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Day-ahead load optimal distribution of thermal power coupled electric energy storage frequency regulation system considering the effect of overtemperature

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Abstract: Coupling energy storage devices on the generation side can significantly improve the AGC frequency regulation performance of thermal power units and bring frequency regulation benefits. In the traditional joint frequency regulation mode, energy storage is generally used to compensate the deviation between thermal power output and dispatching command, without considering the deep coordination between thermal power units and energy storage system. Thermal power units are still in fast variable load operation state, and the potential of coupled energy storage in improving the safety and other comprehensive performance of the units has not been explored deeply. Therefore, in this paper, the energy storage system is used to actively cooperate with the unit for secondary frequency regulation, and the load command is optimally distributed by minimizing the total cost function, including the variable load cost of the unit. The maintenance cost caused by overtemperature is considered in the cost model, and is analyzed through a simulation example. The results show that the total cost, considering the influence of over temperature on the optimal load distribution, is lower than that when the unit responds at a constant high load changing rate. The active load bearing of energy storage alleviates the cost increase caused by rapid load changing of the unit, making the unit benefit from energy storage and the total cost tends to be optimal.

Key words: joint frequency regulation, cost evaluation model, overtemperature cost conversion, variable load rate, load optimal distribution.

1. Introduction

Traditional coal-fueled thermal power generation has caused many problems for the environment, and many countries strongly support the proposal of carbon peaking and carbon neutrality for energy restructuring[1]. Renewable energy generation, such as photovoltaic and wind power generation, is strongly supported and developed, and the proportion of its connection to the power system is on the rise. However, renewable energy is highly stochastic. For example, wind power may have a large power output during the low power consumption period of the day, showing a reverse regulation characteristic. This stochasticity not only poses a challenge to the safe and stable operation of the power system, but also has a greater impact on thermal power units [2]. The power system requires that the active power at the generation side and the customer side can be kept in real-time balance, so that the frequency of the whole power system can be kept stable and the quality of electricity can be guaranteed. However, the random fluctuation of renewable energy output will affect the grid frequency, so it is necessary to adjust the output of power sources such as thermal power units, to maintain the power balance [3]. When the new energy output is high, the more controllable thermal power generation will generate as little power as possible, allowing the new energy to bear the load demand. And vice versa, when the new energy output is small, the generation sources such as thermal power units have to enhance the output to stabilize the load demand [4].

It can be seen that the large proportion of new energy power generation has brought greater frequency regulation pressure to traditional thermal power units, and frequency regulation units need to increase and decrease load frequently to cope with changing user load and new energy output. The power system requires real-time balance of active power, however, the response power units is difficult to keep up with the change of dispatching, limited by the large unit inertia. Electric energy storage devices can be a good aid to thermal power units for frequency regulation because the storage devices can be charged and discharged precisely in a very short time (millisecond level) [5]. This also gained further research and significantly improved the frequency regulation performance of the unit [6].

The traditional coordination mode of thermal power units and energy storage does not fully consider the synergy between them. After receiving the command to adjust the load, the units still rapidly increase and decrease the load. Energy storage is just to make up for the deviation between the unit output and the dispatching command. On

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the one hand, the rapid load change of the unit will bring losses to the unit, such as the increase of total coal consumption, large temperature fluctuation of the unit, large life loss, etc. On the other hand, the rapid charging and discharging capacity of energy storage under this mode is not fully utilized, which has the problem of idle capacity [7]. Therefore, it is necessary to improve the traditional coordination mode, so that the energy storage device can actively bear part of the load demand when allowed, and allocate the dispatching instructions according to the minimum cost target of the frequency regulation process, so that the unit can better perform the secondary frequency regulation with the help of energy storage [8].

In the cost model of the combined unit and energy storage frequency regulation system, the cost of coal consumption of the unit needs to be considered, the configuration of energy storage and other costs are also indispensable, and the frequency regulation revenue should be calculated according to local policies. On this basis, adding the cost increase caused by overheating can make the overall cost model more complete. Related research [9] shows that the overall temperature fluctuation of the unit becomes more drastic when the load changes rapidly, and the losses of each part of the unit will increase because of the excessive temperature and the drastic temperature fluctuations, which on the one hand will increase the life loss of the unit itself, and on the other hand, the maintenance cycle of the unit will become shorter when the losses increase, and the normal power generation revenue will be damaged if the unit is shut down for maintenance. Therefore, it is necessary to consider the effect of overtemperature when optimizing the allocation of load orders, and the load allocation will be more meaningful if the results of the optimal load allocation can make the total cost model considering overtemperature tend to be minimal.

