction of variables and constraints for load shedding and wind curtailment by (7), (13) and (14), establish the day-ahead economic dispatch optimization model by (5)-(15).

Step 6) Solve the optimization problem by quadratic programming (QP) and output the day-ahead scheduled power of the wind farm and thermal plant.

The flowchart of above procedures is shown in Fig.1.

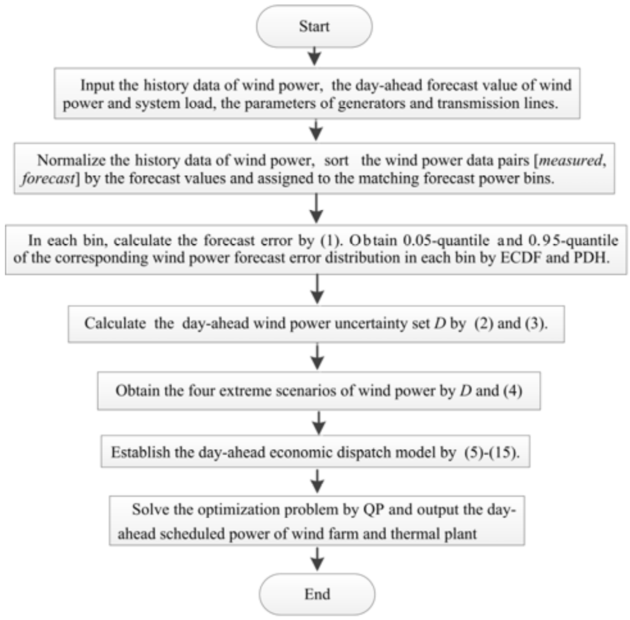

Fig. 1. Flowchart of the day-ahead economic dispatch method considering extreme scenarios.

IV. CASE STUDY

In this section, the proposed day-ahead economic dispatch model is verified on the IEEE 30-bus system with a wind farm connected at the bus 15, as illustrated in Fig.2. The installed capacity of the wind farm is 150MW. The original data of the wind power and system load are from the Ireland's power system [25]. The corresponding day-ahead forecast curves for the wind power and system load are shown in Figure 3. The unit commitment results of the system and other data of the IEEE 30-bus system are listed in Appendixes.

The spinning reserve capacity in the DO method is kept no less than 25% of the wind farm installed capacity. The penalty coefficient α (underestimation cost coefficient) for wind curtailment is 80$/MW and the penalty coefficient β (overestimation cost coefficient) for load shedding is 160$/MW [26]. The maximum allowable load shedding percentage γ is set to be 5%.

As described in Section 1 and Section 3, considering detailed information on forecast error, the proposed method can keep an appropriate reserve capacity with respect to the DO method. By introducing forecast bins and extreme scenarios, the proposed method can overcome the fitting error caused by the distribution function and the difficult solving problem with respect to the SO method. Besides, the proposed method can also avoid an excessively conservative solution by considering both kinds of opposite extreme scenarios with respect to the RO method, in which only the worst scenario is considered. Thus, the DO method, SO method in [13], and RO method in [16] are all employed here for comparison. The four methods are compared in five aspects: 1) dispatched wind power curves, 2) spinning reserve capacity, 3) branch power flow of the system, 4) costs of system, and 5) computation time.

For the DO method, the spinning reserve capacity is kept no less than 25% of the installed capacity of the wind farm and QP is adopted to solve the corresponding optimization model. For the SO method, the versatile probability distribution and the SLP-based algorithm proposed in [13] are used to describe wind power distribution and solve the corresponding optimization model, respectively. For the RO method, the uncertainty set is the same as that of the proposed method and the two-stage relaxation algorithm proposed in [16] is adopted to solve the min-max optimization. The computation is completed in MATLAB R2014a on an Intel Xeon E5-2620 2.10-GHz desktop computer with 48-GB memory.

