Unit commitment of wind integrated power system considering optimal scheduling of reserve capacity

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Abstract. There are multiple uncertainties in the power system with wind farms, such as wind power output, load and forced outage of units, which lead to consider the spinning reserve capacity in unit commitment, which undoubtedly increases the difficulty of problem solving. In order to solve this problem, the fuzzy parameters of wind power output and load are obtained by using the error's fuzzy characteristics, and the mathematical model of generating unit combination is established to optimize the generator output and spinning reserve simultaneously by using the chance constraint, and the model is solved by using intelligent algorithm. The model fully analyses the cost difference of different units providing spinning reserve and the economic benefit of spinning reserve, aiming at minimizing the difference between the cost of generating reserve and the economic benefit of reserve, so as to maximize the overall economic benefit of the system. The feasibility and validity of the proposed model are verified by a 10-unit system with wind farms. The analysis shows that the model can reasonably consider reserve decision-making in unit commitment to deal with uncertainties in power system.

1. Introduction
Inspired by the Renewable Energy Law, the installed capacity of wind power in China has reached 114 million kW. However, the inherent intermittence and fluctuation of wind speed make a lot of errors in the prediction of wind power output, which has a great impact on the operation of the power grid [1-4].

The integration of large-scale wind power into power grid increases the uncertainty of unit commitment and the related risks of system operation, which makes the optimal allocation of spinning reserve capacity more complex. Considering the spinning reserve in unit commitment to response the system uncertainty has gradually become the focus of academic and engineering application research [5-14]. Document [5-7] defines various scenarios of the model according to the error distribution of the predicted value, forms the scenario tree of unit commitment prediction, and solves the problem on the basis of considering the spinning reserve. This kind of model requires a lot of computation to consider multiple cycle scenario trees. References [8-9] optimize the allocation of reserve under the condition of determining unit stop/start, without considering the influence of spinning reserve on unit commitment decision-making [10]. Reference [11-14] considers that under certain reliability level, the total reserve requirement of the system is determined in unit commitment, and there is no optimal allocation of reserve capacity among different units.
The above literature has made some progress in considering the unit commitment of spinning reserve, but the consideration of unit commitment and spinning reserve decision coordination is more in line with the operation nature of power system operation [15]. Reference [16-17] establishes an economic dispatching model for simultaneous optimization of generator output and reserve under power market conditions, but it does not analyze the reserve cost of single unit and the economic benefits of spinning reserve. Reference [18-19] establishes the optimal reserve allocation model of the system after wind power is connected, but only the probability of wind power and load error is taken into account in this paper, and the uncertainty of forced outage of generator units is not taken into account. Moreover, due to the influence of temperature, meteorology, statistical errors and absence of drainage law, the wind power output and load have fuzzy characteristics, so it is more reasonable to adopt the model of fuzzy parameters [20-22]. Literature [20-22] considers the role of spinning reserve in constraints, but no further study has been made on the cost, benefit and optimal allocation of spinning reserve. In view of the multiple uncertainties in power system, the differential model of wind power output, load and forced outage of units is established. Based on the analysis of the cost of spinning reserve and the economic benefit of spinning reserve for single unit, the mathematical model of unit combination for optimizing the output of generators and spinning reserve is established. The improved clear equivalence class is used to deal with the credibility constraints, and the intelligent algorithm is used to solve the model. The feasibility and validity of the proposed model are verified by a 10-unit system with wind farms. The analysis shows that the model can coordinate the reserve decision-making in unit commitment to deal with uncertainties in wind power system.

