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Fuzzy hierarchical analysis applied in high ratio wind power system energy storage

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Abstract: *With the continuous development of wind power generation technology and the increasing investment, the global installed scale of wind power generation is growing rapidly. Since the strong intermittency and fluctuation of wind power easily leads to the difficulty of real-time power balance in system operation and the relatively expensive cost of energy storage, this paper will take the high proportion of wind power system as an example to analyze the configuration and operation of energy storage. Firstly, the generation plan curve of the unit is drawn and the system unit power supply cost is calculated, and finally the reliability of the model and the quadratic planning algorithm is checked by genetic algorithm. Secondly, the solution with the lowest overall system cost is solved. Finally, the model is built and combined with fuzzy hierarchical analysis to obtain the optimal power balance solution, and the feasibility and effectiveness of the solution are determined by consistency test.*

Keywords: *Secondary planning; minimum energy storage allocation plan; minimum system cost planning; fuzzy hierarchical analysis*

1. Introduction

The future power system driven by the goal of "carbon neutrality" will definitely be a high proportion of renewable energy power system, and the strong random fluctuation of renewable energy output power leads to the difficulty of real-time power balance in system operation; energy storage is considered as an effective means to guarantee real-time system power balance, but due to the relatively expensive cost of energy storage, using energy storage to balance system power will increase the system operation cost. The following is an example of a high percentage wind power system to explore the impact of "supply-side" low-carbon transformation on power system operation economy and reliability.

The system to be studied contains thermal power, wind power, energy storage and load, three thermal power units with an installed capacity of 1050MW; wind power and load normalized power (1.0p.u. wind power corresponds to its installed capacity, 1.0p.u. load corresponds to the maximum load power) on a certain day, and the increasing wind power penetration rate (the ratio of maximum wind power to maximum load power) may cause the system to abandon wind and lose load, affecting the system power Balance.

Definition: System unit power supply cost = total system generation cost / total system load power, total generation cost = thermal power cost + wind power cost + energy storage cost + wind abandonment loss + loss of load

First, thermal power should be operated at minimum cost in the case of no wind power access. In this paper, after considering the total generation cost of the system at this time, including thermal power cost (thermal power cost includes operation cost and carbon capture cost) and lost load cost, we use quadratic planning to establish an analytical model. Since the daily load pattern of a region does not change much within a short period of time, the normalized power of a certain day in Annex 1 is used as the basis of reasoning after inverse normalization, and the quadratic planning model is used to obtain the power output of each unit at 15-minute intervals for 96 moments in a day, so as to draw the generation plan curve of the units and calculate the system unit cost of power supply, and finally the genetic algorithm is used to test the reliability of the model and the quadratic planning algorithm. The reliability of the model and the quadratic planning algorithm is checked by genetic algorithm.

Secondly, according to the system to supply power at the lowest cost, this paper discusses the optimal power allocation at each moment with different carbon capture costs in the 2-3 wind power replacement scenarios separately, using quadratic planning, in order to achieve the lowest overall system cost.

Finally, in the scenarios of wind power replacement of thermal power units 2 and 3, the number of moments of mandatory load loss and the number of moments of mandatory wind abandonment are calculated separately for each of the fifteen days without considering energy storage, and then the average user outage time, average wind abandonment time, average imbalance moments, and average balance moments for the fifteen days are derived to measure the power balance problem of the system. After analyzing the system power balance problem, a dual-model approach is used to consider the power balance solution. The first model uses the minimum energy storage allocation plan model, and the second model uses the minimum system cost planning model, and then the optimal power balance solution is obtained by combining the fuzzy hierarchical analysis method, and the feasibility and effectiveness of the solution are evaluated by the consistency test.

2. Model Assumptions

(1) When there is wind turbine without energy storage device, the power generation is greater than the power consumption, that is, the wind abandonment; the power generation is less than the power consumption, that is, the loss of load phenomenon.

(2) If there is a moment of loss of load, there will be a power outage for users from that point to the next moment; if there is a moment of wind abandonment, there will be less power generation from wind power from that point to the next moment.

(3) The power of thermal power units can be continuously adjusted.

(4) The given units must all be put into use, i.e. there is no unit outage.

(5) The load power and wind turbine power are constant within 15 minutes.