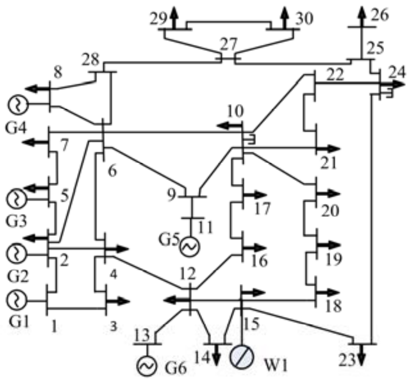

Fig. 2. Modified IEEE 30-bus system.

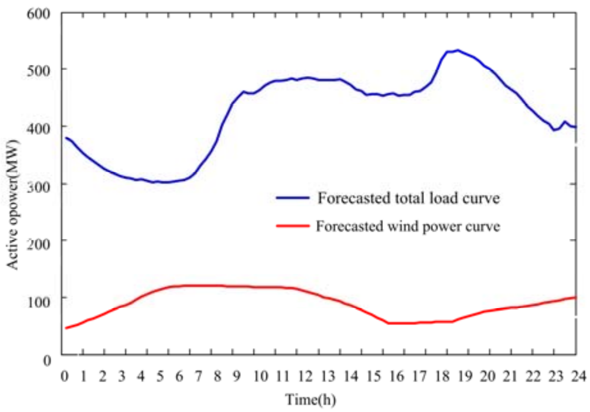

Fig. 3. Day-ahead forecasted wind power and total load curves.

A. *Obtaining of Uncertainty Set*

The forecast and actual data of wind power from the Ireland's power system are used to obtain the uncertainty set *D*. The data was dated from January 1, 2012 to December 31, 2013. The time step of the wind power data is 15 minutes. To make a balance between data size and data scope in every bin [21], the wind power data are divided into 20 bins. The uncertainty set *D* is obtained by calculating $\alpha_{0.05}$ and $\alpha_{0.95}$ of each bin, which are listed in Table I.

For different forecast levels of wind power, the corresponding $\alpha_{0.05}$ and $\alpha_{0.95}$ of the forecast error distribution are different. For a lower forecast output level, the forecast error is usually relatively larger. For a higher forecast output level, the forecast error is usually relatively smaller. By introducing the forecast bin, more information on forecast error can be used to obtain the appropriate uncertainty set, which can keep robustness and avoid excessive conservatism of the solution.

TABLE I
THE 0.05-QUANTILE AND 0.95-QUANTILE IN EACH BIN

No.	Forecast range(p.u.)	0.05-quantile(p.u.)	0.95-quantile(p.u.)
1	[0.00 , 0.05)	-0.7481	2.2310
2	[0.05 , 0.10)	-0.6320	0.9783
3	[0.10 , 0.15)	-0.4842	0.7836
4	[0.15 , 0.20)	-0.4019	0.6067
5	[0.20 , 0.25)	-0.4090	0.4871
6	[0.25 , 0.30)	-0.3792	0.4328
7	[0.30 , 0.35)	-0.3679	0.3625
8	[0.35 , 0.40)	-0.3707	0.2975
9	[0.40 , 0.45)	-0.3629	0.2495
10	[0.45 , 0.50)	-0.3367	0.2028
11	[0.50 , 0.55)	-0.3383	0.1628
12	[0.55 , 0.60)	-0.3533	0.1369
13	[0.60 , 0.65)	-0.3492	0.1158
14	[0.65 , 0.70)	-0.3438	0.1017
15	[0.70 , 0.75)	-0.2953	0.0707
16	[0.75 , 0.80)	-0.3218	0.0355
17	[0.80 , 0.85)	-0.3064	0.0226
18	[0.85 , 0.90)	-0.3422	0.0000
19	[0.90 , 0.95)	-0.2900	-0.0397
20	[0.95 , 1.00]	-0.2294	-0.0685
Total	[0.00 , 1.00]	-0.4633	0.5614

B. *Test Results*

1) *Dispatched Wind Power Curves*

The dispatched wind power curves and extreme wind power curves are all illustrated in Fig.4. The day-ahead forecast wind power curve is illustrated by red line, which is also used as the dispatched wind power of the DO method. The boundary of the uncertainty set, as well as the extreme output scenarios, is described by the upper and lower bound of the wind power. The extreme wind power ramping scenarios are built by setting wind power fluctuating between the minimum and maximum of possible wind power in sequence. The dispatched wind power curves of the proposed optimization (PO), DO, SO and RO methods are plotted by black, red, yellow, and pink line respectively. The worst wind power curve of RO method is plotted by the dark blue dotted line, which fluctuates between the minimum and maximum of the wind power uncertainty set. And it is obtained by the two-stage relaxation algorithm proposed in [16], which may lead to the excessively conservative solution.