2. Fuzzy variables and related fuzzy concepts in unit combination

When studying the fuzzy characteristics of load forecasting errors, the relative errors are usually used, and the membership function is expressed by Cauchy distribution. However, relative error will lose its guiding value when the load is low. This paper chooses absolute error to study the fuzzy model of load. The membership function of the fuzzy variable of load forecasting error is as follows:

$$
\mu_{\Delta P_L} = \begin{cases} 
\frac{1}{1+\eta_L(\Delta P_L / P_L^+)^2}, & \Delta P_L \geq 0 \\
1 & \Delta P_L < 0 
\end{cases}
$$

(1)

In the formula, $P_L^+$, $P_L^-$ the statistical average values of positive and negative errors are expressed respectively; $\eta_L$ are weighted; the absolute errors of load forecasting are expressed as follows:

$$
\Delta P_L = P_L^+ - P_L^-
$$

(2)

In order to obtain the membership function of wind farm output power, the membership function of wind speed is obtained through the fuzzy characteristics of wind speed prediction error, and then the fuzzy model of wind farm output power is obtained based on the functional relationship between wind farm output and wind speed.

The fuzzy model of wind speed is the basis of active power model of wind farm. It is pointed out in literature that the error of wind speed prediction has the same fuzzy characteristics as that of load prediction. Ignoring the wake effect of wind turbines and the difference between wind turbines in wind farms, the total wind power of wind farms including typhoon turbines is:

$$
W_{av} = N_w P_w
$$

(3)

According to wind speed membership function and wind-work curve, the power of wind farm is a mixed type of fuzzy variable, and the fuzzy parameters of wind farm output can be obtained by the definition of membership degree[23]. The degree of membership of the continuous part is:

$$
\mu_{W_{av}} = \mu\{W_{av} = P_w N_w\}
$$

(4)

3. Cost-benefit analysis of reserve capacity
3.1. Cost analysis of reserve capacity
Assuming that the active power output \( P \) of generator is positive spinning reserve \( \Delta P \), the opportunity cost of providing reserve for a generator set is as follows [24]:

\[
S = G' - G
\]  

(5)

According to the theory of marginal cost, the marginal cost of generating set providing positive spinning reserve is shown in the formula (6).

\[
\gamma = \frac{\partial S}{\partial \Delta P} = \rho - b - 2aP - a\Delta P
\]  

(6)

In order to simplify the model, this paper does not consider the effect of time-of-use price on spinning reserve, that is, price is treated as a constant. Without considering the influence of spare capacity on spare cost, the formula can be simplified: \( \gamma = \rho - b - 2aP \).

According to the same idea, the negative spinning reserve cost can be calculated.

3.2. Benefit analysis of reserve capacity
In order to better analyze the benefits of spinning reserve for power grid stability and balance, the possibility of power unbalance is first expressed by variables, as shown in the formula:

\[
Pet = \sum_{i=1}^{N_G} P_{G_{it}} + W_{a_1} - P_{L_t}
\]  

(7)

In the formula: \( N_G \) is the number of generating units opened in the unit combination cycle \( t \); \( P_{G_{it}} \) is the output of the \( i \) generating unit; and \( W_{a_1} \), \( P_{L_t} \) is the fuzzy variable of wind power output and load. The economic benefits of purchasing positive spinning reserve in the power grid lie in improving the reliability of the system and reducing the power consumption which is not enough to meet the expected value, thus reducing the cost of power outage for users. Therefore, the economic benefits of the reserve can be expressed by the change of the outage cost of the users who purchase the reserve:

\[
B_{r21} = \alpha_1 \Delta E_{WAS} = \alpha_1(E_{WAS,1} - E_{WAS,0}) = \alpha_1 \sum_{i=0}^{N_G} \Pr(A_i) \int_0^{D_t} Cr(Pet_t > r) dr
\]  

(8)

Formula: \( \alpha_1 \) indicates the cost of wind energy waste per electric energy; and \( E_{WAS,1} \) and \( E_{WAS,0} \) is the expected value of wind energy waste for the purchase of reserve systems; \( D_t \) is the sum of negative rotation reserve for all generators without forced outage.

