Auxiliary service strategy model of power plant participating in peak load regulation

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Abstract. With the large-scale grid connection of renewable energy, it is necessary to ensure that the peak shaving demand of the system due to the volatility of renewable energy such as wind power can be met. On the premise of ensuring benefits, how to further tap the peak shaving potential of thermal power units and ensure the safe and reliable operation of power system is the primary problem faced by thermal power plants at this stage. According to the mechanism of peak load regulation auxiliary service in Northeast China, this paper puts forward the strategy model of participating in peak load regulation auxiliary service of thermal power plants, so as to provide basis for further tapping the peak load regulation potential of thermal power units and improving the actual consumption of renewable energy such as wind power by power grid.

1. Background

With the continuous development of power supply in China, the proportion of wind power and other renewable energy installed is increasing, power system peak-shaking capacity has been seriously weakened, and the demand of power grid for peak-shaking auxiliary services is increasing. In order to promote large-scale wind power and other renewable energy to be connected to the power grid, it is necessary to ensure that the fluctuation of wind power and other renewable energy can meet the peak demand of the system after it is incorporated. As the main bearer of peak shaving auxiliary services, whether the peak shaving capability of thermal power units can play a full role directly relates to the actual consumption of renewable energy such as wind power by the power system [1].

Northeast power peak-shaving market has been running smoothly since it was started on October 1, 2014, and tapping the potential of thermal power peak-shaving exceeds 1000MW effectively alleviates the difficulty of system peak-shaking. The northeast region has a long heating period in winter, and the heating units account for a large amount of fire capacity, so the peak-shaking ability during heating period is limited. Northeast wind power and nuclear power develop rapidly, but wind power has anti-regulation, and nuclear power has poor flexibility, which makes the operation of power system more difficult. However, the proportion of hydroelectric power is small, and adjustable peak power sources such as pumped storage are seriously insufficient [2]. The combined influence of the above factors leads to the serious insufficiency of power peak-shaking capacity in Northeast China at present, especially in
winter heating period, the difficulty of power system peak-shaking is prominent, which directly threatens the safety and reliability of power system.

2. Policy Analysis of Power Grid Peak-shaking Assistant Services
Graded deep peak-shaking services in the Northeast are divided into basic obligatory peak-shaking services and paid peak-shaking services, and their price mechanism is "ladder". Depending on the depth of peak regulation, each power plant can make floating quotation according to the actual situation in different heating periods and different price limits. In order to prevent the reduction of heavy load capacity of the unit band after deep peak shaving renovation, the compensation fee for peak shaving in power plants with power output less than 80% of the plate capacity is halved.

| Table 1. Peak-shaving Step Compensation Price Table for Northeast Power Grid |
|------------------|------------------|------------------|------------------|
| **Period**     | **Quotation level** | **Type of thermal power plant** | **Load rate of thermal power plant/%** | **Lower limit of quotation/ yuan · kWh⁻¹** | **Upper limit of quotation/ yuan · kWh⁻¹** |
| Non heating period | Level 1 | Pure condensing thermal power unit | 40 < Load rate ≤ 50 | 0 | 0.4 |
|                   | Level 2 | Pure condensing thermal power unit | Load rate ≤ 40 | 0.4 | 1 |
|                   | Level 1 | Thermolectric unit | 40 < Load rate ≤ 48 | 0 | 0.4 |
|                   | Level 2 | Thermolectric unit | Load rate ≤ 50 | 0.4 | 1 |
| Heating period | Level 1 | Pure condensing thermal power unit | Load rate ≤ 48 | 0 | 0.4 |
|                   | Level 2 | Pure condensing thermal power unit | Load rate ≤ 50 | 0.4 | 1 |

In a word, the current policy of peak-shaving ancillary services in Northeast China fully considers the decisive role of market in resource allocation, promotes wind and power consumption by market mechanism, and implements the national policy of renewable energy consumption, taking into account the interests of all parties, on the premise of ensuring the safe operation of power grid and the quality of power supply. The current policy, which takes full advantage of economic means to motivate power generation enterprises to participate in the power auxiliary service market, is a beneficial attempt to better accept renewable resources such as wind power.

3. Benefit analysis of thermal power unit participating in peak shaving auxiliary service
According to the basic peak shaving capacity of thermal power unit, the peak shaving benefit of the system is studied, and little is involved in the qualitative analysis of deep peak shaving of thermal power unit. Most of the peak shaving costs of thermal power units are based on the consumption characteristics of thermal power units in the basic peak shaving stage, while the variable load loss costs and fuel input costs of units under different depths of peak shaving are not considered in the entire economic dispatching model [3].

