Research on Heat Load Distribution Based on Peaking Capacity of Thermal Power Plant

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Abstract. With the rapid development of new energy sources, the peak load regulation of power grids is increasing day by day, while the northern part of China is dominated by cogeneration units. In the heating season, heat supply needs to be prioritized to meet the requirements of peak heating, which further complicates the difficulty of peak load regulation. In order to solve this problem, this paper takes into account the electric thermal characteristics of the unit itself, fully considers the difference of peak load regulation capacity among different types of units, and establishes the peaking capacity optimization model of the whole plant to determine the most thermal load between different types of units. The best distribution plan makes the whole plant have the highest peaking capacity.

1. Introduction
In recent years, with the increasing pressure of environmental protection, the state has intensified the development of new energy power generation. The 13th Five-Year Plan of Renewable Energy Development proposes that by 2020, conventional hydropower, wind power and solar power generation will reach 340 million kilowatts, 210 million kilowatts and 110 million kilowatts, and the proportion of renewable energy consumption will reach more than 12%, the proportion of generating electricity from bio-energy should be more than 30%. However, the development of new energy units in some regions is too fast, because of the particularity of new energy generating units, especially the inverse peak regulation characteristics of wind turbines, the peak regulation of power grids is facing severe challenges, which leads to the increasingly prominent problem of new energy absorption. The inverse peak regulation characteristics of wind turbines are characterized by the fluctuation of daytime output in a certain range, the gradual rise of night wind power output and the seasonal output characteristics of the highest average output in winter and the lowest average output in summer, which lead to the difficulty of peak regulation of wind power grid to a considerable extent. The wind abandonment rate of power generation is serious, which reaches 15% in 2015, 21% in 2016 and 12% in 2017.

For the northern areas lacking hydropower and steam turbine units, the main power of peak shaving in power grid is still thermal power units. With the increase of new energy units connected to the grid, the proportion of thermal power units starting up decreases, the reserve capacity of peak shaving in power grid decreases, and the peak shaving capacity decreases. On the other hand, with the development of urbanization, the proportion of thermal power units in northern areas is increasing, the thermal power unit as the main heat source needs to first meet the heat load, there is a "ordering power by heat"
constraints, the peak-shaving capacity in the heating season is severely constrained, some units with large heat supply can not even peak-shaving, but the output of wind power is significantly increased, "wind-heat conflict" aggravates the difficulty of peak-shaving.

At present, many thermal power plants realize thermoelectric decoupling by means of heat storage, electric boilers, optical axis modification, and low pressure cylinder removal operation, which has a very significant effect on enhancing peak shaving capacity of thermal power units, but the cost of modification is also high. For thermal power plants covering a variety of types of thermal power units, the operation characteristics and peak-shaving capacity of different units are different. Under certain conditions of total heat supply, the maximum peak-shaving capacity of the whole plant can be obtained by reasonable distribution of heat load among units. The greater the difference of electric and thermal characteristics between units, the effect of heat load distribution on enhancing peak shaving capacity of the whole plant is more obvious. Therefore, it is not necessary to reform the unit, only through the optimal distribution of heat load among units, the total peak shaving capacity of the plant can be improved. Starting from the electrothermal characteristics of the units, this paper fully considers the differences of peak-shaving capacity among different types of units, by establishing the optimization model of peak-shaving capacity of the whole plant, the optimal distribution scheme of heat load among different types of units is determined, so that the total peak-shaving capacity of the whole plant is maximized.

2. Analysis of electric and thermal characteristics of thermoelectric units

The correlation and coupling relationship between the generating power $P$ and the extraction steam quantity $G$ of the thermoelectric units is called the "electrothermal characteristics" of the units. When the extraction quantity $G$ is fixed, the generating power $P$ varies in a certain range. $P_{\text{max}}$ and $P_{\text{min}}$ respectively indicate the maximum and minimum electric power that the unit can emit under the current extraction quantity $G$, that is, the upper and lower peak shaving limits of the unit. When the external extraction capacity $G$ changes, the maximum electric power $P_{\text{max}}$ and the minimum electric power $P_{\text{min}}$ that the unit can emit will also change. By connecting the maximum and minimum electric power corresponding to different extraction capacity into a line, the electric-thermal relationship curve of the unit can be obtained.