2. Total cost model of the joint frequency regulation process

In the process of joint frequency regulation, the costs of the units and energy storage system need to be characterized and used as the objective function for subsequent optimization. For thermal units, the cost of coal consumption, the cost of life loss caused by overtemperature and the cost of shorter maintenance cycles are mainly considered. The cost of energy storage system, such as configuration, is considered and its life loss is described. Frequency regulation gain is the main source of revenue. The more detailed the cost model portrayal is, the better understanding and calculation of the length of its payback period can be obtained [10].

2.1 Coal consumption cost model

2.1.1 Steady-state coal consumption model

A thermal power unit will have a corresponding supply coal consumption value for a specific load output. Generally, five sets of supply coal consumption tests are performed on the units and the supply coal consumption versus load curves are obtained by regression analysis. In order to obtain the supply coal consumption curve more conveniently and accurately, [10] conducted data regression analysis for various types of units and found that the specific load and specific supply coal consumption of most thermal power units can be approximated in the following form:

$$\mu = ae^{-\beta/t} + b \tag{1}$$

where μ is the specific supply coal consumption, defined as $\mu = b_g / b_{g0}$, b_{g0} is the coal consumption of the unit under THA condition, and b_g is the supply coal consumption at a certain load *P*, and the unit is g/(kWh). β is the specific load, defined as $\beta = P / P_0$ and P_0 is the unit lode under THA condition, with *a=0.798, t=0.245, b=0.988.*

The model has high accuracy and is generally used as a generic specific coal consumption curve. Since turbines of different capacities can be considered as similar models with similar relative trends of internal efficiency with main steam flow, the specific coal consumption characteristic curve of the target unit can be considered to have the same shape as the general specific coal consumption characteristic curve. Since the shape is the same, it only needs to be shifted up and down to get as close as possible to the two or more test specific coal consumption data points of the unit. Since at least two points are required to determine the exact location, the "two-point method" is used to calculate the target unit. The steady-state coal consumption model of the unit used in this simulation can be calculated by the "two-point method" as follows:

$$b_g = b_{g0}\left[ae^{-(P/P_0+\beta_1)/t} + b - \mu_0\right] \tag{2}$$

where $b_{g0} = 312.02g/(kWh), P_0 = 300.014MW, \beta_1 = -0.0348, \mu_0 = 0.0035$

2.1.2 Transient coal consumption model

When the initial and final steady-state conditions of the unit are the same but the variable load rate (transient process) is different, the total coal consumption will also be different during the whole variable load process. It was found in [12] that the transient coal consumption increment values were different when the unit raised or lowered the load at different variable load rates, and showed a certain variation pattern. The relationship between the variable load rate and the incremental transient coal consumption can be obtained by segmental fitting of the thermal test data.

$$\delta B = \frac{p_1 x + p_2}{x + q_1} \tag{3}$$

where δB is the transient coal consumption increment in *kg/s*, *x* is the unit variable load rate, and the parameters of its segment fitting are shown in the following table.

Table 1 Table of model parameters

Calculated working condition	p1	p2	q1
50%-75% load up	1.313	0.9506	-1.181
75%-100% load up	1.182	0.3521	-1.192
75%-50% load down	-1.689	0.8297	0.2797
100%-75% load down	-1.102	-0.4988	1.226

The general idea of its cost conversion is as follows:

$$C_{coal} = \sum_{t=1}^{24} CB \times f_{coal}^{t}(P_{power}^{t}) \quad (4)$$

where CB is the price of coal combustion, in million RMB/kg; f_{coal}^{t} is the coal consumption of thermal power unit at moment *t*, in kg/h; *t* denotes the time period serial number, in h. P_{power}^{t} is the electric power output of thermal power unit, in MW.

In this paper, the price of coal taken in the simulation is 469 RMB/ton and its calorific value is 4700 kcal/kg, which is converted into the price per kg of standard coal. For a specific variable load process, the steady-state coal consumption and transient coal consumption values of each process are added up and multiplied by the converted price to accumulate the coal consumption cost.