3.1. Peak shaving cost analysis
The cost of peak shaving auxiliary service includes investment cost, operation cost (including oil input cost), damage to equipment components or life reduction due to peak shaving, increase of maintenance cost, personnel cost, unit start-up and shutdown cost, and insufficient generation due to peak shaving [4].

Usually coal consumption cost for thermal power unit operation is

\[
f(P) = (aP^2 + bP + c)S_{coal}
\]
Where: \( P \) generates power for thermal power units; \( a, b, c \) values are related to unit type, boiler type and coal quality; \( S_{coal} \) is the price of coal in the current season.

During peak shaking without oil depth, due to the effect of alternating stress, low-cycle fatigue loss of rotator metal and creep loss of high temperature and continuous load force, the unit life is reduced, and the unit loss cost is

\[
\omega_{\text{cost}}(P) = \beta S_{\text{unit}} / 2 N_f(P)
\]  

(2)

Where: \( \beta \) is the influence factor of unit operation; \( N_f(P) \) is the number of cycles of rotor cracking; \( S_{\text{unit}} \) is the unit purchase cost.

During peak shaking of oil depth, the cost of oil input is

\[
C_{\text{oil}} = C_{\text{con}} \times S_{\text{oil}}
\]  

(3)

Where: \( C_{\text{con}} \) is the fuel consumption when the unit is put into steady fuel; \( S_{\text{oil}} \) is the oil price for the current season.

To sum up, the operating cost \( C(P) \) of the thermal power unit under different operating conditions is the following piecewise function, and \( P^a_l \) is the limit load value of the unit oil depth peak shaving and steady combustion, and its characteristics are shown in Figure 1.

\[
C(P) = \begin{cases} 
  f(P), & P_{\text{min}} < P \leq P_{\text{max}} \\
  f(P) + \omega_{\text{cost}}(P), & P_a < P \leq P_{\text{max}} \\
  f(P) + \omega_{\text{cost}}(P) + C_{\text{oil}} P_b < P \leq P_a
\end{cases}
\]  

(4)

Figure 1. Operation cost of thermal power unit

Emergency start-up and shut-down peak cost of thermal power unit includes unit life loss and coal consumption increase caused by start-up and shut-down. For example, the life of 300MW units in Shanghai Waigaoqiao Power Plant is reduced by 15 hours and the coal consumption is increased by 50 g/kWh per start-up.

The research shows that some thermal power units can get better economic benefit by participating in deep peak shaving auxiliary service, but the peak shaving benefit does not increase monotonously with the increase of peak shaving depth. When the peak shaving depth of some units reaches 55% \( PN \), the peak shaving efficiency is the highest. With the further increase of the peak shaving depth, the peak shaving efficiency of the system decreases gradually, and after the peak shaving depth is greater than 65% \( PN \), the peak shaving efficiency is lower than the basic peak shaving. The higher the coal price, the greater the impact of peak shaving depth on peak shaving benefits. With the increase of peak shaving depth of the system thermal power unit, the change of coal consumption cost of the system is not significant, but the change trend of system cost is mainly affected by the start-up and shut-down cost of the unit and the oil input cost and variable load wear cost of the unit.
### 3.2. Peak shaving profit analysis

According to the operation rules of the northeast electric power auxiliary service market (Trial) and the supplementary provisions of the operation rules of the northeast electric power auxiliary service market (Northeast China regulatory energy market [2017] No. 147), thermal power plants provide in-depth peak shaving auxiliary services, and the peak shaving compensation fees obtained are:

\[ C_R = \sum_{j=1}^{n} \left( E_j \times q_j \right) \times k \]  

(5)

Where: \( C_R \) is the compensation amount for peak load regulation obtained in the heating period of the thermal power plant; \( E_j \) is the paid peak load regulation power of the i-th stage; \( q_j \) is the actual clearing price of the i-th stage; \( n \) is the number of units in the thermal power plant; \( k \) is the correction coefficient; \( k = 1 \) in the heating period and \( k = 0.5 \) in the non-heating period.

According to the different actual load rates, the thermal power plants participating in the compensation allocation for peak load regulation are divided into three grades to increase the allocation proportion in turn, and carry out “step-by-step” allocation:

\[ C_T = \frac{E_{T1}}{E_T + E_w + E_N} \times C_z \]  

(6)

Where: \( C_T \) is the amount of peak load adjustment compensation shared by the thermal power plant; \( E_{T1} \) is the revised generation of the thermal power plant; \( E_T \) is the total revised generation of all the thermal power plants participating in the sharing in the province; \( E_w \) is the total revised generation of all the wind farms in the province; \( E_N \) is the total revised generation of the nuclear power plant in the province; \( C_z \) is the total amount of peak load adjustment compensation.

\[ E_{T1} = \sum_{i=1}^{3} (E_i \times k_i) \]  

(7)

Where: \( E_i \) is the actual power generation of the i-th gear, the first gear is when the load rate is less than 70%, the second gear is when the load rate is between 70% and 80%, the third gear is when the load rate is higher than 80%, and the correction coefficient \( k_1 = 1, k_2 = 1.5, k_3 = 2 \).

