Environmental protection analysis of thermal power units operating under unconventional conditions

Shunjiang Wang[1], Weichun Ge[1], Mofan Wei[2], Wuyang Zhang[3], Lina Cao[1], Xuming Lv[1]

[1]State Grid Liaoning Electric Power Supply Co., Ltd., No. 18, Ningbo Road, Shenyang, China.

[2]School of Electric Power, Shenyang Institute of Engineer, No. 18, Puchang Road, Shenbei New District, Shenyang, China

[3]Electric Power Research Institute, State Grid Liaoning Electric Power Supply Co., Ltd., 55 Siping Street, Heping District, Shenyang, China

362406784@qq.com

Abstract. Aiming at the problem of optimal distribution of dust removal, desulfurization and denitrification load in thermal power plants, considering the cost of environmental protection, from the perspective of improving the comprehensive economic benefits of the whole plant, the relationship between coal consumption and power generation of the unit is described by using quadratic polynomial. Based on this model, it can be obtained. The unit corresponds to the fuel cost of different power. Considering the cost of environmental protection, the cubic polynomial is used to model the relationship between the pollutant concentration of the unit and the power generation of the unit. The total cost of peak shaving of the unit is calculated by the unit price of pollutant emissions in different periods. In addition, considering the efficiency of desulfurization and denitrification when the unit is operated under low load conditions, the concentration of pollutants in the exhaust gas is increased, which causes additional environmental costs of government fines, and a model of additional cost is proposed. Based on the actual operating data of the unit, a model for optimal comprehensive economic benefit was established and the constraints were established. And verify the correctness of the model.

1. Introduction

At present, the flue gas pollution control policy of China's coal-fired generating units has undergone a historic transformation. The flue gas dedusting, desulfurization and denitrification have implemented mandatory emission standards, carbon dioxide emission reduction has started, and flue gas demercuration has been put on the agenda, monitoring of PM2.5 and Control is valued, and power generation companies face the dual pressure of improving operational efficiency and reducing emissions of multiple pollutants.

After the implementation of dust removal, desulfurization and denitrification reform, according to the economic performance indicators and pollutant discharge indicators of each unit of the whole plant, a reasonable whole plant load optimization allocation plan is determined, which is to ensure the maximum comprehensive benefit of the existing coal-fired generating units. An effective way. After large-scale wind power is connected to the grid, the peaking capacity of the power system is severely weakened. In addition, the wind power output has the characteristics of intermittent, volatility, anti-peak shaving characteristics, low prediction accuracy and low confidence of capacity, which greatly increases the equivalent load peak-to-valley difference of the system and increases the difficulty of system peak shaving. At this stage, China's thermal power unit has a high proportion of capacity, and the rapid adjustment of power supply capacity is far from meeting the peaking demand. In the context of increasingly serious abandonment of wind power, the voice of the social, power grid and wind power enterprises demanding the deep peaking of thermal power units is more The higher it is. On the other hand, the utilization hours of thermal power units in China have been decreasing year by year. In 2015, the downward adjustment space of only 4329h basic peaking has dropped to the lowest level in history. If we can make full use of economic means under the existing compensation framework, increase the peak shaving depth of thermal power units, and fully tap the existing downside reserve space, it will be one of the most effective ways to stabilize wind power fluctuations. Therefore, it is necessary to study the deep peak shaving capacity, peak shaving cost and efficiency of thermal power units under the background of large-scale wind power integration, and provide theoretical support for improving the peak shaving ability of the system and promoting wind power consumption. After the large-scale transformation of the thermal power unit, the peak shaving depth is indeed improved. However, in the process of deep peak shaving of the thermal power unit, reducing the unit load will increase the unit operating cost and increase the unit loss. In addition, when the unit is running at low load, the efficiency of dust removal, desulfurization and denitrification will be reduced, so the concentration of pollutants will increase, which will increase the pressure on the environmental protection of the thermal power unit.