2.2 Unit life loss cost

Related studies have shown that in the process of joint frequency regulation, if the fluctuation of load is small, the life loss caused by it is a very low, which is approximately negligible. However, when the unit is loaded and unloaded at a large variable load rate, the life loss will increase significantly. For example, when the unit is variable load at 5MW/min, the turbine rotor life loss is 4-7 times higher than that at 3MW/min. Therefore, the unit should reduce the variable load rate with the help of energy storage to reduce the life loss [13].

The life of a unit is inevitably lost when the unit is over-tempered and over-pressurized under rapidly varying load conditions. However, it is very difficult to characterize the life loss of a unit to a very precise degree, it is possible to approximate the life loss percentage of different variable load rates by an approximate order of magnitude. The life of a normal unit can be considered as 100%, and different life loss percentages are generated at different variable load rates. A model fit to the relevant experimental estimation data yields the following estimation model:

$$\mathrm{L} = p_1 x^3 + p_2 x^2 + p_3 x + p_4 \quad (5)$$

where L is the approximate percentage of life loss for one round-trip regulation, x is the unit variable load rate, and p1=4.329e-05, p2=-0.0002897, p3=0.000636, p4=-0.0002896.

When performing cost translation, it can be converted to opportunity cost C_{rep}:

$$C_{rep} = C_{jz} * \mathrm{L} \quad (6)$$

where C_{jz} is the unit's cost in million RMB. This equation characterizes that the greater the variable load rate, the greater the potential lifetime loss opportunity cost. In the day-ahead optimal allocation, this cost is summed up over the lifetime loss opportunity cost generated by all variable load round-trip processes in a day.

2.3 Maintenance costs due to overtemperature

A related study [14] showed that in the process of joint frequency regulation, the temperature variation of different heating surfaces of the boiler in the unit increases with the increase of variable load rate. It selected five locations for dynamic process analysis: water-cooled wall outlet, screen superheater outlet, horizontal low-temperature reheater inlet, vertical low-temperature reheater outlet, and coal-saving wall outlet. It was found that the greater the variable load rate, the more drastic the temperature fluctuation of its heating surface. According to the ASME stress calculation standard, the alternating thermal stress can be corresponded to the maximum temperature deviation of the heating surface. In addition, the heat transfer capacity of the mass side is much stronger than that of the flue gas side, so the maximum temperature deviation of the mass can be used to reflect the maximum temperature deviation of the heating surface. In this way, the maximum temperature deviation of working medium is corresponding to the alternating thermal stress.

The larger the variable load rate is, the more drastic the fluctuation of the temperature of the mass on the heating surface is, and the greater the alternating thermal stress is, the greater the losses suffered by the unit, and the maintenance cycle will be shorter accordingly. First of all, according to the data of thermal test, it is found that the maximum temperature deviation of the working mass at each location of the unit has different deviations at different variable load rates. Therefore, the maximum temperature deviation of the mass at each position is averaged to measure the maximum temperature deviation of the mass at a specific variable load rate, i.e., the magnitude of alternating thermal stress. The following relational model is obtained by fitting the average value:

$$T_{dif} = p_1 x^3 + p_2 x^2 + p_3 x + p_4 \quad (7)$$

where T_{dif} denotes the maximum temperature deviation of the average unit mass, which reflects the magnitude of the alternating thermal stress. *x* is the variable load rate. The lift-load process is fitted separately to improve the model accuracy. When *x* is positive, it indicates the lift-load, in which p1=0.001013, p2=-0.04737, p3=1.37, and p4 =6.788; when *x* is negative, it means decreasing load, and then the absolute value of input *x* is found and then substituted into equation, where p1=-0.003387, p2=0.1266, p3=-0.4742, p4=12.02.

It is difficult to portray very precisely the value of the variation of the maintenance cycle time caused by different variable load rates. In this regard, in the simulation, the cost per day was estimated based on engineering experience and shrunk to an order of magnitude consistent with engineering experience by multiplying it by an estimation factor:

$$C_{gs} = C_{wx} * T_{dif} * k \tag{8}$$

where C_{gs} is the estimated cost of maintenance corresponding to the variable load process at different variable load rates, and C_{wx} is the cost corresponding to one unit repair, in million RMB, taken as 10 million RMB in the simulation. T_{dif} is the alternating thermal stress term related to the variable load rate, this multiplied by the maintenance cost of a single time has initially reflected the trend of the maintenance cost becoming larger as the variable load rate becomes larger, but the cost value obtained from this trend is often not consistent with the actual engineering experience, therefore, the estimation factor k is multiplied at the end to shrink this cost to a quantitative level consistent with the engineering experience.