3. Model construction and solving

3.1 Thermal power output allocation model only

3.1.1 Data pre-processing: inverse normalization

The base value is Pmax, and Pmax is 900MW at this time, which means that the daily load power is obtained for 96 moments in this case.

$$P_* = \frac{P}{P_{\max}} \tag{1}$$

3.1.2 Model building

If the objective function of a nonlinear plan is a quadratic function of the independent variable x and the constraints are all linear, the plan is called a quadratic plan[1].

The mathematical model of quadratic programming in Matlab can be expressed as follows.

$$\begin{aligned} &\min \quad \frac{1}{2}x^T Hx + f^T x \\ &\text{s.t.} \quad \begin{cases} Ax \le b \\ Aeq \cdot \text{x=beq} \end{cases} \end{aligned} \tag{2}$$

The command for solving quadratic programming in Matlab is.

```
[X, FVAL] =QUADPROG (H, f, A, b, Aeq, beq, LB, UB, X0, OPTIONS)
```

Where the return value X is the value of the decision vector x and the return value FVAL is the value of the objective function at x.

The percentage of wind power in this question is 0. The total cost of power generation is only thermal power cost and loss of load, and thermal power cost includes operation cost and carbon capture cost, among which thermal power operation cost is composed of operation and maintenance cost and coal consumption cost of power generation[2]. As the relationship between coal consumption and its output is shown in Equation 3.

$$F = aP^2 + bP + c \tag{3}$$

Therefore, quadratic planning is used to find the power output distribution under minimum cost operation of thermal power.

However, it should be noted that the loss of load exists only when the unit output is less than the system load, so the quadratic planning framework is then categorized and discussed into two cases, with and without loss of load, and then the costs of the two cases are compared for 96 moments to arrive at the solution with the lowest economic cost.

The quadratic planning model with loss of load is as follows.

$$\min M_Z = \min\{M_1 + M_5\}$$
$$\text{s.t.}\begin{cases} 180 \le P_{G1} \le 600 \\ 90 \le P_{G2} \le 300 \\ 45 \le P_{G3} \le 150 \\ P_{G1} + P_{G2} + P_{G3} \le P_L \end{cases} \tag{3}$$

The quadratic programming model without loss of load is as follows.

$$\min M_Z = \min\{M_1\}$$
$$\text{s.t.}\begin{cases} 180 \le P_{G1} \le 600 \\ 90 \le P_{G2} \le 300 \\ 45 \le P_{G3} \le 150 \\ P_{G1} + P_{G2} + P_{G3} \ge P_L \end{cases} \tag{4}$$

The cost of thermal power is the sum of the operating cost of thermal power and the cost of carbon capture.

$$M_1 = M_{11} + M_{12} \tag{5}$$

The formula for calculating the operating cost of thermal power is as follows.

$$M_{11} = 0.2625 * (F_1 + F_2 + F_3) \tag{6}$$

The cost of carbon capture is calculated as follows.

$$M_{12} = \frac{24}{96} * \mathrm{c} * \left(0.72 * P_{G1} + 0.75 * P_{G2} + 0.79 * P_{G3}\right) \tag{7}$$

The loss of load is calculated by the following equation.

$$M_5 = 2000 * \left[P_L - (P_{G1} + P_{G2} + P_{G3})\right] \tag{8}$$

3.1.3 Model solving

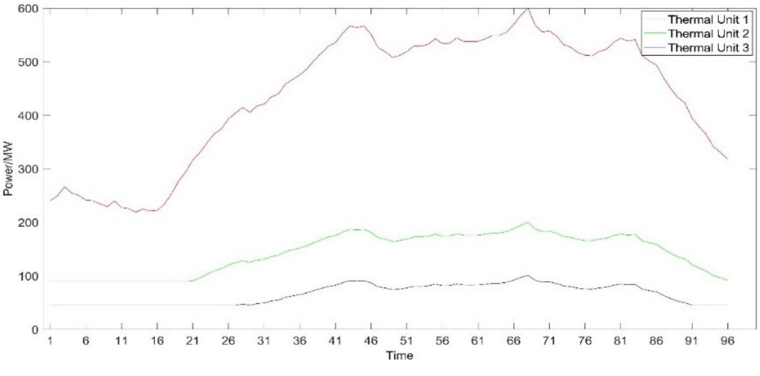

Figure 1: Daily generation plan curve

Based on the above model, the daily generation schedule curve is plotted as shown in Figure 1 below by solving for different carbon capture costs.