The benefits of thermal power plant participating in paid peak load regulation are as follows:

\[ C_H = C_R - C_T \]  

(8)

### 3.3. Research example of peak load regulation economy of a power plant in Northeast China

A 350 MW supercritical unit boiler is produced by Harbin Boiler Plant Co., Ltd. with the model of HG-1110 / 25.4-HM2. The steam turbine is produced by Harbin Steam Turbine Plant Co., Ltd. with the model of C350 / 280-24.2/0.4/566/566. In order to meet the actual conditions of hierarchical deep peak shaving and on-site peak shaving, the premise of economic benefit calculation is as follows: the power plant carries out full load denitration, and the on grid price adopts the environmental protection price; the boiler does not put oil in the deep peak shaving state; the power plant does not consider the impact of peak shaving on the unit life when participating in the deep peak shaving economic analysis.

Assuming that the price of standard coal entering the plant is 700 yuan / t, the power generation cost under different loads of the power plant is shown in Table 2. The coal consumption for power supply of the unit in the table is the coal consumption for power supply after unit test correction. According to the actual test on site, the minimum load in the test process of the thermal power plant is 130MW.
Table 2. Power generation cost under different loads of power plant

| Load/MW | Load Rate/% | Power Consumption/(g · kWh⁻¹) | Generation Cost/(yuan · kWh⁻¹) | Fuel Cost/10,000 yuan |
|---------|-------------|-------------------------------|-------------------------------|-----------------------|
| 220     | 63          | 300.55                        | 0.2104                        | 4.628                 |
| 210     | 60          | 302.67                        | 0.2118                        | 4.449                 |
| 200     | 57          | 304.77                        | 0.2133                        | 4.266                 |
| 190     | 54          | 307.09                        | 0.2150                        | 4.083                 |
| 175     | 50          | 306.64                        | 0.2146                        | 3.756                 |
| 160     | 46          | 315.25                        | 0.2207                        | 3.531                 |
| 150     | 43          | 318.37                        | 0.2228                        | 3.343                 |
| 140     | 40          | 321.69                        | 0.2252                        | 3.153                 |
| 130     | 37          | 326.42                        | 0.2285                        | 2.970                 |
| 120     | 34          | 328.95                        | 0.2302                        | 2.762                 |
| 110     | 31          | 332.88                        | 0.2330                        | 2.563                 |

The peak regulation revenue is calculated according to the power grid peak regulation step compensation price in Table 1. The coal consumption of power supply in Table 2 is obtained from the test of non heating period, which is reduced by half when calculating the cost of deep peak regulation. The unit participates in the denitrification of the whole load in the process of deep peak load regulation, and the on grid price is 0.384 yuan / kWh. See Table 3 for the income under the condition of unit grading and deep peak load regulation, and see Figure 3 for the income under different loads. According to the actual operation, under the condition that the power grid needs deep peak regulation, there is no possibility of high load operation for the unit, so the table does not give the relevant data of high load. When calculating the benefits of deep peak load regulation, the cost apportioned for whether the power plant is peak load regulation is not considered according to the actual operation status of the power plant [5].

Table 3. Profit under the condition of grading and deep peak load regulation of unit

| Load/MW | Load Rate/% | Total Cost of Power Generation/10,000 yuan | Profit without considering peak shaving/10,000 yuan | Profit considering peak shaving/10,000 yuan |
|---------|-------------|--------------------------------------------|---------------------------------------------------|-------------------------------------------|
| 220     | 63          | 4.629                                       | 3.144                                             | 3.144                                     |
| 210     | 60          | 4.449                                       | 2.970                                             | 2.970                                     |
| 200     | 57          | 4.267                                       | 2.799                                             | 2.799                                     |
| 190     | 54          | 4.084                                       | 2.628                                             | 2.628                                     |
| 175     | 50          | 3.715                                       | 2.426                                             | 2.426                                     |
| 160     | 46          | 3.531                                       | 2.122                                             | 2.398                                     |
| 150     | 43          | 3.343                                       | 1.956                                             | 2.416                                     |
| 140     | 40          | 3.153                                       | 1.793                                             | 2.437                                     |
| 130     | 37          | 2.971                                       | 1.622                                             | 2.726                                     |
| 120     | 34          | 2.763                                       | 1.477                                             | 3.041                                     |
| 110     | 31          | 2.563                                       | 1.323                                             | 3.347                                     |
Figure 2. Profit chart of power plant under different loads

The revenue of the unit under different loads is:

\[ B_{\text{unit}} = \begin{cases} -0.0267P^2 + 189.61P - 6070.1 & \text{if } P < 1.0482 \, \text{and } P > 0.4837 \\ -1.0482P^2 - 334.6P + 52814 & \text{if } P \leq 1.0482 \\ 0.4837P^2 - 451.65P + 80225 & \text{if } P > 0.4837 \end{cases} \]  

(9)

Where: \( B_{\text{unit}} \) is the unit revenue; \( P \) is the unit load.

