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Optimal economic dispatch for wind farm considering uncertainty of wind power

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Abstract. Because of the wind power generation characteristics, the wind turbine's dispatch model is based on wind power prediction. Even though the current average forecast error of ultra-short-term wind power prediction is already low, there are still some errors and uncertainties. Therefore, the scenario analysis method is used to estimate the forecast error. The deterministic modeling is realized by using the spare amount. In order to plan the operating cost of the wind farm reasonably, the scenario analysis method and the possible spare cost are combined with the idle cost of the unit to establish an economic dispatch model within the wind farm. The example analysis shows that the model is feasible.

1. Introduction

In recent years, it is more difficult to regulate wind power only through the power grid because of the large-scale centralized development of wind power. In the entire power system, the current wind power dispatch management of the power grid can only reach the wind farm side, and there is no optimal management of the internal dispatch of wind farms. The optimization of the power distribution of the unit in the wind farm not only better grasps the power output of the wind farm, but also plays an important role in improving the execution ability of the wind farm dispatch instructions and reducing the operation and maintenance cost.

According to the unit object of optimal dispatch, the research on wind power dispatch can be classified into economic dispatch of power system with wind farm and internal dispatch of wind farm. Among them, wind farm internal dispatch research can be roughly divided into three types of wind farm optimization dispatch, including optimization of wind turbine start-stop arrangements, wind turbine output and load distribution, optimization of unit start-stop plan and active output scheme based on mixed integer nonlinear programming. Reference [1] establishes and solves the model based on the relative wear value of wind turbines during normal operation and shutdown. Reference [2] establishes an optimization model with the objective of minimizing the sum of blade damage of wind turbines in wind farms, the number of start-up and shutdown of wind turbines, and the difference between the total output of wind farms and power grid dispatch instructions. The binary arithmetic is used to solve the unit combination scheme.

The above literature does not consider the wind power forecast error, but in this paper, scenario analysis method is applied to estimate the prediction error, and uses the reserve amount to achieve deterministic modeling. The corresponding impeller loss cost is calculated based on the relative fatigue damage loss method [3] in order to plan the operating cost of the wind farm reasonably. The economic dispatch model in the wind farm is built using the scenario analysis method and the possible reserve cost, combined with the unit idle cost. The case study shows that the model is feasible.
2. Scenario-based wind power forecast error model

In fact, due to the forecast error and the influence of various factors in the real environment, there is always a deviation between the predicted wind power and the actual power. However, statistical methods can be used to analyse the forecast error, and as the result, the corresponding distribution law of forecast error is obtained. In this paper, the uncertainty of wind power is described by scenario analysis method [4,5] on the premise that the prediction error of wind power obeys normal distribution, so as to determine the reserve amount.

The steps for generating wind power forecast error scenarios are as follows:

Step1: The wind power prediction error $\varepsilon_j$ is divided into seven intervals with a mean of 0, as shown in Fig. 1. The width of each interval is its standard deviation $\sigma$.

![Figure 1. Sketch of discretization of normal distribution.](image)

Step2: The non-standard normal distribution function is converted to a standard normal distribution using Formula 1. Then, the standard normal distribution table is checked to obtain the probability of the seven intervals corresponding to the discretization of the normal distribution probability curve in each period, so that the sum of the seven intervals after the normalization is 1.

$$\varepsilon_j^* = \frac{\varepsilon_j - \mu}{\sigma}$$  \hspace{1cm} (1)

In the formula: $\sigma$ — standard deviation of wind power forecast error; $\mu$ — mean value of wind power forecast error; $\varepsilon_j$ — wind power forecast error in time period $j$.