In this paper, the design heat supply working condition diagram of the unit is used to draw the electric-thermal relationship curve of the unit. Fig. 1 is the design heat supply working condition diagram of a unit.

![Design heating working diagram of unit 1](image)

Fig. 1 Design heating working diagram of unit 1

The abscissa of Fig. 1 is the generating power $P$ of the unit, the ordinate is the main steam flow $G_c$, and the enclosed area in Fig. 1 is the running range of the unit under heating condition. The oblique line 1-6 is the equal extraction line, the top line is the maximum main steam flow limit line, and the bottom line is the minimum main steam flow limit line for heating. The oblique line 8 is the minimum intake flow limit line of the low pressure cylinder. The abscissa corresponding to the intersection point of the equal extraction line and the maximum main steam flow limit line is the maximum electric power that
the unit can emit under the extraction amount, i.e. the peak shaving upper limit; the abscissa corresponding to the intersection point of the equal extraction line and the minimum main steam flow limit line or the minimum intake flow limit line of the low pressure cylinder is the minimum electric power that can be emitted under the extraction amount, i.e. the lower limit of peak shaving.

By inputting the values of the maximum and minimum electric power of different steam extraction volume into excel respectively, the electric-thermal relationship curve of the unit can be generated, as shown in Figure 2. The abscissa of Fig. 2 is the extraction quantity G, and the ordinate is the generating power P. The blue curve above the figure is the variation curve of the unit peak shaving upper limit with the extraction quantity, and the red curve below is the variation curve of the unit peak shaving lower limit with the extraction quantity. The area surrounded by the two curves is the operation interval of the unit under the heating condition. The upper and lower limits of peak shaving can be obtained from the relation curve diagram under different external steam extraction volumes.

![Fig. 2 Electric thermal relationship diagram of unit 1](image)

Using excel to add trend lines to the peak-shaving upper limit curve and the peak-shaving lower limit curve respectively and fit them with formulas. The peak-shaving upper limit curve is generally approximated to a straight line and can be fitted by linear fitting; the peak-shaving lower limit curve is generally a broken line and can be fitted by polynomial fitting, and the accuracy can be satisfied by using the fourth-order polynomial fitting at most. In this way, the one-variable function expressions of the upper and lower limits of peak shaving varying with the amount of pumping steam can be obtained respectively. The upper and lower limits of peak shaving of a computer group under any amount of pumping steam can be obtained by using the above mathematical expressions, which is convenient for modeling and analyzing the peak shaving ability of the unit. The curve of the upper and lower limits of peak shaving with the change of extraction steam volume in Fig. 2 is added with trend line and fitting formula respectively, as shown in Fig. 3.

![Fig. 3 Electric thermal relationship diagram of unit 1 after increasing the trend line and fitting formula](image)

There are more or less differences in capacity, parameters, heating mode and extraction position of different thermoelectric units, so the electrothermal characteristics are also different. Figure 4 shows the electric-thermal relationship curves of different types of units. Compared with Figure 2, there are obvious differences. The upper limit curve of peak shaving in the two groups is similar to straight line,
but the slope is slightly different. The lower limit curve of peak shaving is a broken line, there is an obvious inflection point, but the coordinate position of inflection point is quite different.

![Fig. 4 Design heating working diagram of unit 2](image)

As shown in Fig. 5, the trend line and fitting formula are added to the second electrothermal relationship curve of the generating unit.

![Fig. 5 Electric thermal relationship diagram of unit 2 after increasing the trend line and fitting formula](image)

3. **Optimization model of peak shifting capacity of the plant**

Peak-shaving capacity of thermal power units refers to the capacity of load adjustment of units under a certain amount of steam extraction, the main indicators are the upper and lower limits of peak-shaving under the current amount of steam extraction; the peak-shaving capacity of the whole plant is shown as the upper and lower limits of the total peak-shaving capacity of the whole plant, that is, the sum of the upper and lower limits of peak-shaving of all units in the plant under the current amount of steam extraction. The upper and lower limits of unit peak shaving will change with the change of extraction steam volume, and the upper and lower limits of total peak shaving will also change.

