Optimal Load Distribution of Power Plants Based on Linear Programming Method and Equal Micro-increment Method

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Abstract. Optimal load distribution was an important way for power generation enterprises to save energy, reduce consumption and improve market competitiveness. At present, a lot of relevant studies had been carried out and many schemes have been put forward. In this paper, the application of equal micro-increment method and linear programming method in load optimization distribution was introduced. The results showed that the general trend of the two distribution methods was that the heat consumption rate of the steam turbine decreases with the increase of the load, and the change rate of the heat consumption of the steam turbine decreases gradually. At the lowest load, the difference between the two methods was the smallest. At 55% load, the difference of steam turbine heat consumption rate was the largest. Between 55% load and rated load, the difference between the steam turbine's heat consumption rates was gradually reduced. The analysis conclusion had certain reference value to the current energy saving optimal scheduling.

1. Introduction

With the sharp decline of primary energy, its price continues to rise. Fuel costs dominate the cost of electricity generation, and the cost of electricity generation was increased. This severe situation forced power generation enterprises to find all kinds of energy saving means to reduce power generation costs and enhance market competitiveness. At the same time, the grid's orders to power plants had changed from generating load to generating load for the whole plant. Therefore, optimizing the load of each unit was a necessary way for power generation enterprises to save energy. Optimal load distribution not only improved the economic benefits of power generation enterprises, but also had important significance to the sustainable development of national economy.

Experts and scholars at home and abroad had also studied this problem and put forward many solutions. The priority method was to arrange the loads according to the efficiency of the unit. Simulated annealing algorithm was to obtain the extreme solution of the problem according to the motion law of particles in thermal equilibrium at a certain temperature. Ant colony algorithm (ACO) was an optimization algorithm to find the shortest path in multiple points according to the law of ant foraging. Tabu search algorithm was to record the local solution obtained at present and exclude the local solution in the subsequent iterative calculation until the global optimal solution is obtained. At present, power generation enterprises had realized the irrationality of the priority method for load distribution and eliminated this method. However, the computational process of intelligent algorithms such as tabu search algorithm and neural network algorithm represented by simulated annealing was
quite complex. Therefore, these intelligent algorithms were still in the optimization research, and had not been widely promoted.

At present, the efficiency of boiler was assumed to be constant when load allocation was carried out in most power generation enterprises. However, boiler efficiency was not always constant due to the influence of environmental temperature, coal quality characteristics and other factors. Based on this consideration, the optimum objective was to minimize the heat consumption of the unit by the paper. At the same time, the linear programming method and the equal micro-increment method were analysed in combination with two typical domestic units. The analysis results had certain reference value for the current energy saving optimal scheduling.

2. The mathematical model based on linear programming

2.1. The principle of linear programming

The corresponding feasible solution was obtained from a pole in the feasible region, and the optimal solution was judged. If the solution was optimal, the calculation ends; if not the optimal solution, calculate the feasible solution for the next pole. Repeat the steps until you find the optimal solution. Objective function and boundary conditions were obtained according to the actual problem. If the problem was not of standard type, relaxation variables should be introduced to standardize the problem. In order to quickly find the initial feasible basis of the constrained equations, artificial variables were introduced as needed. At this point, we could do the initial solution. According to the solution result, the test number was used to judge whether the solution was the optimal solution. If the solution was optimal, the calculation ends; if it was not the optimal solution, according to the test number and technical coefficient to determine whether there was an optimal solution; if there was an optimal solution, find the input and output variables respectively. Repeat the steps with the new feasible basis until the optimal solution was found.

2.2. The standard form of linear programming

In order to facilitate the programming of computation, a variety of non-standard problems needed to be converted into standard problems before calculation. The form of standard problems was as follows:

\[
\begin{align*}
\max & \quad z = c_1 x_1 + c_2 x_2 + \cdots + c_n x_n \\
\text{s.t.} & \quad a_{11} x_1 + a_{12} x_2 + \cdots + a_{1n} x_n = b_1 \\
& \quad \vdots \\
& \quad a_{m1} x_1 + a_{m2} x_2 + \cdots + a_{mn} x_n = b_m \\
& \quad x_i \geq 0 \quad (1 \leq i \leq n)
\end{align*}
\]

In where: \(z\) was the objective function; \(x_i\) was the decision variable; \(c_i\) was cost coefficient; \(a_{ij}\) was the technical coefficient; \(b_j\) was the resource coefficient.

\[
\begin{align*}
\max & \quad Z = CX \\
AX & = B \\
X & \geq 0
\end{align*}
\]

In where: \(C\), \(X\), \(A\) and \(B\) were the matrix forms corresponding to each coefficient of equation (1).