4. Model of unit commitment

4.1. The objective function
Based on the ideas in the literature, this paper takes the generator output and reserve capacity as optimization variables, and establishes a new unit combination model considering the reserve cost and benefit. The objective function of the model is:

\[
\min f = \sum_{i=1}^{N_g} \sum_{t=1}^{N_T} [I_i f_i(P_{G_{it}}) + I_i(1 - I_{t(i-1)})S_{it} + \sum_{t=1}^{N_T} \sum_{i=1}^{N_g} I_i(\gamma_{\theta} U_{it} + \gamma_{\theta} D_{it}) - B_{st} - B_{s2}]
\]  

(9)

Formula: \( P_{G_{it}} \) is planning output for the unit \( i \) in the first dispatching cycle \( t \); \( I_i \) is starting-up state for the unit in the first dispatching cycle, starting-up state is 1, stopping state is 0; \( f_i \) is fuel cost function for the unit \( i \); \( S_{it} \) is starting-up cost for the unit \( i \) in the \( t \) dispatching cycle; \( \gamma_{\theta}, \gamma_{\theta} \) is offer for the positive and negative spinning reserve capacity of the unit \( i \) respectively; \( U_{it}, D_{it} \) are up-regulation and reduce the reserve capacity of the unit \( i \) in the \( t \) dispatching cycle; and \( B_{st}, B_{s2} \) are the economic benefits of the positive and negative spinning reserve during the scheduling cycle.

4.2. Constraint condition
Conventional generator constraints include upper and lower output limit constraints, reserve capacity constraints, ramp rate constraints and minimum start-up and shut-down time constraints [21]. During each unit combination cycle, the output of conventional units keeps power balance with the predicted value of wind power output and load output.

\[ \sum_{i=1}^{N_{\text{Gr}}} P_{\text{Gr}} - \bar{W}_{\text{out}} = 0 \]  

(10)

In the formula, \( \bar{W}_{\text{out}} \) and \( P_{\text{L}} \) are the predicted value of wind power and load output in the cycle, that is, the value of membership degree of wind power output and load fuzzy parameters is 1. The positive reserve units can deal with the uncertainties of negative error in wind power forecasting, positive error in load forecasting and forced outage of conventional generators at a certain confidence level.

\[ P_{\text{OS}} \left\{ C_r \left( \sum_{i=1}^{N_{\text{Gr}}} (U_i + P_{\text{Gr}}) \geq P_{\text{L}} - \bar{W}_{\text{out}} \right) \geq \beta_j, t \in T \right\} \geq \beta_1, t \in T \]  

(11)

Formula: 0 \leq j \leq N_{\text{Gr}}, number of outage generators (0 means no outage of generators); \( \beta_1, \beta_2 \) are Fuzzy and probabilistic confidence levels, respectively.

When the generator unit is forced to shut down, the power in the system is insufficient, and the significance of negative reserve is not obvious, so the chance constraints need not be considered. Negative reserve units can deal with uncertainties such as positive error and negative error in wind power forecasting at a certain confidence level.

\[ C_r \left( \sum_{i=1}^{N_{\text{Gr}}} D_i \geq \sum_{i=1}^{N_{\text{Gr}}} P_{\text{Gr}} - P_{\text{L}} + \bar{W}_{\text{out}} \right) \geq \beta_j, t \in T \]  

(12)

Formula: \( \beta_j \) is the level of fuzzy confidence. In order to ensure the safety of the system after the forced outage of generators, the generator can satisfy the power balance of the power grid without considering the spinning reserve response time, and has a certain spinning reserve. Its chance constraints are as follows:

\[ \sum_{i=1}^{N_{\text{Gr}}} P_{\text{Gr}, \text{max}} \geq \bar{P}_{\text{L}}, t \in T \]  

(13)

Formula: \( \beta_4 \) is the level of fuzzy confidence.