At present, research on load optimization allocation of thermal power plants mainly focuses on the whole plant load optimization distribution model and intelligent optimization algorithm before coal-fired generator set dedusting, desulfurization and denitrification reform [1-10]. The load optimization distribution model considers coal consumption and NO_x emissions. Factors such as load adjustment time, but the research did not comprehensively consider the current compensation price of dust removal, desulfurization and denitrification, and the cost of multiple pollutants at the starting point. The obtained plant-optimized distribution plan cannot effectively solve the comprehensive economic situation of the whole plant. The most effective problem. To this end, this paper starts from the maximization of the comprehensive benefits of thermal power plants, based on the actual operating data of the unit, builds a model of coal consumption and a variety of pollutant discharge concentration characteristics, according to the dust removal, desulfurization, denitrification compensation electricity price and the sewage cost standard at the starting point. The new algorithm calculates the actual data collected by the power plant and verifies its effectiveness.

2. Thermal power unit deep peak shaving capacity and power generation cost

According to the peaking efficiency of the basic peaking capacity research system of the thermal power unit, the literature [11] analyzes the economic benefits of the peaking measures on the grid side and the power plant side from the perspective of energy saving economic dispatch, and qualitatively discusses the peak shaving of thermal power units. The economic cost of oil-fired combustion. The literature [12] quantifies the peak-shaving value of the peak-shaving unit based on the economic dispatch model, and analyzes the value of the peak-shaving unit to the economic operation of the system, and proposes the compensation method for the peak-shaving cost of the unit. A grid economic operation plan with large-scale wind farms considering the deep peak shaving of large-capacity coal-fired power units is proposed. The unit life loss compensation coefficient is introduced, and the compensation for the life loss of thermal power units is calculated based on the compensated depth peak-shaping capacity.

The peaking cost of the thermal power unit is mostly based on the consumption characteristics of the basic peaking stage of the thermal power unit, and the variable load loss cost and oil cost of the unit under different depth peaking are generally not considered in the whole economic dispatching model [14]–[15]. In this paper, the power plant side mainly uses desulfurization, denitrification, dust removal and other environmental protection costs, power plant peaking coal consumption and coal price, and excessive discharge fines to comprehensively evaluate the power plant benefits. After considering the on-grid price, the load optimization distribution model is established to develop a peak plan for the power plant to maximize the efficiency of the power plant.

The load optimization distribution model starts from the economic operation and environmental protection requirements currently faced by thermal power plants, and uses the actual operation data after unit dust removal, desulfurization and denitrification to build unit load and power supply coal consumption, dust emission concentration, SO_2 emission concentration and NO_x emission concentration. The relationship characteristic model considers the current dust removal, desulfurization, denitrification compensation electricity price and the sewage discharge cost standard at the starting point, and establishes the optimal economic benefit optimal load distribution model that takes into account both economic and environmental indicators. In order to make full use of wind power, the current system dispatching will require some thermal power units with regulation capability to operate below the minimum technical output (usually 45% to 50% of rated power). At this time, the thermal power unit works in the deep peaking stage. In recent years, with the continuous reduction of the average utilization hours of wind power, the problem of wind curtailment has become more and more serious, and the voice of the society to explore the ability of deep thermal peaking of thermal power units is getting higher and higher. The grid company has significantly increased the peaking depth of the peaking unit within the peak range allowed by the thermal power plant.

According to the operating state and energy consumption characteristics of thermal power units, the peak shaving process can be divided into three stages: RPR (routine peaking regulation), DPR (deep peaking regulation) and DPRO (deep peaking regulation with oil), as shown in Figure 1. In the figure: $P_{\max}$ is the maximum output of the unit; P_a is the minimum technical output of the unit RPR stage; P_b is the lowest steady-state output of the unit DPR stage; P_c is the steady-state limit of the unit DPRO stage.