For the DO method, the day-ahead forecasted wind power is used as the dispatched wind power, by which the forecast error of wind power is not considered in detail. For the SO method, the dispatched wind power is close to the forecast wind power to minimize the average costs. Due to the fitting errors of the versatile probability distribution and the constraints of the model, the dispatched wind power of the SO method is different from that of the DO method. For the RO method, the dispatched wind power is smaller than that of other three methods to minimize the total costs considering the worst wind power. For the PO method, the dispatched wind power considers the possible four extreme scenarios of wind power to minimize the average costs. When the forecast wind power is small and the system total load is large (T=15~20h), the dispatched wind power of the PO method is as much as possible to keep power balance and minimize the total cost under the premise of system safety. At the same time, all the actual wind power points belong to the set of uncertainty and the surplus or shortage of wind power at each time slot can be indirect indicated in Fig.4.

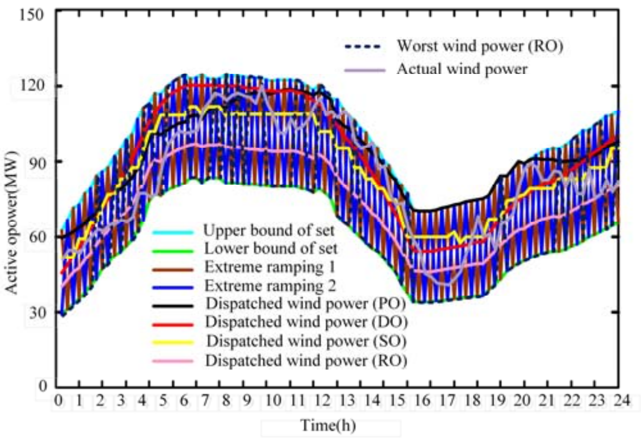

Fig. 4. Wind power curves for four methods.

2) *Spinning Reserve Capacity*

The upward and downward spinning reserve capacities of the system for the four methods are illustrated by the bar charts in Fig.5, Fig.6, Fig.7, and Fig.8, respectively. When wind power fluctuates within the uncertainty set *D*, the maximum requirement for upward and downward reserve with respect to the corresponding dispatched wind power are also illustrated by the red and black curves. As shown, with the same wind power the uncertainty set *D*, the upward and downward reserve of the system and the maximum requirement for upward and downward reserve are different in the four methods.

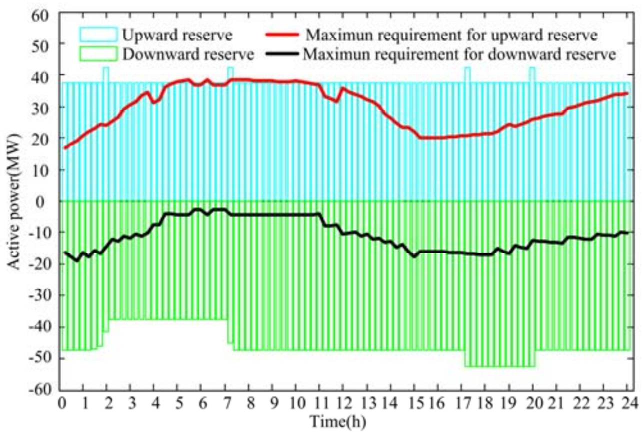

Fig. 5. Spinning reserve capacity of the system for the DO method.