The objective of this paper is to solve the maximum and minimum of peak shaving upper limit and lower limit and the corresponding heat load distribution scheme on the premise that the total external heating capacity of the whole plant remains unchanged.

According to the analysis of the electric and thermal characteristics of thermal power units, it is known that the upper and lower limits of peak shaving are one-dimensional functions of the extraction capacity, so the upper and lower limits of peak shaving are multivariate functions of the extraction capacity of all units in the plant, so we can transform the optimization problem of peak shaving capacity of the whole plant into the problem of finding the extremum of multivariate functions with constraints. The independent variable of the multivariate function is the external steam extraction capacity of each unit, and the extreme value of the multivariate function is the upper and lower limits of peak shaving of the whole plant. The constraints of the multivariate function are that the total external heat supply of the whole plant remains unchanged and the steam extraction capacity of each unit does not exceed the design maximum.
The formulas for calculating the upper and lower peak shaving limits of each unit are as follows:

\[ P_{\text{max}, n} = f'_{\text{max}}(G_n) \]  

(1)

In the formula: \( P_{\text{max}, n} \) is the peak shaving upper limit of the \( n \) units, MW; \( G_n \) is the \( n \) unit's external extraction capacity, t/h; \( f_{\text{max}}(G_n) \) is the one-variable function of the external extraction capacity, which is obtained by using the fitting formula of the unit peak shaving upper limit curve.

\[ P_{\text{min}, n} = f'_{\text{min}}(G_n) \]  

(2)

In the formula: \( P_{\text{min}, n} \) is the upper limit of peak shaving for the \( n \)th unit, MW and \( f_{\text{min}}(G_n) \) are the univariate functions of the external steam extraction capacity, which are obtained by using the curve fitting formula of the lower limit of peak shaving for the unit.

According to formulas (1) and (2), the objective functions of the total peak shaving upper and lower limits and the external steam extraction capacity of each unit can be obtained as follows:

\[ P_{\text{max}, n} = P_{\text{max}, 1} + P_{\text{max}, 2} + \ldots + P_{\text{max}, n} = f'_{\text{max}}(G_1) + f'_{\text{max}}(G_2) + \ldots + f'_{\text{max}}(G_n) \]  

(3)

In the formula: \( P_{\text{max}, n} \) is the upper limit of peak shaving, MW;

\[ P_{\text{min}, n} = P_{\text{min}, 1} + P_{\text{min}, 2} + \ldots + P_{\text{min}, n} = f_{\text{min}}(G_1) + f_{\text{min}}(G_2) + \ldots + f_{\text{min}}(G_n) \]  

(4)

In the formula: \( P_{\text{min}, n} \) is the lower limit of peak shaving, MW.

The objective functions for calculating the upper and lower limits of peak shaving in the whole plant are given above, and the following expressions for the constraints are given as follows:

\[ Q_n = G_1(h_1 - h_{1s}) + G_2(h_2 - h_{2s}) + \ldots + G_n(h_n - h_{ns}) \]

\[ 0 \leq G_1 \leq G_{1\text{max}} \]

\[ 0 \leq G_2 \leq G_{2\text{max}} \]

\[ 0 \leq G_n \leq G_{n\text{max}} \]  

(5)

In the formula: \( Q_n \) is the total external heat supply of the plant, GJ/h, which is a fixed value; \( G_1, G_2, \ldots, G_n \) denotes the external steam extraction capacity of the first to the \( n \)th units, t/h; \( h_1, h_2, \ldots, h_n \) are the heat extraction enthalpy, kJ/kg of the first to the \( n \)th units; \( h_{1s}, h_{2s}, \ldots, HNS \) are the heat extraction enthalpy, kJ/kg of the first to the \( n \)th units; \( G_{1\text{max}}, G_{2\text{max}}, \ldots, G_{n\text{max}} \) are the design maximum steam extraction volume of the first to the \( n \)th units, t/h, which is a fixed value and can be obtained by using the design heat supply working diagram of each unit.