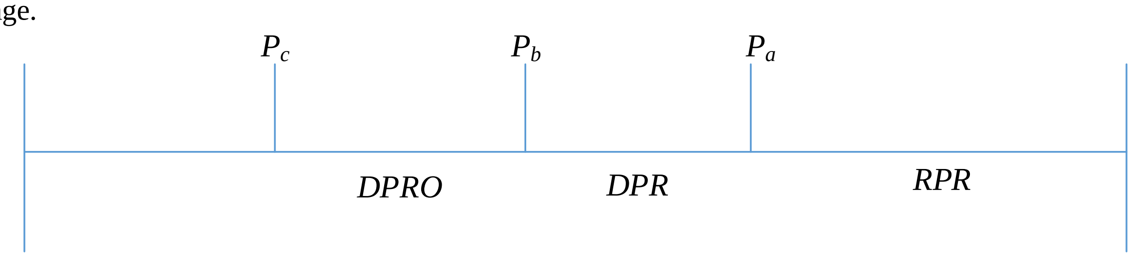

Figure 1 Schematic diagram of peaking process of thermal power unit

Boilers with 200MW and 300MW low-parameter units with earlier production in China are designed with basic load, P_b 60%~70% of rated load (P_n), was not suitable for frequent start and stop. The boilers of 600MW and 1000MW high-parameter units are designed with basic load and certain peak-shaving capability, P_b usually between 45% and 50% of P_n . According to the “Detailed Rules for the Implementation of Auxiliary Service Management of Grid-Connected Power Plants in North China”, the basic peaking standard of the directly regulated thermal power unit is 50% of P_n . According to the general situation of the existing domestic production units, the DPR of the thermal power unit has been reached limit. As showed in figure 2.

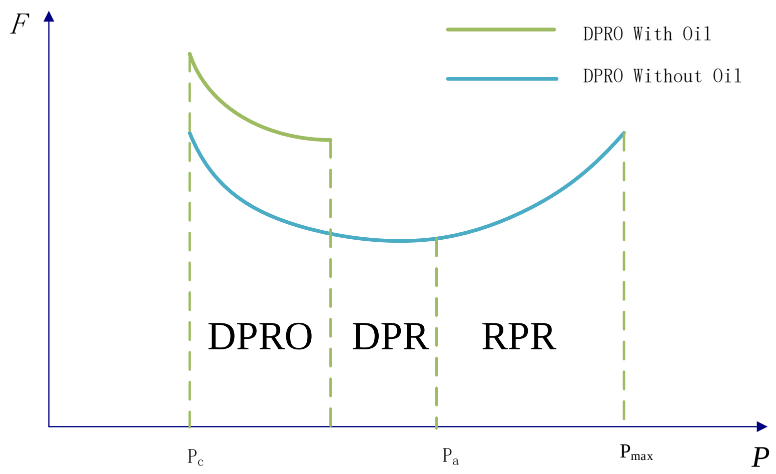

Figure 2 Thermal power unit peaking cost curve

In recent years, with the continuous improvement of the design and manufacturing technology of the unit, the newly-introduced thermal power units such as supercritical units and ultra-supercritical units adopt new technical means and high-quality steel with high temperature corrosion resistance, and the temperature difference thermal stress of the unit is effective under variable working conditions. The reduction is more important than the previous thermal power units in terms of combustion stability and safety of hydrodynamic conditions. The 200MW and 300MW low-parameter units can be reduced to 45% after the transformation, and the minimum stable combustion load of 600MW and 1000MW high-parameter units can be reduced to 30%~35%.

3. Load optimization allocation model considering environmental cost

For the existing units of the thermal power plant, the relationship between the unit load and the coal consumption of the power supply is described by using a quadratic polynomial as:

$$f_i(P_i) = a_i P_i^2 + b_i P_i + c_i \tag{1}$$

$$B_{1i}(P_i) = (a_i P_i^2 + b_i P_i + c_i) S_{coal} \tag{2}$$

Where: i indicates the number of thermal power units; f_i is the coal consumption for the i-th unit, g/(KW•h); P_i is the load of the i-th unit, MW; a_i , b_i ,and c_i is the coal consumption characteristic model coefficient of the i-th unit; $P_{i,\min}$ and $P_{i,\max}$ respectively represent the minimum and maximum values of the i-th unit load, MW. S_{coal} is the unit coal price in the current season. B_{1i} is the coal consumption cost for the unit operation.