3.1.4 Model testing: testing the feasibility of quadratic planning with genetic algorithms

In this paper, we will find out the optimal solution of the model by genetic algorithm, compare the results obtained by genetic algorithm with the results of quadratic programming, and calculate the error between them, so as to judge whether quadratic programming is reliable in the solution process[3].

The error of the two algorithms on the output of the three thermal units is first compared by MAPE, and the results are obtained in Table 1.

Table 1: MAPE Analysis

	Thermal Unit 1	Thermal Unit 2	Thermal Unit 3
MAPE	0.77%	2.26%	0.68%

It can be seen that the results obtained by the genetic algorithm are less different from the results obtained with quadratic programming.

3.2 Modeling: High-scale wind power system output allocation

In the case with loss of load, the model is as follows.

$$\min M_1 = \min\left\{M_1 + M_2 + M_5\right\}$$
$$\text{s.t.}\begin{cases} 180 \le P_{G1} \le 600 \\ 90 \le P_{G2} \le 300 \\ P_{G1} + P_{G2} + P_W \le P_L \end{cases} \tag{9}$$

3.2.1 Solving of the model

As an example, we calculate the coal consumption cost of thermal power generation, carbon capture cost, loss of load and O&M cost of wind power during 0:00:00-0:15:00 with loss of load, and calculate the coal consumption cost of thermal power generation, carbon capture cost, loss of load and O&M cost of wind power during 0:00:00-0:15:00 without loss of load. O&M cost of wind power. After finding the costs in these two cases separately, a comparison is made and the least costly of these cases is taken as the lowest cost scenario.

After 96 comparative operations, the final total generation capacity of the generator is shown in Figure 2.

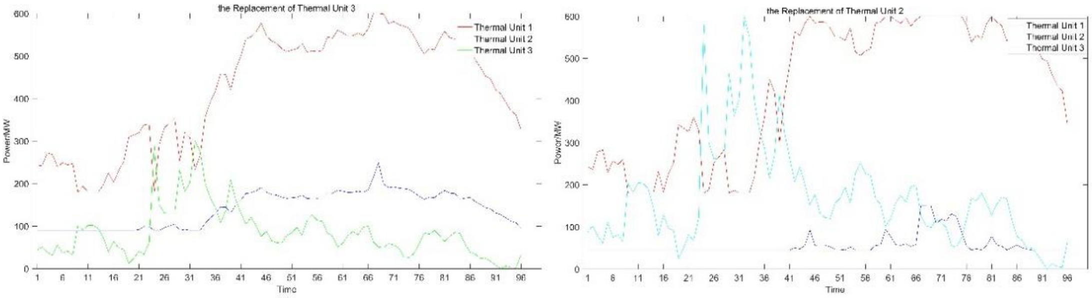

Figure 2: Lowest cost solution for power distribution with different replacement units

3.3 Dual model approach to consider power balance solutions

3.3.1 Analyze system power balance problems

Combined with the fifteen-day load power maximum of 1200 MW and the installed capacity of wind power of 1200 MW, in the scenario where wind power replaces thermal power units, the average number of unbalanced moments is larger, i.e., there are more cases where system power generation and power consumption cannot be matched, and there is a 71.87% probability of load loss or wind abandonment. At the same time, the average power outage time is longer than the average wind abandonment time, which makes it easier to lose load[4].

3.3.2 Modeling of Model 1: Minimum Energy Storage Allocation Plan Model

Based on the above analysis, a power balancing solution needs to be sought to ensure the reliability of the system power supply.

First, we introduce the minimum energy storage allocation plan model to balance the system power by energy storage to cope with the system power imbalance problem. Since the cost of energy storage is relatively expensive, using energy storage to balance the system power will increase the system operation cost, so it is necessary to find the minimum energy storage allocation plan.

The required energy storage power of the system per unit dispatch time period is taken as the optimization variable, and the double random variables of load prediction error and wind power prediction error are introduced to establish the following mathematical model.

1) Objective function.