It can be seen that before the unit enters the first gear peak load regulation, the generating revenue of the unit is positively related to the unit load. After entering the first gear of peak load regulation, the unit revenue first decreases and then increases with the increase of load. After entering the second gear peak load regulation, the unit revenue increases with load reduction. There is a turning point in the power plant's power generation revenue when the coal price is determined. The coal price has a great impact on the revenue of the unit under different loads. See Figure 3 for the peak load regulation revenue of the unit under different coal prices. The lower the price of standard coal entering the plant, the higher the unit income, and the higher the price of coal entering the plant, the more advantageous it is for thermal power units to actively participate in deep peak shaving.

Figure 3. Profit under different coal prices and loads

It can be seen that when the thermal power plant carries out the auxiliary peak load regulation service, due to the existence of peak load regulation compensation, the power generation revenue and power generation capacity of the power plant are not simply linear relationship, in order to obtain the maximum economic benefits, corresponding strategies should be taken. The peak regulation yield curve is approximately "U" type. When the power plant participates in hierarchical deep peak regulation, it should participate in deep peak regulation according to the power grid conditions, if necessary.

The practice of power grids and thermal power plants in different regions shows that the auxiliary service market of peak load regulation is forming in different regions, and thermal power units will bring
greater benefits by actively participating in the auxiliary service of peak load regulation. Large capacity thermal power units have good peak load regulation capacity.

4. Auxiliary service strategy for thermal power plants
The practice of power grids and thermal power plants in different regions shows that the auxiliary service market of peak load regulation is forming in different regions, and thermal power units will bring greater benefits by actively participating in the auxiliary service of peak load regulation. Large capacity thermal power unit has better peak load regulation capacity. When the thermal power plant participates in the peak load regulation auxiliary service, according to the different peak load regulation requirements of the power grid, the power grid will adjust according to the actual peak load regulation demand and peak load regulation capacity, and the thermal power unit will also carry out the marginal benefit analysis according to the adjusted parameters at any time. In this paper, it is suggested that the thermal power units of actively prepare for peak load regulation auxiliary service and adopt the following strategies [6].

1. When the power supply enterprises are carrying out the flexibility transformation of thermal power, the investment scale should be appropriately controlled. At the same time, in order to prevent excessive peak regulation capacity and excessive competition in the later stage, thermal power transformation should not be carried out in large-scale.

2. In order to reduce the cost of peak shaving, we can take measures such as changing coal type, blending combustion or adding plasma ignition system to realize deep peak shaving.

3. The peak demand period is mainly in the winter heating period. In the non heating period, only the thermal power unit is required to participate in the basic peak load regulation period. The thermal power unit shall operate under the peak load regulation range of maximum system revenue as far as possible.

4. For the cogeneration unit without thermal power flexibility transformation and thermal power decoupling measures, the thermal inertia of the heat supply network and buildings shall be fully utilized during the heating period, and the heat supply shall be conducted in advance before the peak adjustment compensation price and apportionment price are very high at the lowest or the most difficult time of peak adjustment of the system. When the valley comes, there should be no heating or less heating so as to participate in the peak regulation of the system to the maximum extent and obtain the maximum peak regulation revenue.

5. Since the implementation of the auxiliary service of peak load regulation, the policy changes greatly and the quotation mechanism is complex, the optimal operation mode brought by this needs to be obtained through the analysis and comparison of economic benefits. The economic operation department shall be familiar with the operation rules as early as possible and establish relevant calculation models.

5. Conclusion
This paper introduces the calculation method of revenue of thermal power units participating in peak load regulation auxiliary service, and analyzes the economic performance of a peak load regulation example in Northeast China. When the thermal power unit is operated with low load and flexibility, the coal consumption of power supply increases due to the deviation of operation state from the design value, so when the thermal power plant participates in peak load regulation operation, appropriate strategies should be taken to obtain the maximum economic benefits. When the thermal power plant carries out the auxiliary peak regulation service, due to the existence of peak regulation compensation, the power generation revenue and power generation capacity of the power plant are not simply linear relationship, it is necessary to get peak regulation compensation through reasonable bidding, in order to maximize the economic benefits of the power plant.

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