During the peaking stage of oil injection, the combustion stability of the boiler and the safety of the hydrodynamic working conditions are rapidly declining, and there is a situation in which stable combustion cannot be achieved. The unit needs to be fueled to ensure safe operation of the unit. The fuel consumption cost is:

$$B_{oil} = E_{\cos t} S_{oil} \tag{3}$$

Where: $E_{\cos t}$ is the fuel consumption of the unit during the peaking stage of the oil injection; S_{oil} is the oil price for the season.

$$B(P_i) = B_{1i}(P_i) + B_{oil} \tag{4}$$

Where: $B(P_i)$ is the fuel consumption cost for the unit operation.

Considering the pollutant emission index of dust emission concentration, emission concentration and emission concentration of coal-fired generating units, the relationship between unit load and the concentration of these three pollutants is described by three polynomial:

$$f_{2i}(P_i) = \alpha_{2i}P_i^3 + \beta_{2i}P_i^2 + \gamma_{2i}P_i + \lambda_{2i} \tag{5}$$

$$f_{3i}(P_i) = \alpha_{3i}P_i^3 + \beta_{3i}P_i^2 + \gamma_{3i}P_i + \lambda_{3i} \tag{6}$$

$$f_{4i}(P_i) = \alpha_{4i}P_i^3 + \beta_{4i}P_i^2 + \gamma_{4i}P_i + \lambda_{4i} \tag{7}$$

Where: f_{2i} is the dust emission concentration of the i-th unit, mg/m^3; f_{3i} is the SO_2 emission concentration of the i-th unit, mg/m^3; f_{4i} is the NO_x emission concentration of the i-th unit, mg/m^3; α_{2i} , β_{2i} , γ_{2i} and λ_{2i} are the dust characteristic model coefficients of the i-th unit respectively. α_{3i} , β_{3i} , γ_{3i} and λ_{3i} are the SO_2 characteristic model coefficients of the i-th unit, respectively. α_{4i} , β_{4i} , γ_{4i} and λ_{4i} are the NO_x characteristic model coefficients of the i-th unit.

The three pollutant discharge costs of the unit are:

$$B_{2i}(P_i) = f_{2i}V_iM_{FC} \tag{8}$$

$$B_{3i}(P_i) = f_{3i}V_iM_{SO_2} \tag{9}$$

$$B_{4i}(P_i) = f_{4i}V_iM_{NO_x} \tag{10}$$

$$B_p(P_i) = \sum_{n=1}^{3} B_{ni}(P_i) \tag{11}$$

Where: V_i represents the amount of boiler flue gas, m^3/h and M represents the unit price of pollutant emissions, $yuan/t$.

In the deep peaking stage, the thermal power unit will reduce the desulfurization efficiency and increase the sulfur content in the pollutant emissions. In addition, the unit fuel will increase the emission of pollutants such as nitrogen oxides and soot, resulting in an increase in the sewage charges of the thermal power plant; the discharge of pollutants will violate the standards of air pollutant emissions from thermal power plants and result in government fines. Therefore, the environmental additional costs are:

$$B_{ev}(P_i) = 1600 f_{1i}(P_i)\delta_s\Delta\eta + o_{\cos t}W_{pollute} + S_{punish}(P, o_{\cos t}) \tag{12}$$

Where: $\Delta\eta$ is the value of the desulfurization efficiency change; δ_s is the total sulfur content of the coal; $o_{\cos t}$ is the fuel consumption when the unit is put into operation; $W_{pollute}$ is the exhaust gas discharge fee for the unit fuel; S_{punish} is the penalty function when the pollutant discharge exceeds the standard. The extent to which pollutant emissions exceed the standard is related.

In summary, this paper believes that the energy cost of the thermal power plant peaking process can be expressed in stages. If the unit loss is not considered, the cost is only in the stage of conventional peak shaving (RPR) and unit steady fueling and no oil injection depth peaking (DPR). The coal consumption cost of the unit and the cost of desulfurization, denitrification and dust removal. In the DPRO stage, the cost consists of unit coal consumption cost, desulfurization and denitrification, dust removal cost and pollutant discharge exceeding the standard.