The mathematical model and constraints of the upper and lower limits of the total peak shaving are given, the solution of the model is a typical multi-variable function extremum problem with constraints. This paper uses the fmincon function of the optimization toolbox of MATLAB to solve the problem. However, the fmincon function can only be used to solve the minimum value, and can not be directly used to solve the calculation model of the peak shaving upper limit, therefore, we transform the problem of solving the maximum value of the objective function \( P_{\text{max}, n} \) of the peak shaving upper limit into the problem of solving the minimum value of the negative function of the objective function \( P_{\text{max}, n} \).

The objective functions - \( P_{\text{max}, n}, P_{\text{min}, n} \) and the corresponding constraints are input into MATLAB, and the fmincon function is invoked to calculate the upper limits of peak shaving maximum and the lower limits of peak shaving minimum of the whole plant as well as the corresponding unit extraction capacity.

4. Examples of calculation

The basic situation of a thermal power plant is as follows: units 1 and 2 in the first phase of the project are two subcritical, primary reheating and extraction condensing units, the model is NC330/242-16.7/0.8/535, the extraction position is medium pressure cylinder exhaust, the rated heating pressure is 0.8MPa, the rated extraction flow is 340t/h, and the maximum extraction flow is 400t/h; in the second
phase of the project, units 3 and 4 are two supercritical, primary reheating and steam extraction condensing units. The model is C350/294-24.2/0.43/566, the extraction position is the exhaust of medium pressure cylinder, the rated extraction pressure is 0.43 MPa, the rated extraction flow is 400 t/h and the maximum extraction flow is 500 t/h.

The current operation of units in the thermal power plant is #1, #3, #4 units, and #2 units are out of operation. In order to verify the accuracy of the model and enhance the peak shaving capacity of the whole plant, the model is used to optimize the current extraction conditions of each unit in the power plant. On the premise that the total external heat supply of the whole plant remains unchanged, the maximum peak shaving and the minimum peak shaving of the whole plant are respectively taken as the objectives to re-optimize the distribution of the steam extraction capacity of each unit.

The external heat supply of each unit and the whole plant is shown in Table 1.

| Number | Name                                      | Unit 1 | Unit 3 | Unit 4 |
|-------|-------------------------------------------|--------|--------|--------|
| 1     | Actual extraction capacity/ (t/h)          | 152.84 | 252.45 | 379    |
| 2     | Extraction pressure /MPa                  | 0.64   | 0.2    | 0.16   |
| 3     | Extraction temperature /°C                | 340.81 | 227.11 | 272.14 |
| 4     | Exhaust flow/ (t/h)                       | 152.84 | 252.45 | 379    |
| 5     | Drainage and hydrophobic temperature /°C  | 90.28  | 84.14  | 80.32  |
| 6     | Extraction enthalpy/ (kJ/kg)              | 3146.13| 2925.28| 3016.96|
| 7     | Drainage enthalpy/ (kJ/kg)                | 377.98 | 352.28 | 336.28 |
| 8     | Heating capacity / (GJ/h)                 | 423084.06| 649553.31| 1015978.56|
| 9     | Total heat supply / (GJ/h)                | 2088615.93|

The upper and lower limits of pumping capacity and peak shaving before and after optimization are shown in Table 2.

| Number | Name                                      | Unit 1 | Unit 3  | Unit 4  |
|-------|-------------------------------------------|--------|---------|---------|
| 1     | Actual steam extraction capacity/ (t/h)   | 152.84 | 252.45  | 379     |
| 2     | Extraction capacity based on peak shaving maximum optimization/ (t/h) | 0      | 290.95  | 500     |
| 3     | Extraction capacity based on minimum peak shaving optimization/ (t/h) | 370.94 | 202.23  | 202.04  |
| 4     | Actual upper limit of peak shaving        | 307.40 | 341.00  | 315.66  |
| 5     | The upper limit of peak shaving after optimization / MW | 341.96 | 333.29  | 291.42  |
| 6     | Actual lower limit of peak shaving        | 179.12 | 194.03  | 237.60  |
| 7     | The lower limit of peak shaving after optimization /MW | 131.93 | 190.32  | 190.32  |

Before and after optimization, the plant's external steam extraction capacity and peak shaving upper and lower limits are compared as shown in Table 3.