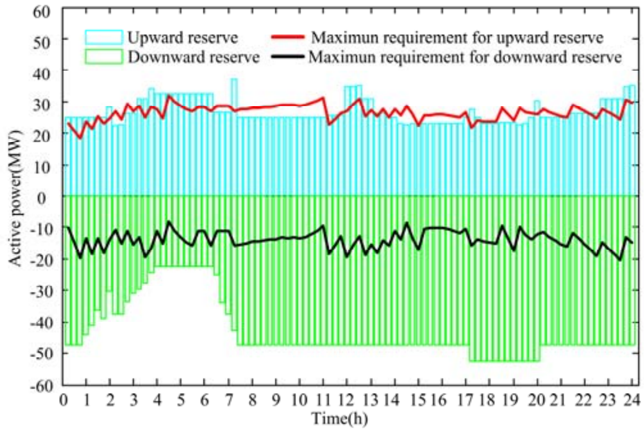

Fig. 6. Spinning reserve capacity of the system for the SO method.

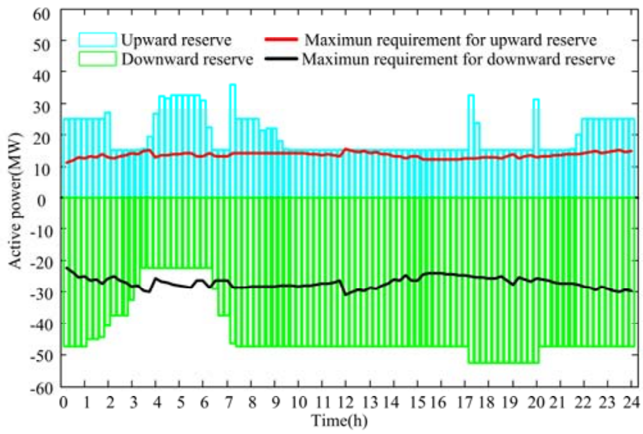

Fig. 7. Spinning reserve capacity of the system for the RO method.

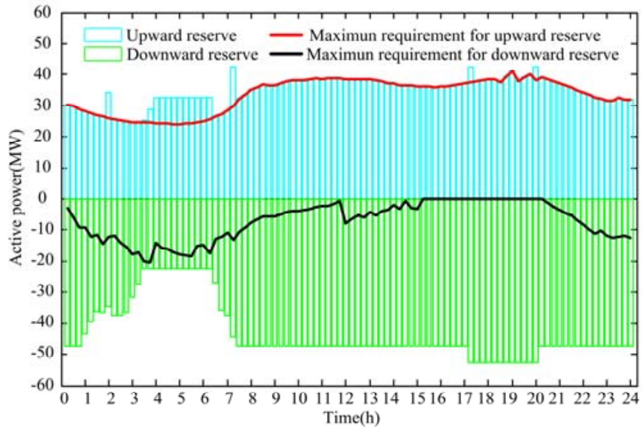

Fig. 8. Spinning reserve capacity of the system for the PO method.

For the DO method, the spinning reserves of the system are always adequate to deal with the fluctuation of wind power. As the details of the forecast error are not fully considered, the spinning reserves are excessively conservative, as shown in Figure 5. For the SO method, due to the fitting errors of the versatile probability distribution, the system cannot always provide enough spinning reserves to deal with the fluctuation of actual wind power. Especially from 8:00am to 11:00am, due to great fluctuation of wind power, the SO method cannot rationally allocate upward and downward spinning reserves. For the RO method, as the spinning reserve constraints are not considered [16], the spinning reserves of the RO method are not adequate due to G2 out of service from 3:00am to 7:00am, as shown in Figure 7.

For the PO method, when wind power fluctuates in D, the spinning reserves of the system are always adequate. Considering detailed information on forecast error by forecast bins, the spinning reserve capacity of the proposed method is more reasonable than that of the DO, SO, and SO methods. Therefore, the proposed method can avoid the waste of resources under the premise of system safety. Especially from 3:00am to 7:00am, in response to G2 out of service and wind power output increasing, PO method rationally allocates upward and downward spinning reserves to ensure safety without excessive waste of resources.

3) *Branch Power Flow of the System*

The active power transmission capacity limitation of each transmission line is set to be 100MW. The branch power flow results of four methods are illustrated in Fig.9, Fig.10, Fig.11, and Fig.12, respectively. For each transmission line, the bars with different color represent the branch power flow at different time.