4.3. The solution of model

The unit commitment problem proposed in this paper is a non-linear, high-dimensional, non-convex mixed integer programming problem with chance constraints. It is divided into two steps: decision-making of stop/start and joint decision-making of generator output and reserve scheduling. It is very difficult to solve by traditional optimization algorithms. Intelligent optimization algorithms, including genetic algorithm, simulated annealing, adaptive dynamic programming and particle swarm optimization, have achieved good results in power system unit commitment problems. In this paper, genetic algorithm is selected to optimize the start-up stop/start state of generating units. Particle swarm optimization is used to make joint decision on generator output and reserve. Particle swarm optimization (PSO) is relatively simple in structure and fast in operation, so it is used for joint decision-making of generator output and reserve. For negative reserve chance constraints, this paper simplifies them into inequality constraints by using clear equivalence classes. For positive reserve chance constraints, because their random events are discrete, the probability of positive reserve chance constraints can be obtained by judging the fuzzy chance constraints under each random event condition, and then adding the probability of meeting the constraints. Then, the constraints are dealt with by means of penalties.
5. Calculation and analysis of examples

5.1. The basic data and parameters
This paper chooses IEEE 10 system to study. The characteristic parameters and system parameters of generator set can be seen in reference [22]. The wind farm is connected to bus 20, and the rated capacity of a single typhoon unit is 2.0MW. There are 100 wind turbines. The wind speed of cut-in/rated/cut-out is 3, 13 and 25m/s, respectively. The wind speed and load forecasting values are shown in Table 1, respectively. Due to the high repeatability of load daily, the positive and negative prediction errors are 4% and 5% respectively. The daily regularity of wind speed is poor, with positive and negative prediction errors of 14% and 15%, and weights of 2.33. The price of electricity is 80, the cost of energy loss is 100, and the cost of wind energy waste is 50. This paper uses MATLAB programming to solve the problem. The maximum number of iterations is 100, the population number is 50, and the repeated optimization operation is 20 times.

5.2. The calculation results and analysis
Fuzzy confidence level is set to $\beta_1 = 92\%, \beta_2 = 96\% , \beta_3 = 92\% , \beta_4 = 92\%$. The optimal output, positive reserve capacity and negative reserve capacity of thermal power units are calculated by using the model proposed in this paper. Fig. 1, 2 and 3 show the optimal output, positive reserve capacity and negative reserve capacity of thermal power units.

![Figure 1. Unit commitment schedule](image1)

![Figure 2. Positive spinning reserve schedule](image2)
Fig. 1 shows that under the influence of N-1 fault constraints, generators 1, 2 and 5 with lower overall generation cost and reserve cost are always in the open state. With the increase of load, the remaining generators will be opened from small to large according to the priority index under the condition of meeting the minimum start-stop time.

From Figure 2 and Figure 3, we can see that the reserve cost is an important basis for deciding the generator to provide reserve. In the forward spinning reserve plan, the reserve cost of generator 1 is higher, so it does not bear any reserve, while the cost of generator 2 and generator 5 is lower, so it bears more reserve capacity. When the remaining generators are opened over time, the reserve capacity is assumed according to the reserve cost. In the negative spinning reserve plan, the system needs very little reserve capacity, the generator 5 has been in the open state, and the negative reserve cost is low, so it undertakes most of the reserve.

The positive and negative spinning reserve capacity purchased by the system is shown in Fig. 4. Affected by both load forecasting errors and wind speed forecasting errors, the positive and negative reserve have similar trends, but the positive and rotary reserve is affected by the forced outage of generators, so it is higher than the negative spinning reserve. In the period 7-8 and 20-22, the negative reserve is significantly lower than the positive reserve, because in these two periods, the wind speed is super-rated, and the wind farm output is more likely to be rated capacity, so the impact of the reserve is also greater. Moreover, the probability of wind farm output exceeding rated power is 0, so the negative reserve is obviously reduced.
Table 2 shows the reserve capacity, reserve cost and reserve under different fuzzy and probabilistic confidence levels. As can be seen from the figure, with the increase of confidence level, the reserve capacity required by the system increases gradually, and the corresponding reserve cost and reserve income increase. In order to further study the cost-effectiveness of positive reserve, this paper defines the net income index of positive reserve as shown in the formula: 

$$I_A = B_{s1} - U_{cost}$$  \hspace{1cm} (14) 

The sixth item in the table is the net income under the confidence level. It can be seen that with the increase of the confidence level, the net income index first increases and then decreases. Therefore, in the actual system, if there is no compulsory requirement of confidence level, the fuzzy confidence level should be set to 90%, and the probability confidence level should be set to 95%. At this time, the reserve is passing through the highest net income.