The optimization objective is the minimum energy storage power required by the system in the whole dispatching period.

$$\min f\left(\cdot\right) = C_t^{\mathrm{ES}}, t = 1, \ldots, T \tag{10}$$

2) Opportunity Constraints

$$C_t^{\mathrm{ES}} + \sum_{i=1}^{N_G} \bar{P}_i^G - P_t^{L,F} + P_t^{W,F} \geq 0 \tag{11}$$

$$\sum_{i=1}^{N_G} \underline{P}_i^G - C_t^{\mathrm{ES}} + P_t^{L,F} + P_t^{W,F} \leq 0 \tag{12}$$

$$u_t C_t^{\mathrm{ES}} + \sum_{i=1}^{N_G} P_{i,t}^G + P_t^{W,A} = P_t^{L,A} \tag{13}$$

$$\underline{P}_i^G \leq P_{i,t}^G \leq \overline{P}_i^G \tag{14}$$

3.3.3 Modeling of Model 2: Minimum System Cost Planning Model

Since the realistic operation needs to consider not only the system balance but also the economy of operation cost, the minimum system cost planning model is established to minimize the power supply cost of the system while ensuring the system power balance.

The corresponding model is as follows.

$$\begin{aligned} &\min \quad M_Z = M_1 + M_2 + M_3 + M_4 + M_5 \\ &\text{s.t.} \ \begin{cases} P_C \leq \max(C_1, C_2) \\ \underline{P}_G \leq P_G \leq \overline{P}_G \end{cases} \end{aligned} \tag{15}$$

3.3.4 Solution of the model: fuzzy hierarchical analysis to derive the optimal solution

Fuzzy hierarchical analysis (FAHP) and computational process hierarchy analysis (AHP) is a qualitative and quantitative system analysis method proposed by Professor T.L. Saaty of American Operations Research in 1970s[5].

The method provides a basis for quantifying evaluation indicators and selecting the optimal solution, and has been widely used. However, AHP has the following shortcomings: it is very difficult to test whether the judgment matrix is consistent, and the criterion CR<0.1 for testing whether the judgment matrix is consistent lacks scientific basis; the consistency of the judgment matrix is significantly different from the consistency of human thinking. In the fuzzy hierarchical analysis, when making a two-by-two comparison judgment between factors, if the triangular fuzzy number is not used to quantify, but the quantitative representation of the importance of one factor over another, the fuzzy judgment matrix is obtained.

The basic idea of fuzzy hierarchical analysis is to decompose the problem itself by levels according to the nature of the multi-objective evaluation problem and the overall objective, which constitutes a bottom-up ladder hierarchy. Therefore, when applying FAHP decision making, it can be broadly divided into the following four steps.

1) Analyze the problem, determine the causal relationships between the factors in the system, and model the multi-level (multi-level) recursive structure of the various elements of the decision problem.

2) To make a two-by-two comparison of the elements of the same level (hierarchy) with the elements of the previous level as the criterion, and to determine their relative importance according to the rating scale, and finally to establish a fuzzy judgment matrix accordingly.

3) Determining the relative importance of each element through certain calculations.

4) To prioritize all alternatives through the calculation of comprehensive importance, so as to provide a scientific decision basis for decision makers to select the optimal solution.

First establish the fuzzy complementary judgment matrix, in the fuzzy hierarchical analysis, for the two-by-two comparison judgment between factors, using a quantitative representation of the importance of one factor over another, then the fuzzy judgment matrix obtained.

$$A = \left(a_{ij}\right) n * n \tag{16}$$

The formula for solving the weights of the fuzzy complementary judgment matrix is as follows.

$$W_i = \frac{\sum_{j=1}^{n} a_{ij} + \frac{n}{2} - 1}{n\left(n-1\right)} \tag{17}$$

Whether the weight values obtained from equation (17) are reasonable should also be tested for consistency in comparative judgment. When the offset consistency is too large, it indicates that the calculation result of the weight vector is unreliable as the basis of decision making at this time. On the contrary, the decision basis is reliable.

The solution obtained by the fuzzy hierarchical analysis is compared with the

The optimal theoretical allocation scheme is the optimal thermal power output and the minimum energy storage capacity under the condition of ensuring the system power balance, and the relationship between the two is.

$$P_G + P_W \pm P_C = P_L \tag{18}$$

The following results were obtained.