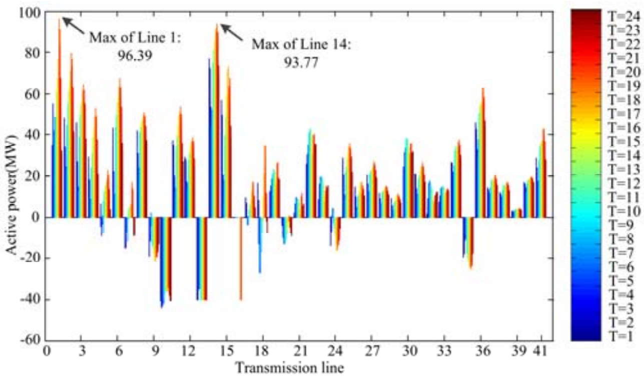

Fig. 9. Branch power flow for the DO method.

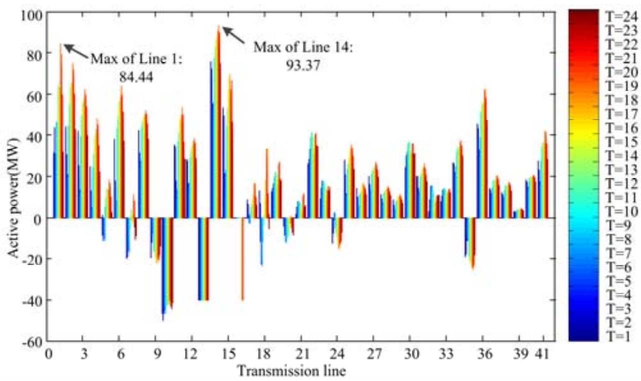

Fig. 10. Branch power flow for the SO method.

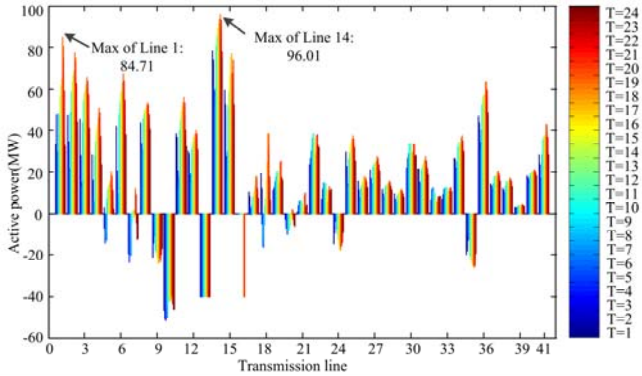

Fig. 11. Branch power flow for the RO method.

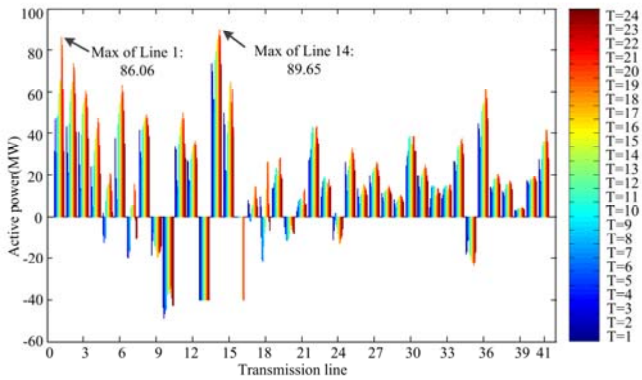

Fig. 12. Branch power flow for the PO method.

As shown in Table II, the maximum active power in all transmission lines is limited to 89.65MW by using the PO method. However, the maximum active power of the DO, SO, and RO methods reaches 96.39MW, 93.37MW, and 96.01MW, respectively, which means better robustness and security of the PO method.