2.3. Linear programming was applied to a mathematical model of load distribution

\[
\begin{align*}
\min & \quad q = (c_1, c_2, \cdots, c_n, P_1, P_2, \cdots, P_n)^T \\
\text{s.t.} & \quad P_{\text{min}} \leq p_i \leq P_{\text{max}} \\
& \quad \sum_{i=1}^n p_i = P
\end{align*}
\]

In where: \(q\) was the heat consumption rate of steam turbine; \(p_i\) was the load of each unit; \(P_{\text{min}}\) and \(P_{\text{max}}\) were respectively the minimum and maximum loads of unit \(i\).
It could be seen from equation (3) that it should be changed into a standard type in calculation. For the objective function, the minimum value of the steam turbine heat loss rate could be converted to the maximum value of the negative heat loss rate. The constraints could be turned into equations by adding relaxation variables. The linear programming method was used to find the safe and economical operation mode of the system under known constraints.

3. The mathematical model based on the equal micro-increment method

Assuming that the power generation enterprise had n units running side by side and the total load was \( P \), the equal micro-increment method was a distribution method that distributes the total load to each unit, and made each unit operate safely between the maximum load and the minimum load, and minimized the total steam turbine heat consumption.

\[
q_{\text{min}} = q_1 + q_2 + \cdots + q_n = \sum_{i=1}^{n} q_i
\]  

(4)

In where: \( q \) was the total steam turbine heat consumption rate of the power generation enterprise; \( q_i \) was the heat consumption rate of unit \( i \).

In practical operation, it was assumed that each unit runs stably for the sake of simple calculation. Considered only the following constraints:

\[
p = p_1 + p_2 + \cdots + p_n = \sum_{i=1}^{n} p_i
\]  

(5)

In where: \( p \) was the total load of the power generation enterprise; \( p_i \) was the load borne by unit \( i \).

\[
P_{\text{imin}} \leq p_i \leq P_{\text{imax}} \]  

(6)

In order to solve the minimum steam turbine heat consumption rate, the conditional extreme value was transformed into the unconditional extreme value, and the Lagrangian function \( W \) and the parameter \( \beta \) were introduced.

\[
W = q_{\text{min}} + \beta (P - p_1 - p_2 - \cdots - p_n) + \sum_{i=1}^{n} q_i + \beta (P - \sum_{i=1}^{n} p_i)
\]  

(7)

In equation (7), there was a functional relationship between steam turbine heat consumption rate \( q_i \) and load, namely \( q_i=f(p_i) \). So the auxiliary function \( W \) was load multivariate function, namely \( W=\varphi(p_1,p_2,\ldots,p_n) \).

According to the necessary condition of the extremum of the function, the first partial derivative of the function with respect to each variable was 0.

\[
\frac{\partial W}{\partial p_i} = \frac{\partial (\sum q_i)}{\partial p_i} + \frac{\partial (\beta p_i)}{\partial p_i} \frac{\partial (\sum p_i)}{\partial p_i} = 0
\]

\[
\frac{\partial W}{\partial p_j} = \frac{\partial (\sum q_i)}{\partial p_j} + \frac{\partial (\beta p_j)}{\partial p_j} \frac{\partial (\sum p_i)}{\partial p_j} = 0
\]

\[
\frac{\partial W}{\partial \beta} = \frac{\partial (\sum q_i)}{\partial \beta} + \frac{\partial (\beta)}{\partial \beta} \frac{\partial (\sum p_i)}{\partial \beta} = 0
\]  

(8)

When solving equation (8), it should be noted that the heat consumption rate of each unit was only related to its own load. The total load \( P \) was a given constant, namely:

\[
\frac{\partial q_i}{\partial p_j} = \begin{cases} 
0, & i \neq j \\
\frac{\partial q_i}{\partial p_i}, & i = j 
\end{cases}
\]  

(9)
\[
\frac{\partial P}{\partial P_i} = 0
\]  \hspace{1cm} (10)

From equations (9) and (10), equation (8) could be resolved into equation (11):

\[
\frac{\partial q_1}{\partial p_1} = \frac{\partial q_2}{\partial p_2} = \ldots = \frac{\partial q_n}{\partial p_n}
\]  \hspace{1cm} (11)

Equation (11) showed that the heat consumption micro-increment rate of each unit was the same, which was also the origin of equal micro-increment rate. Equation (11) could also be called the equation of heat consumption rate of equal micro-increment rate. In order to facilitate the research and within the allowable error range, the steam turbine heat loss characteristic curve was fitted into a quadratic polynomial, namely \(q_i = a_i p_i^2 + b_i p_i + c_i\). According to equation (11), we could get the equation \(P_i = (\beta - b_i)/2a_i\). From equation (5) and the above formula, the equation (12) could be got.

\[
p = p_1 + p_2 + p_3 + \ldots + p_n = \frac{\beta}{2} \sum_{j=1}^{n} \frac{1}{a_j} - \frac{1}{2} \sum_{j=1}^{n} \frac{b_j}{a_j}
\]

\[
\beta = \left( 2 \frac{p + \sum_{j=1}^{n} \frac{b_j}{a_j}}{\sum_{j=1}^{n} \frac{1}{a_j}} \right)^2 - \sum_{j=1}^{n} \frac{1}{a_j}
\]  \hspace{1cm} (12)

4. The example analysis

Based on the data on a 300 MW unit and a 600 MW unit in a certain power generation enterprise, load distribution was carried out respectively by means of the linear programming method and the micro-increment method. According to the above two mathematical models, program it with software so that the results could be calculated.