Step3: A random number between 0 and 1 of the M scenario in T periods is randomly generated, and then it is determined which sections the random numbers belong to. In this way, the corresponding wind power prediction error value is obtained. The generated scenario is expressed in the form of Formula 2.

$$\text{Scene}_m = \{\varepsilon_1^m, \varepsilon_2^m, \ldots, \varepsilon_T^m\}$$  \hspace{1cm} (2)

In the formula: $\varepsilon_t^m$ represents the wind power prediction error of the $t$ period in scenario $m$, where $m = [1,2,3,\ldots,M]$ and $t = [1,2,3,\ldots,T]$.

Step4: Calculate the probability $P(\text{Scene}_m)$ of each scenario according to Formula 3.

$$P(\text{Scene}_m) = \frac{\prod_{t=1}^T \beta_{m,t}}{\sum_{m=1}^M \prod_{t=1}^T \beta_{m,t}}$$  \hspace{1cm} (3)

In the formula:

$P(\text{Scene}_m)$ — the probability of occurrence of wind power prediction error in scenario $m$.

$\beta_{m,t}$ — the discretization interval probability of the wind power prediction error during time period $t$ in scenario $m$. 
After completing the generation of the wind power forecast error scenarios, under the condition of ensuring certain calculation accuracy, a large number of generated scenarios are cut. In this paper, the synchronous backward scenario-reduction method [6] is adopted, and the scenario reduction steps are as follows:

Step1: Two scenarios \(m, m^*\) are arbitrarily selected from all generated scenarios and the probability distance between the two scenarios is calculated according to Formula 4.

\[
d_{m,m^*} = P(\text{Scene}_m)P(\text{Scene}_{m^*})\sqrt{(\epsilon_m^1 - \epsilon_{m^*}^1)^2 + (\epsilon_m^2 - \epsilon_{m^*}^2)^2 + \cdots + (\epsilon_m^I - \epsilon_{m^*}^I)^2}
\]  

(4)

Step2: In the probability distance of all pairs of scenarios, find the two scenes corresponding to the smallest probability distance. Find the two scenarios corresponding to the smallest probability distance, and remove one of the scenarios after the probability distance calculation between all pairs of scenarios are completed. Only one is retained and the rest are eliminated in the case where there are more than two scenarios with the smallest probability distance. As shown in Formula 5, the final scenario probability is a sequential superposition of the culled scenario probability and the retained scene probability.

\[
P'(\text{Scene}_m) = P(\text{Scene}_m) + P(\text{Scene}_{m^*})
\]  

(5)

In the formula, \(P'(\text{Scene}_m)\) represents the updated scenario probability.

Step3: Repeat Step1~Step2 until the number of generated scenes is reduced by the set number of reservations.

Step4: Because this paper only considers the shortage of electricity caused by wind power uncertainty, the minimum prediction error of each time period in the remaining scenario is taken to form a boundary scenario to determine the spare capacity required for each time period.

3. Economic dispatch model in wind farm

3.1 Objective function

1) Wind turbine impeller loss cost

Because of the power generation characteristics of wind turbines, they have no energy cost. However, there will be losses during the use of the unit. Therefore, it is necessary to consider the loss cost of blades and hubs, which account for about 23% of the total cost of wind turbines and bear the most complex forces. The impeller loss cost expression is:

\[
G = \sum_{j=1}^{T} \sum_{i=1}^{n} E_f[A_i f_i u_i + B_i u_i (1-u_{i,j-1}) + C_i (u_{i,j-1} - (1-u_{i,j}))]
\]  

(6)

In the formula: \(G\) —— the cost of the wind turbine impeller loss; \(E_f\) —— the cost coefficient of wind turbine impeller.

2) Reserve capacity cost

Even though current wind power forecast techniques have improved a lot, there are some forecast power errors due to the uncertainty of wind power. Therefore, it is necessary to configure the reserve capacity to cope with the impact of fluctuations in wind power output. Then the reserve capacity cost expression is as follows:

\[
Q = \sum_{j=1}^{T} C_{by} \alpha_j \left[p_{by} - (p_{yuce} \ast u_j - p_{load}^j)\right]
\]  

(7)

In the formula: \(Q\) —— reserve cost; \(C_{by}\) —— reserve cost coefficient; \(\alpha_j\) —— determination coefficient; \(p_{by}\) —— the reserve capacity required in time period \(j\); \(p_{yuce}\) —— the predicted output power of the wind turbine in time period \(j\); \(u_j\) —— wind turbine start and stop combination in time period \(j\); \(p_{load}^j\) —— the amount of power generation required by the dispatch instructions of the wind farm in time period \(j\).