In this way, when the AGC load command and energy storage state change, the variable load rate of the unit will also change, so that its reasonable maintenance single-day commuted cost will also change between the quantity levels in line with the engineering experience. For the unit selected in the simulation, when it changes between the minimum and maximum variable load rate allowed, the single-day cost will fluctuate between 1000 and 8000 RMB. Of course, the cost will fluctuate depending on the specific maintenance situation due to the degree of wear and tear and different maintenance components of different units, but the trend of changing with the variable load rate is in line with the actual situation. In addition, when conducting the optimal allocation of load for thermal storage, if the result of the allocation can make its reasonable order of magnitude tends to the minimum cost, then the result of the optimal load allocation is also meaningful, it gets the lowest possible unit variable load rate, which makes the total cost tends to the minimum and the investment payback period tends to the shortest.

2.4 Energy Storage Costs and FM Benefits

When energy storage is first put into operation, its configuration costs should be considered. Then, its operation and maintenance (O&M) costs need to be considered. The cost of its configuration can be characterized by the following equation:

$$P_{storage} = C_b \frac{E_b}{\eta} + C_{pac} P_b + C_a E_b \tag{9}$$

where C_b is the unit energy price of the battery body, in million RMB/MWh; E_b is the rated capacity of the energy storage, in MWh. η is the total charging and discharging efficiency of the energy storage; C_{pac} is the unit power price of the converter of the energy storage system, in million RMB/MW. P_b is the charging and discharging power of the energy storage, in MW; C_a is the unit energy price of auxiliary facilities, in million RMB/MWh.

The O&M cost of energy storage system can be characterized by the following equation:

$$P_{oc} = c_{fix} P_b \tag{10}$$

where c_{fix} is the fixed operating cost per unit of power, in million RMB/MW.

When performing the day-ahead load optimization allocation, the total annual cost of energy storage is divided by 365 equally to a specific day as the cost of energy storage for a single day.

The frequency regulation gain can be characterized by the following equation:

$$gain_{tp} = k_p D' Q_{price} \tag{11}$$

where k_p is the comprehensive performance index of frequency regulation, which is taken as 2.4 when energy storage is involved in frequency regulation compensation and 1.1 when energy storage is not involved (based on historical data statistics). D' is the approximate frequency regulation mileage, and the difference between the two load points before and after the dispatch phase is used as the equivalent mileage calculation, in MW. Q_{price} is the frequency regulation compensation price, which is taken as 10 RMB/MW in the simulation. The total revenue of this load distribution can be obtained by summing up the revenue generated by all the variable load processes in a single day [15].

3. Analysis of the day-ahead optimization case

The capacity of the thermal power unit analyzed in this case is 330MW, and the storage capacity is 4.5MWh, and the rated charging and discharging power is 9MW.

According to the unit load command and unit output power history data for load optimization distribution simulation, the energy storage output and unit output should meet the load balance constraint. The load command fluctuation of a typical day is shown as follows.

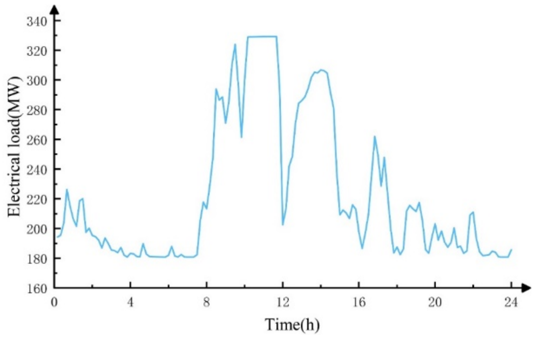

Figure 1 Typical daily electricity load demand (AGC command) graph

3.1 The objective function

The objective function of the day-ahead optimization is the total cost function of the joint frequency regulation system, and the load distribution of the unit and storage should make the total cost function tend to minimize and reduce its payback period. It can be expressed by the following equation:

$$OBJ = C_{coal} + C_{bat} + C_{gs} - gain_{tp} \tag{12}$$

where C_{coal} is the total cost of coal consumption obtained by accumulating all variable-load processes in a single day, in million RMB. C_{bat} is the total cost of the energy storage unit levelized to a single day. C_{gs} is the cost of life loss plus the estimated cost of maintenance due to overtemperature spread to a single day. $gain_{tp}$ is the total frequency regulation gain obtained by accumulating all variable load processes in a single day.