The peaking cost of the thermal power unit is:

$$B(P_i) = \begin{cases} B_{1i}(P_i) + B_p(P_i) & P_b \le P_i \le P_{i,\max} \\ B_{1i}(P_i) + B_p(P_i) + B_{oil} + B_{ev}(P_i) & P_c \le P_i \le P_b \end{cases} \tag{13}$$

Under the premise of meeting the national mandatory standards for pollutant discharge, the optimal distribution of the overall economic benefits of the whole plant is used as the optimization target. The comprehensive economic benefit is the electricity sales revenue and coal consumption cost and sewage discharge considering the dust removal, desulfurization and denitrification compensation electricity price. The difference in fees. Assuming that the plant's power consumption rate is the same as that of the unit, the amount of electricity on-line during the time T is:

$$E(P_i) = (1000 - n)T\sum_{i=1}^{m} P_i \tag{14}$$

Where: $E(P_i)$ indicates the total power consumption of the entire factory during the time T, $KW{\bullet}h$.

If the electricity price is in $yuan / KW{\bullet}h$, the electricity sales revenue in the time is:

$$W(P_i) = E(P_i) \times p_1 \tag{15}$$

According to the government's peaking subsidy policy for the current season, if the power plant unit is in the state of deep peak shaving. According to the peak shaving depth of different stages, the government will respond to the increase in the unit's power generation cost caused by the unit's power generation due to the stable frequency of the grid frequency in compensation.

Assume that when the unit load is lower than $n_1\%$, the unit is in the state of deep peak shaving, and the peaking subsidy price is B_1 . Assumed that when the unit load is lower than $n_2\%$, the unit is in the peak level of the deeper level. In this state, the unit desulfurization and denitrification. The efficiency has dropped drastically and the cost of environmental protection has increased; during this peaking phase, the peak subsidy price is B_2 .

The peak subsidy benefit W_d is:

$$W_d = \begin{cases} (n_1\%P_N - P_i)B_1 & n_2\%P_N \le P_i \le n_1\%P_N \\ \left(n_1\% - n_2\%\right)P_N B_1 + (n_2\%P_N - P_i)B_2 & P_{i,\min} \le P_i \le n_2\%P_N \end{cases} \tag{16}$$

4. Unit load constraints

Under the condition of optimizing the load distribution model of the whole plant, after the peaking is completed, the total output of the unit should be equal to the total power generation load command issued by the grid dispatching, and the peaking time should be as short as possible. The maximum time used for plant-wide load scheduling is:

$$t_{p,\max} = \left| P_{ful} - \sum_{i=1}^{m} P_{now,i} \right| \Big/ \sum_{i=1}^{m} \upsilon_{net,i} \tag{17}$$

Where: P_{ful} denotes the total power generation total load command issued for the power grid dispatching. $P_{now,i}$ is the current load assumed by the i-th unit. $\upsilon_{net,i}$ is the ith unit load change rate limit specified for the power grid dispatch.

The unit power constraints are:

$$P_{ful} = \sum_{i=1}^{m} P_i \tag{18}$$

The whole plant load optimization allocation is based on the current load of the unit, and the optimal load distribution plan of the whole plant is calculated within the load range $t_{p,\max}$ that can be achieved within the load. The constraint conditions for defining the load distribution model are:

$$s.t.\begin{cases} P_{ful} = \sum_{i=1}^{m} P_i \\ P_{i,now\min} \le P_i \le P_{i,now\max} \end{cases} \tag{19}$$

Where, $P_{i,now\min}$ and $P_{i,now\max}$ are respectively the upper and lower limits of the adaptive load threshold calculated based on the current load of the unit, and the calculation formula is:

$$P_{i,now\min} = \max\left\{P_{i,\min}, P_{now,i} - \upsilon_{i,de\max} t_{p,\max}\right\} \tag{20}$$

$$P_{i,now\max} = \max\left\{P_{i,\max}, P_{now,i} + \upsilon_{i,in\max} t_{p,\max}\right\} \tag{21}$$

Where, $\upsilon_{i,de\max}$ and $\upsilon_{i,in\max}$ are the maximum load and lift rate of the i-th unit.

5. Calculation example based on actual data of power plant

The selected unit's power generation rated power P_n is 660MW, and the power plant pollutant emission model coefficient is as follows (as in Table 1).