TABLE II
MAXIMUM POWER FLOW IN ALL TRANSMISSION LINES

Method	Maximum power flow(MW)
DO method	96.39
SO method	93.37
RO method	96.01
PO method	89.65

4) *Economy Analysis*

The fuel costs, average penalty costs and total costs of four methods are listed in Table III. As listed, the fuel costs of the PO method, i.e., $ 512,315, is much lower than those of the DO, SO and RO methods. Considering four extreme wind power scenarios, although the penalty costs of the PO method, i.e., $ 71,119, is higher than those of the DO, SO and RO methods, the total costs of the PO method, i.e., $ 583,434, is less than those of the other three methods. As RO method considers the worst wind power by the two-stage relaxation algorithm, its solution may be excessively conservative [16]. In general, the proposed method has better overall economy.

TABLE III
THE COSTS OF FOUR METHODS

Costs	Fuel costs($)	Penalty costs($)	Total costs($)
DO method	522,530	67,523	590,053
SO method	519,287	64,452	583,793
RO method	538,094	51,894	589,988
PO method	512,315	71,119	583,434

5) *Computation Time*

The computation time of four methods are listed in Table IV. For the DO method, the ED model is solved by QP with interior point algorithm, which is a mature and efficient optimization algorithm. The computation time of the DO method is about 0.50s. For the SO method, the ED model is solved by the SLP-based algorithm [13], by which the sub-optimization problem is solved by linear programming (LP) with simplex algorithm. The ED problem of the SO method converges after 160 iterations with the SLP-based algorithm. The computation time of the SO method is about 651.99s. For the RO method, the ED model is solved by the two-stage relaxation algorithm [16], by which the sub-optimization problem is solved by nonlinear programming (NLP) with interior point algorithm. The ED problem of the RO method converges after 148 iterations with the two-stage relaxation algorithm. The computation time of the RO method is about 12149.87s. For the PO method, with the introduction of four extreme scenarios and corresponding load shedding and wind curtailment, the ED model with uncertainty is transformed into a deterministic optimization ED model and solved by QP with interior point algorithm. The computation time of the PO method is about 0.85s, which is a little longer than that of the DO method and much shorter than that of the SO and RO method.

TABLE IV
THE COMPUTATION TIMES OF FOUR METHODS

Method	Time(s)
DO method	0.50
SO method	651.99
RO method	12149.87
PO method	0.85

V. CONCLUSIONS

In this paper, a day-ahead economic dispatch model considering extreme scenarios based on wind power uncertainty set is proposed. By introducing forecast bins, the abundant forecast error information can be utilized and the uncertainty set is more accurate to depict the intermittency of wind power in comparison with the DO method. Afterwards, the proposed model can be easily solved by the intake of four extreme scenarios and corresponding load shedding and wind curtailment, leading to better algorithm realization with QP in comparison with the SO and RO methods. Finally, test results on the modified IEEE30-bus sys-tem show obvious predominance of the proposed method in aspects of security, robustness, economy, and effectiveness over the DO, SO, and RO methods. Further work will focus on extreme scenarios of multiple correlative wind farms and the application in a real power grid.

APPENDIX

A. *The Modified IEEE 30-bus System*

The parameters of generators and the load distribution of the system are listed in Table V and Table VI. The branch data of the IEEE-30 bus system can be found in detail in [27].

TABLE V
PARAMETERS OF CONVENTIONAL GENERATORS

Unit	Lower (MW)	Upper (MW)	Ramp rate (MW/h)	a ($/MW^2h)	b ($/MWh)	c ($/h)
G1	50	200	60	0.1524	38.5397	786.7988
G2	20	100	40	0.1058	46.1591	945.6332
G3	15	60	30	0.0280	40.3965	1,049.9977
G4	20	80	40	0.0354	38.3055	1,243.5311
G5	10	40	20	0.0211	36.3278	1,685.5696
G6	10	40	20	0.0179	38.2704	1,365.6592

TABLE VI
DISTRIBUTION OF SYSTEM LOADS

Bus No.	1	2	3	4	5	6	7	8	9	10
Load distribution (%)	0	0.06	0.05	0.07	0.05	0	0.06	0.04	0	0.08
Bus No.	11	12	13	14	15	16	17	18	19	20
Load distribution (%)	0	0.05	0	0.03	0.04	0.03	0.04	0.05	0.05	0.04
Bus No.	21	22	23	24	25	26	27	28	29	30
Load distribution (%)	0.03	0	0.05	0.04	0	0.07	0	0	0.03	0.04

B. *Results of the Unit Commitment*

The results of the unit commitment are the input of the day-ahead ED for the four methods. The results of the unit commitment are listed in Table VII.