3.2 Constraints

The most fundamental constraint in the joint frequency regulation system is the power balance, as shown in the following equation.

$$P_{power}^{t} + P_{bat}^{t} = P_{load}^{t} \tag{13}$$

where P_{power}^{t} is the power output of the unit at a certain moment *t*, in MW. P_{bat}^{t} is the power output of energy storage at the same time. P_{load}^{t} is the load command value at the same time, i.e. the load required by the power grid.

Further, there is a unit output constraint as follows:

$$P_{power}^{min} \le P_{power}^{t} \le P_{power}^{max} \tag{14}$$

where P_{power}^{min} is the minimum power output value; and P_{power}^{max} is the maximum power output value that can be achieved by the unit.

Upper and lower limit constraints of energy storage system:

$$P_{bat}^{min} \le P_{bat}^{t} \le P_{bat}^{max} \tag{15}$$

where P_{bat}^{min} and P_{bat}^{max} are the maximum charging and discharging power of the energy storage system respectively.

For the sake of operation safety, there are the following residual energy constraints for energy storage devices:

$$E_{stor}^{min} \le E_{stor}^{t} \le E_{stor}^{max} \tag{16}$$

where E_{stor}^{min} is the minimum required residual energy of energy storage, which ensures that the energy storage power cannot be too low, and its corresponding SOC value is generally 0.2. The residual energy of the highest requirement E_{stor}^{max} is to ensure that the energy storage cannot be overcharged, and its corresponding SOC value is generally 0.8. The residual energy is limited in order to make the energy storage work in a reasonable energy range and prolong its service life.

3.3 Optimization algorithm and results

In this paper, the artificial bee colony algorithm (IGABC) [16, 17] is used to solve the optimal load distribution problem. For the day-ahead optimization, the optimization variables selected are the power output values of the units and energy storage. The scheduling cycle is 5 minutes. Thus, there are 576 variables to be optimized. At the very beginning, 100 sets of random solutions (corresponding to the number of employed bees or onlooker bees) are generated in its solution space. A more optimal solution is continuously searched according to its solution process, in which the scout bees will avoid the solution process from falling into a local optimum. Its detailed solution flow chart is shown below.

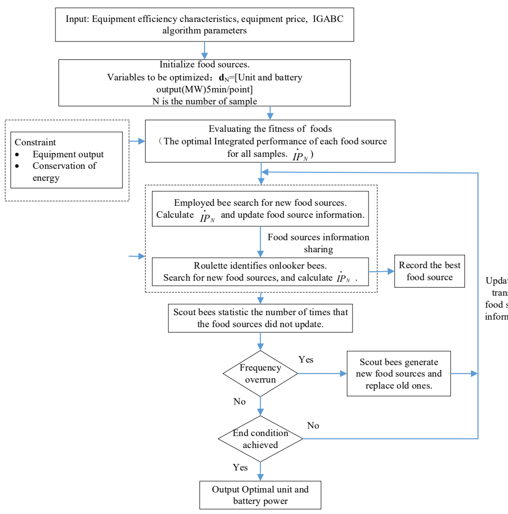

Fig. 2 Flow chart of artificial bee colony algorithm

After loading the load demand for a typical day in Figure 1 into the program, running the program according to the steps of the IGABC algorithm yields the following graph of convergence results.

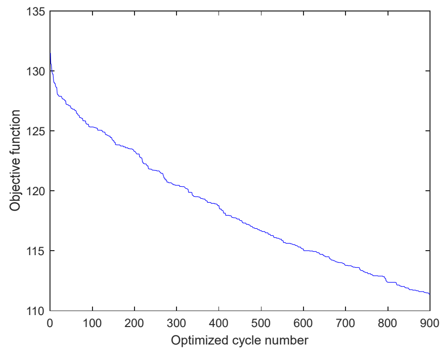

Fig. 3 Convergence diagram of the optimization search process

As can be seen from the diagram of the optimization search process, the optimal solution that makes the total cost tend to be smaller is refreshed as the solution is updated iteratively. After the maximum cycle of 900, the minimum cost of this example day is 1,115,160,000 RMB. Further, the output of thermal units and energy storage for a typical day of load demand in Figure 1 can be obtained as follows.