Then, the formula for determining the coefficient \(J\) is shown in formula 8:
$\alpha_j = 1, p_{j,yuce}^{l} u_j - p_{load,j}^{l} \leq p_{by,j}^{l}$

$\alpha_j = 0, p_{j,yuce}^{l} u_j - p_{load,j}^{l} \geq p_{by,j}^{l}$

(8)

3) idle cost of the unit
When wind turbines stop generating electricity, they will consume electricity and generate idle costs. The expression is:

$$Z = \sum_{j=1}^{T} \sum_{i=1}^{n} C_c (1-u_i) \Delta p$$

(9)

In the formula: $Z$ —unit idle cost; $C_c$ —electricity cost coefficient; $\Delta p$ —the power consumption of a single wind turbine when it is idle.

The objective function of the economic dispatch model in the wind farm is as follows:

$$F = \min(G + Q + Z) = \min\left[ \sum_{j=1}^{T} \sum_{i=1}^{n} E_j \left( A_i u_i t + B_i u_i (1-u_{i,j-1}) + C_i u_{i,j-1} (1-u_i) \right) \right]$$

$+ \sum_{j=1}^{T} C_{by,j} \alpha_j \left[ p_{by,j}^{l} - (p_{j,yuce}^{l} u_j - p_{load,j}^{l}) \right] + \sum_{j=1}^{T} \sum_{i=1}^{n} C_i (1-u_i) \Delta p$ 

(10)

3.2 Constrains
1)Unit start-up constraint combination

$$p_{load,j}^{l} \leq p_{j,yuce}^{l} u_j$$

(11)

2)Wind turbine output range constraint

$$p_{i,\text{min}} \leq p_{j} \leq p_{j,yuce}^{l}$$

(12)

In the formula: $p_{i,\text{min}}$——lower limit of output power of the wind turbine $i$ in the wind farm; $p_{j,yuce}^{l}$——upper limit of the predicted output power of the wind turbine $i$ in time period $j$ of the wind farm.

3) Load dispatch constraint

$$\sum_{i=1}^{n} u_i p_i^{l} = p_w^{l}$$

(13)

4. Example simulation and analysis
This paper uses the data of a wind power plant with a capacity of 183MW in north China to carry out simulation experiments to build the prediction error model of wind power based on scenario analysis method. Firstly, 1000 error scenarios of wind power prediction are generated by scenario analysis method, and the number of scenarios is reduced to 5 by synchronous backward scenario-reduction method. Then compare and select the minimum value of each session in the reserved scenario. Then the minimum value(This article considers upregulated reserve capacity, which is both vacant and negative.) of each period in the reserved scenario is selected by comparing and the boundary scene is generated to determine the reserve capacity needed in the next 4 hours. The remaining 5 wind power prediction error scenarios and the resulting generation of boundary scenarios are shown in Table 1.