Table 1 Pollutant emission model coefficient table

	a	b	c	α_k	β_k	γ_k	λ_k	P_{max}	P_{min}	V_k
660MW	0.000142	-0.2044	362.97	0.00000075	-0.00075	0.0691	119.12	220	660	165*10^4
660MW	0.000091	-0.1530	349.24	0.00000134	-0.00173	0.5914	30.89	220	660	165*10^4
330MW	0.000392	-0.3157	381.11	0.00001601	-0.01019	1.8188	2.12	110	330	110*10^4
310MW	0.000818	-0.5659	412.82	0.00000296	-0.00093	-0.2733	148.74	104	310	110*10^4

According to the current government subsidy policy, the first-grade deep-adjusted subsidy price is $200 yuan/MW$, the second-grade deep-adjusted subsidy price is $700 yuan/MW$, and the deep-adjusted power T_d is calculated below the peaking limit.

The selected power plant unit calculates the environmental protection economy according to the peaking depth of 35%. The peaking policy for the quarter is: when the generating power of the unit is lower than 50%, the unit is considered to be in the peak peaking and peaking, when the generating power of the unit is 40%~50 The price subsidy is $200 yuan/MW$; when the unit's power generation is within the range of 30%~40%, the price subsidy is $700 yuan/MW$.

Coal consumption by computer group for coal consumption model is:

$$f_i(P_i) = a_i P_i^2 + b_i P_i + c_i = 0.000142 \times 229^2 - 0.2044 \times 229 + 362.9 = 323.61 g/KW \bullet h$$

Multiply the coal consumption by the coal price in the current season to get the fuel consumption cost of the unit.

$$\mathrm{B}_{1i}(P_i) = (a_i P_i^2 + b_i P_i + c_i) S_{coal} = 323.61 \times 10^{-6} \times 229 \times 10^3 \times 300 = 22232.01 yuan/\mathrm{h}$$

Considering that the unit is in the case of deep peak shaving, the concentration of the cubic polynomial computer group is:

$$f_{4i}(P_i) = \alpha_{4i} P_i^3 + \beta_{4i} P_i^2 + \gamma_{4i} P_i + \lambda_{4i} = 0.00000075 \times 229^3 - 0.00075 \times 229^2 + 0.0691 \times 229 + 119.1 = 104.6 mg/m^3$$

Using the current NO_x emission rate calculate the cost, the emission cost is about:

$$\mathrm{B}_{NO_x} = f_{4i}(P_i) V_k M_{tx} = 104.6 \times 165 \times 10^4 \times 630 \times 10^{-9} = 108.73 yuan/\mathrm{h}$$

Then the compensation fee for the deep peak shaving of the unit is:

$$W_d = T_{di} B_i = (50\% - 40\%) P_n B_1 + (40\% - 35\%) P_n B_2 = 0.1 \times 660 \times 10^3 \times 0.2 + 0.05 \times 660 \times 10^3 \times 0.7 = 36300 yuan/h$$

Therefore, the peaking income of the unit is:

$$W = W_d - B_{1i}(P_i) - B_{NO_x} = 36300 - 22232.01 - 108.73 = 13959.26 yuan / h$$

6. Conclusion

Under the environmental protection regulations of the new thermal power plant, considering the factors such as the coal consumption of the unit, the operating conditions of the low-load units, and the emission concentration of various pollutants, the whole plant load optimization allocation model is proposed. This model considers the unit to operate under low load conditions. When the efficiency of desulfurization and denitrification is reduced, the additional cost of the environment can meet the dispatching requirements of the grid on the grid side, and the peaking benefit of the power plant can be maximized on the power plant side, making the budget more reliable. This model can be used to scientifically plan the actual power generation of the power plant, not only to meet the plant-wide load command issued by the power grid, but also to minimize the fuel cost of the power plant, environmental protection costs, and unit losses. The peaking plan is limited at the rate at which the unit load changes. The algorithm of this paper can significantly improve the comprehensive economic benefits of the whole plant under the premise of meeting the power grid dispatching instructions.

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