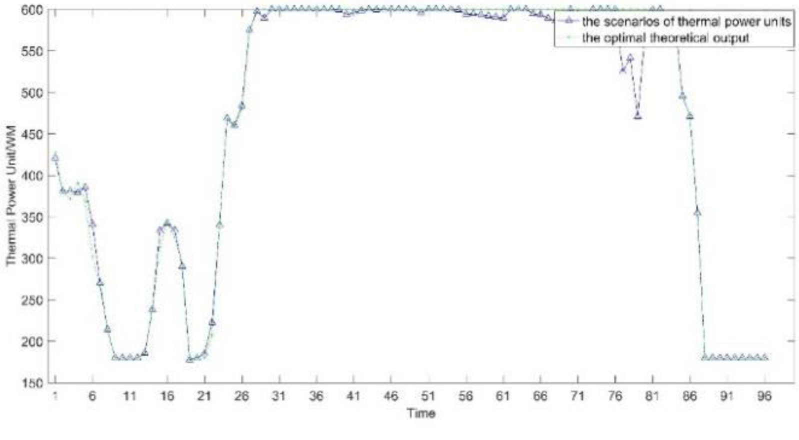

Figure 3: Comparison of the scenarios of thermal power units with the optimal theoretical output

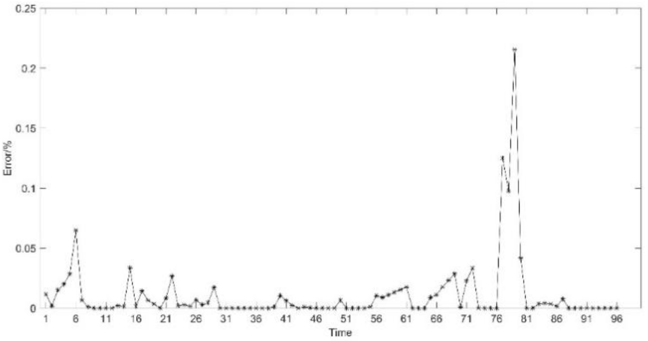

Figure 4: Thermal power output error

From Figure 3 and Figure 4, it can be seen that the decision scheme is closer to the results obtained from the optimal theoretical output case with less error.

The energy storage configuration capacity obtained from the scheme is compared and analyzed with the optimal theoretical configuration capacity on day 15, and the following results are obtained.

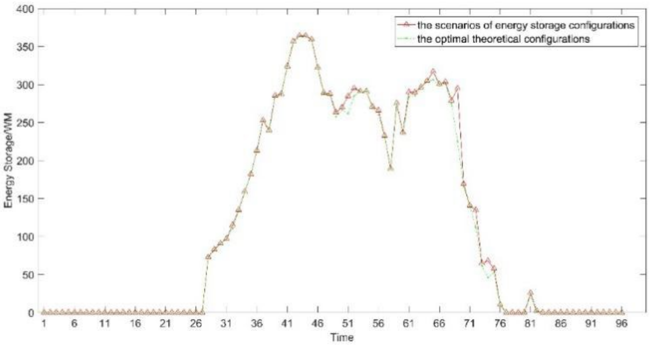

Figure 4: Comparison of theoretical and optimal theoretical configurations of energy storage configurations

It can be observed that the scheme obtained from the analysis is approximately equal to the optimal theoretical configuration scheme with less error.

In summary, it can be concluded that the optimal thermal power output and optimal energy storage allocation capacity obtained by using the dual model method and then the scheme obtained by fuzzy hierarchical analysis are more reasonable and feasible.

4. Conclusion

In this paper, by analyzing a large amount of load data and unit output data, and with the help of plotting and statistics, we use quadratic planning analysis to analyze only thermal power output allocation model and use genetic algorithm for feasibility check; high proportional wind power system output allocation model; minimum energy storage allocation plan model, minimum system cost planning model and pass the consistency check using fuzzy hierarchical analysis method. When considering the reliability of power supply, this paper gives a scheme to predict the optimal thermal power unit output and the optimal energy storage allocation, which is beneficial to the system power balance.

The optimal thermal unit output can be obtained by the dual model of fuzzy hierarchical analysis, which is a reference value for power system dispatch. Through multiple choices in the minimum energy storage power configuration model and the lowest system day-ahead operation cost model, the lowest cost and most suitable energy storage configuration can be found, which can ensure the reliability of the power system.

Wind power has more influencing factors, intermittency and volatility, and more natural factors are not considered, and parameters such as creep rate of thermal power and rotating reserve capacity are not explicitly given.

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