| Number | Name                                  | Whole plant |
|-------|---------------------------------------|-------------|
| 1     | Actual steam extraction capacity/ (t/h) | 784.29      |
| 2     | Extraction capacity based on peak shaving maximum optimization / (t/h) | 790.95      |
| 3     | Extraction capacity based on minimum peak shaving optimization / (t/h) | 775.21      |
| 4     | Actual peak shaving upper limit / MW   | 964.06      |
| 5     | Upper limit of peak shaving after optimization / MW | 966.67      |
| 6     | Actual lower peak shaving limit / MW   | 610.74      |
| 7     | Lower limit of peak shaving after optimization / MW | 512.58      |
From the calculation results in Tables 2 and 3, the following conclusions are drawn:

1) Before and after optimization of peak shaving capacity, the total external steam extraction capacity of each unit varies greatly, but the total external steam extraction capacity does not change much, because the enthalpy of extraction of each unit varies little, and the total external steam extraction capacity does not change much on the premise of guaranteeing the constant total heat supply capacity of the whole plant.

2) Before and after the optimization of peak shaving capacity, the upper and lower limits of peak shaving of each unit vary in varying degrees. Some units may have lower or higher peak shaving upper limits, but the lower limits of the total peak shaving of the whole plant increase. Because the optimization model established in this paper is from the point of view of the whole plant, it is possible to sacrifice the peak shaving performance of a single unit in order to improve the overall capacity of the plant.

3) After optimizing the heat load distribution of the whole plant, the total peak shaving limit of the whole plant increases from 964.06 MW to 966.67 MW, and the lower limit of peak shaving decreases from 610.74 MW to 512.58 MW. Among them, the lower limit of peak shaving, which is more meaningful for new energy consumption, has been reduced by 98.16MW and the depth of peak shaving has been increased by 16%. After optimization, the lower peak shaving limit of the plant is obviously reduced, but the upper peak shaving limit is not raised much. Comparing Figure 2 and Figure 4, it can be seen that the upper limit curve of peak load regulation of two types of units is approximately linear and the slope difference is not large, while the lower limit curve of peak load regulation is a broken line, and the position of slope and inflection point are quite different. The bigger the gap of electric and thermal characteristics between units, the better the optimization effect of heat load distribution.

5. Conclusion

In view of the problem that the thermal power units in heating season are not able to adjust peak load due to the influence of heat supply, thus affecting the absorption of new energy such as scenery and so on, this paper starts with the study of the electro-thermal relationship among the units in thermal power plants, and establishes the mathematical models of the upper and lower limits of peak load regulation and the steam extraction capacity of each unit, and then obtains the upper and lower limits of the total peak load regulation and the steam extraction capacity of each unit in the plant. The objective function is solved by using fmincon function of MATLAB toolbox on the premise of keeping the total external heating capacity unchanged. Two optimal heat load distribution schemes are given, which make the maximum peak shaving and the minimum peak shaving respectively.

On-line optimization of the operation conditions of a thermal power plant verifies the accuracy and optimization effect of the model. The effect of reducing the lower limit of peak shaving is very obvious, thus freeing up more load space for the power grid and promoting the absorption of new energy such as wind and light, which has significant economic and social benefits.

References

[1] National Development and Reform Commission. 13th Five-Year Plan for Renewable Energy Development [R]. Beijing: National Development and Reform Commission, 2016, 12.

[2] Xu Dan, Ding Qiang, Huang Guodong, et al. [J]. Power system protection and control, 2017, 45 (11): 59-64, considering the dynamic dispatch model of heat load of cogeneration of heat and power considering peak shaving.

[3] Wu Long, Yuan Qi, Liu Xin. Analysis of the Optimum Distribution Method of Thermoelectric Load for Heating Units [J]. Chinese Journal of Electrical Engineering, 2012, 32 (35): 6-12.

[4] Lv Quan, Chen Tianyou, Wang Haixia, et al. Peak shaving capacity analysis of thermal power units after thermal storage [J]. Power system automation, 2014, 38 (11): 34-41.

[5] Wang Xuedong, Wei Dong, Sun Shuyao, et al. Optimal distribution of electric and thermal load and peak regulation performance of different types of heating units [J]. Steam Turbine Technology, 2010, 52 (5): 387-390.