### Table 1. Positive reserve capacity, cost and benefit at different confidence levels

| Fuzzy confidence | Probability confidence | Reserve capacity/MW | Reserve cost/\$ | Reserve benefits/\$ | Net income/\$ |
|------------------|------------------------|---------------------|----------------|-------------------|--------------|
| 86%              | 95%                    | 892.5               | 51 914         | 183 308           | 131 394      |
| 88%              | 95%                    | 947.9               | 55 141         | 186 879           | 131 738      |
| 90%              | 95%                    | 1011.7              | 58 846         | 190 591           | 131 745      |
| 92%              | 96%                    | 1086.0              | 63 172         | 194 429           | 131 257      |
| 92%              | 97%                    | 1283.5              | 74 662         | 202 714           | 128 052      |
| 92%              | 98%                    | 1607.3              | 93 497         | 212 238           | 118 741      |
| 92%              | 99%                    | 2322.0              | 135 068        | 224 278           | 89 210       |

Table 2 shows the negative reserve capacity, reserve cost and reserve at different levels of fuzzy confidence. As can be seen from the figure, with the increase of confidence level, the reserve capacity required by the system increases gradually, and the corresponding reserve cost and reserve income increase. In order to further study the cost-benefit of negative reserve, this paper defines the net cost index of positive reserve as shown in the formula: 

$$I_B = D_{cost} - B_{s2}$$  \hspace{1cm} (15) 

Fifth in the table is the net income under the confidence level. It can be seen that with the increase of the confidence level, the net income index has been increasing. Therefore, different levels of fuzzy confidence should be set according to the system risk in the actual system.

### Table 2. Capacity, costs and benefits of down reserve under different confidence levels

| Fuzzy confidence | Probability confidence | Reserve capacity/MW | Reserve cost/\$ | Reserve benefits/\$ |
|------------------|------------------------|---------------------|----------------|-------------------|
| 86%              | 742.6                  | 42 890              | 21 049         | 21 841            |
| 88%              | 781.3                  | 45 123              | 21 451         | 23 672            |
| 90%              | 824.1                  | 47 596              | 21 861         | 25 735            |
| 92%              | 872.0                  | 50 362              | 22 281         | 28 081            |
| 94%              | 926.3                  | 53 493              | 22 712         | 30 781            |
| 96%              | 988.5                  | 57 087              | 23 158         | 33 929            |
| 98%              | 1061.1                 | 61 284              | 23 622         | 37 662            |

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$$I_B = D_{cost} - B_{s2}$$  \hspace{1cm} (15) 

Fifth in the table is the net income under the confidence level. It can be seen that with the increase of the confidence level, the net income index has been increasing. Therefore, different levels of fuzzy confidence should be set according to the system risk in the actual system.

### 6. Conclusion

The output of wind farm is uncertain and intermittent, which makes it more difficult to solve the unit commitment problem in power grid. The spinning reserve is an important method to solve such problem, and the decision-making of reserve is closely related to unit commitment.
In order to solve this problem, the output and load of wind farm are expressed by fuzzy parameters, and the related costs and benefits brought by spinning reserve to power system operation are analyzed through economic benefits. A mathematical model of unit commitment is established to optimize both generator output plan and spinning reserve plan, and particle swarm optimization method is proposed for the model solution. The feasibility and validity of the proposed model are verified by a 10-unit system with wind farms. The analysis shows that the model can reasonably consider the reserve decision-making in unit commitment to cope with large-scale wind power access.

7. References
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