| Table 1. Scenarios for wind power forecast error after reduction |
|---|---|---|---|---|
| Scenario | Period 1 | Period 2 | Period 3 | Period 4 |
| 1 | -775.1 | -1953.0 | 2369.7 | 759.8 |
| 2 | 1447.3 | 2622.6 | 1637.1 | 366.6 |
| 3 | 811.5 | 1621.9 | -1962.7 | 1001.0 |
| 4 | -2038.9 | 91.1 | 1258.4 | -1896.1 |
| 5 | -2122.2 | -1840.4 | -1689.4 | 901.1 |
| Boundary | -2122.2 | -1953.0 | -1962.7 | -1896.1 |
The boundary scenarios in Table 1 correspond to the reserve capacity required for the next four periods. The algorithm model used in this paper is the Discrete Multi Interactive Artificial Bee Colony and Multi Interactive Artificial Bee Colony (DMIABC-MIABC) algorithm model [7]. The cost coefficient $E_j$ of the wind turbine impeller includes the cost of the impeller, the cost of installation and transportation, and the cost of maintenance of the impeller within 20 years. The idle energy consumption $\Delta p$ of each wind turbine is about 20KWh, the reserve capacity cost coefficient $C_{by}$ is about 0.035yuan/KWh, and the electricity cost coefficient $C_p$ is about 0.035 yuan/KWh [8,9]. In order to verify the advantages of adding reserve capacity cost to the dispatch optimization goal, this paper will carry out experimental simulation of two dispatch models.

Model 1: Formula 14 is used as one of the constraints to ensure that the sum of the wind power output margins (The predicted value of wind power minus the actual power distribution) of wind turbines scheduled for operation in each period is greater than the potential wind power output decline in corresponding periods. In order to achieve the safety of wind power output, reserve capacity cost should be avoided as far as possible.

$$p_{load}^j + p_{by}^j \leq p_{yuce}^j \times u_j$$ (14)

Model 2: Formula 10 is used as the objective function of dispatch optimization, and the constraints in Section 3 are used as the model constraints. Reserve capacity is used as a measure to deal with the possible fluctuation of wind power. The dispatch model can automatically balance the spare capacity with the cost of impeller loss and idle unit cost under the condition of guaranteeing the safety of wind power output. Finally, a better wind turbine output distribution scheme is selected.

The two models are simulated by 20 experiments, and the average value of simulation results is obtained. The model 1 is about 2073.4 yuan, and the model 2 is about 1891.7 yuan. In Figure 2, the convergence curve is optimized for the two dispatch models.

![Figure 2. Comparison diagram of optimal convergence curve of dispatch model.](image)

| Dispatch model | Impeller loss cost (yuan) | Reserve cost (yuan) | Idle cost (yuan) | Total cost (yuan) | Optimization (yuan) |
|----------------|---------------------------|---------------------|-----------------|-------------------|---------------------|
| Model 1        | 2052                      | 0                   | 10.5            | 2062.5            | 9.02%               |
| Model 2        | 1696.4                    | 156.9               | 23.1            | 1876.4            |                     |

Table 2. Comparison of optimal results.
It can be observed from Figure 2 that the economic cost corresponding to the output scheme of model 2 is lower than that of model 1 at the beginning of the search. In the subsequent search process, the search optimization space of model 2 is also larger than that of model 1, while the optimization space of model 1 is smaller. The optimal space of impeller loss cost of wind turbines can be greatly reduced because model 1 eliminates the unit start-up and shutdown combinations that do not meet the margin requirements by using constraint conditions. At the same time, it can also be observed that the actual power generation of the operating wind turbine is less than the predicted power generation which is also known as the existence of power generation margin. The possibility of wind farm wind power fluctuations is shared with each unit, instead of relying entirely on a single unit or a small number of generating units. Although the reserve cost and idle cost of model 2 are higher than that of model 1, it can not only make full use of the start and stop of the unit, but also improve the impeller loss cost to optimize the space. This results in more cost reduction and lower cost for the impeller.

According to Table 2, the reserve cost of model 2 is increased by 156.9 yuan and idle cost by 12.6 yuan compared with model 1. However, the impeller loss cost is reduced by 355.6 yuan, which reduces the total cost by 186.1 yuan and optimizes the ratio by 9.02%.

5. Conclusion
This paper studies the economic dispatch optimization model in wind farms, and converts the margin problem in the constraint condition into the spare capacity cost problem as one of the scheduling optimization objectives, which improves the model optimizable space. The simulation results of DMIABC-MIABC algorithm model show that the model reduces the operation cost of wind farms.

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