4.1. An example of the linear programming method

To obtain the set heat loss characteristics, the \(\varphi = \text{span}[\varphi_0(x), \varphi_1(x), \ldots, \varphi_n(x)]\) space with known data\((p_i, q_i)\) was used to synthesize the heat loss characteristics curves. In order to meet the requirements of accuracy, fitting rule was: the sum of squared errors between \(q(P_i) = \sum a_i \varphi_i(p_i)\) and the known data \(p_i\) was the smallest, that was, \(\sum a_i \varphi_i(p_i) - q_i\) was the smallest. The fitting results were shown in equation (13).

\[
\begin{align*}
q_1 &= -1.190 \times 3P_i + 8821.4 \\
q_2 &= -0.778 \times 6P_i + 8394.3
\end{align*}
\]  \hspace{1cm} (13)

\(q_1\) and \(q_2\) were the heat consumption rates of 300 MW units and 600 MW units respectively. The lower output limit and upper output limit of 300 MW units were 100 MW and 300 MW respectively. The lower output limit of 600 MW unit was 200 MW, and the upper output limit was 600 MW. According to the theory of linear programming, it was necessary to carry out standardization treatment before calculating the minimum heat consumption. FIG. 1 was a fitting linear diagram of the steam turbine's heat consumption rate and load. FIG. 2 was a software flow chart of the linear programming method. The calculation results of the linear programming method were shown in Table 1.
4.2. The example of the equal increment method

According to the above fitting rules, the heat loss characteristics of the unit were fitted into a quadratic polynomial, as shown in equation (14). \( q_1 \) and \( q_2 \) were the heat consumption rates of 300 MW and 600 MW units respectively.

\[
\begin{align*}
q_1 &= 0.0006P_1^2 - 0.9522P_1 + 8741.7 \\
q_2 &= 0.0002P_2^2 - 0.9322P_2 + 8427.6
\end{align*}
\] (14)

It could be seen from equation (14) that the heat consumption rate of the unit had a strictly monotonically increasing relation, so the method of equal rate of increase was tenable here. In order to ensure the safe operation of the unit, the load must be between the maximum load and the minimum load. If the load allocated by the unit exceeds the maximum load, the unit will operate at full load. The residual load was distributed to the remaining units at the same rate of slight increase. The situation was similar when the load was below the minimum load. The software flow chart was shown in FIG.3.
The calculation results were shown in Table 2. In order to visually reflect the load distribution of the two methods, the calculation results of the equal micro-increment method and the linear programming method were represented by the graph, as shown in FIG. 4.

![FIG. 3 Software flow chart of the method](image1)

![FIG. 4 The graph of the two allocation methods](image2)

It could be seen from FIG. 4 that the overall trend of the two distribution methods was that the unit heat consumption rate continuously decreases with the increase of load. When the load was less than 300 MW, the unit was operated by 300 MW unit. The difference between the two distribution methods was the smallest at 120 MW, 2.8 kJ/kWh. The two units run side by side between 300 MW and 900 MW. With the increase of load, the difference between the two distribution methods first increased and then decreased. The maximum difference was 38.15 kJ/kWh at 55% load. Between 55% load and rated load, the difference of heat consumption rate of the unit decreased continuously. At rated load, the difference of heat consumption rate of the unit was 12.5 kJ/kWh.

5. Conclusion
(1) The basic principles of equal micro-increment method and linear programming method applied to optimal load distribution in power generation enterprises were introduced. Combined with two typical domestic units, the two methods were analysed.

(2) The analysis results showed that the overall trend of the two distribution methods was that the heat consumption rate of the unit decreases with the increase of load, and the change rate of the heat consumption rate of the unit decreased gradually. The difference between the two distribution methods first increased and then decreased with the increase of load. It was necessary to ensure that the micro increase rate of heat consumption increases strictly monotonically when using the method of equal micro increase rate.

(3) There were many factors affecting load distribution, such as environmental temperature, exhaust pressure and coal quality characteristics. Further research was needed to determine the influence of these factors on load distribution. According to the load distribution of specific power generation enterprises, the factors affecting load distribution should be considered according to the specific situation. At the same time, selected the appropriate distribution method to achieve the purpose of energy conservation.

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