TABLE VII
RESULTS OF THE UNIT COMMITMENT

Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
G1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
G2	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
G3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
G4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
G5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
G6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0

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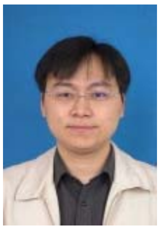


Jian Xu (M'08) received the B.S. and Ph.D. degrees, both in electrical engineering, from Wuhan University, Wuhan, China, in 2002 and 2007, respectively. He joined Wuhan University as a Lecturer in 2007. During 2013–2014, he was a visiting scholar at the Energy Systems Innovation Center, Washington State University, Pullman, WA, USA. Since 2016, he has been an Professor of the School of Electrical Engineering at Wuhan University. His research interests include power system stability and control, and large-scale wind-integrated power systems.

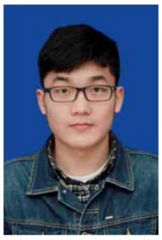
Bao Wang received the B.Sc. degree in electrical and electronic engineering from Huazhong University of Science and Technology, Wuhan, China, in 2013, and the M.Sc. degree in electrical engineering, from Wuhan University, Wuhan, China, in 2016.

Currently, he is working in Guangzhou Power Supply Bureau Co., Ltd., Guangzhou, Guangdong, China. His research interest focuses on power system economic dispatch, stability and operation.

Yuanzhang Sun (M'99–SM'01) received the B.S. degree from Wuhan University of Hydro and Electrical Engineering, Wuhan, China, the M.S. degree from the Electric Power Research Institute (EPRI), Beijing, China, and the Ph.D. degree from Tsinghua University, Beijing, China, all in electrical engineering, in 1978, 1982 and 1988, respectively.

Currently, he is a Professor with the School of Electrical Engineering, Wuhan University, Wuhan, China, and a Chair Professor with the Department of Electrical Engineering and Vice Director of the State Key Lab of Power System Control and Simulation, Tsinghua University. His research interests include power system dynamics and control, wind power, voltage stability and control, and reliability.

Qi XU received the B.Sc. and the M.Sc. degree, both in electrical engineering, from Wuhan University, Wuhan, China, in 2013 and 2016, respectively. Currently, she is working in Electric Power Research Institute of Guangdong Power Grid Co., Ltd., Guangzhou, Guangdong, China. Her research interest focuses on energy storage application technology and micro-grid.



Ji Liu received the B.Sc. degree in electrical engineering from Wuhan University, Wuhan, China, in 2015. Currently, he is pursuing the master's degree in Wuhan University. His current research interest includes the schedule of the new energy in power system, control theory and state estimation.

Huiqiu CAO received the B.Sc. degree in electrical engineering from Wuhan University, Wuhan, China, in 2015. Currently, she is pursuing the master's degree in Wuhan University. Her current research interest includes the schedule of the new energy in power system.

Haiyan Jiang received the B.S. degree in Electric Engineering from Wuhan University, Wuhan, Hubei Province, China, in 2012 and is currently pursuing the Ph.D. degree in electric engineering at Wuhan University. Her research interest includes optimal unit commitment, optimal combination of reserves and optimal control of AGC.

Ruobing LEI received the B.Sc. and the M.Sc. degree, both in electrical engineering, from Wuhan University, Wuhan, China, in 2013 and 2016, respectively. Currently, he is working in Suzhou Power Supply Bureau Co., Ltd., Suzhou, China. His research interest focuses on dynamics modeling of Wind farm group and frequency control of power system.

Mengjun Shen received the B.Sc. degree in electrical engineering from Wuhan University, Wuhan, China, in 2016. He is currently pursuing the M.Eng. degree at The University of Nottingham. His research interests include the benchmarking system of major branch companies of SGCC and measures to promote their management, dispatch of wind power generation system based on universal distribution, wind power prediction, new synchronous generator power angle stabilizer based on Lyapunov stability.