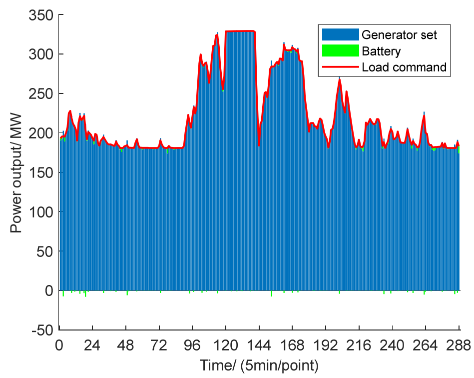

Figure 4 Thermal power unit and energy storage output map

Here the electrical load command is divided into 5 minute points, for a total of 288 load demand points in a day.
Further, the variation of the energy storage SOC value (reflecting the residual energy) can be obtained as shown below.

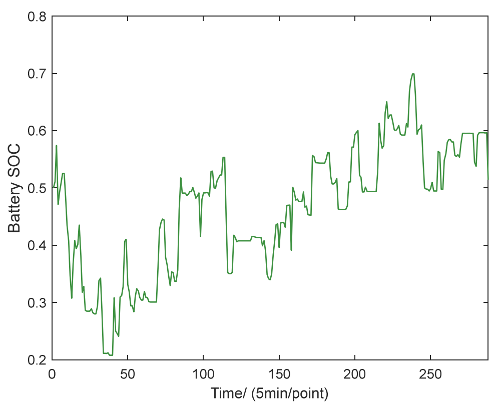

Figure 5 Graph of SOC variation of energy storage device

During the peak load hours, the energy storage will be discharged more to match the load of the unit, and its SOC value starts to show a decreasing trend. When the electricity consumption comes to the valley hours, the load of the unit starts to drop, and more energy is charged to the energy storage, and the energy storage SOC value starts to show an increasing trend.
Further analysis of each cost, comparing the optimized cost with the cost of the unit when the maximum variable load rate fast response command is applied, can be shown by the following table.

Table 2 Cost comparison table

Contrast Methods	Total Cost / (million RMB)	Coal consumpt-ion cost	Frequency regulation gain	Energy storage cost	Lifetime and maintenance costs
Unit optimized rate response	111.516	110.0854	12.95245	13.37955	1.0035
Unit constant and fast response	112.829	109.9505	11.0465	12.09516	1.82984
Relative change (%)	-1.1637	0.1227	17.254	10.619	-45.159

It can be seen that the total cost is reduced by operating under the optimally assigned load command. Especially for the life and maintenance costs, the relative change is large. This means that the unit is operated at the lowest possible variable load rate with the help of energy storage, so that the temperature fluctuation of the unit's own heating surface is not particularly sharp. The alternating thermal stress on the heating surface is lower than that at fast variable load, so that the calculated life time and maintenance cost estimates are lower.

4. Conclusion

By incorporating the estimated maintenance cost and life depreciation cost caused by overtemperature into the traditional cost model, the total cost of combined thermal unit and storage system is more detailed and complete, which is closer to the real cost of the frequency regulation process. This provides a certain reference value for the cost calculation and cost recovery period estimation of the combined thermal storage frequency regulation project.
In the optimal distribution of AGC load commands, the results show that with the help of energy storage, the response speed of the units to the commands is improved, and the overall frequency regulation performance index is improved. Therefore, compared with the fast response of the units, the energy storage only compensates for the deviation, and the frequency regulation benefit is increased, which is one of the main objectives. Let thermal power units benefit from the rapid load changing capability of energy storage and better meet the requirements of frequency regulation. It can also be seen that the coal consumption cost occupies a large percentage of the total cost, because coal consumption is needed every moment to maintain the unit's output value with the variable load rate value for lifting and lowering the load. This cost is subject to a range of fluctuations in the SOC status of energy storage, depending on the change in coal price and the size of the load command demand.

In addition, when the unit is frequency regulated at an optimized rate, energy storage can help the unit take on some of the load, and the unit can lift the load at the lowest allowable variable load rate in this case. In this way, the life loss of the unit will be greatly reduced, which can effectively extend the service life of the unit and reduce the commutation cost. After the load change rate is reduced, compared with the quick response command, the temperature fluctuation and alternating thermal stress of the internal boiler and turbine become smaller. Therefore, the maintenance cycle of the unit is extended. The relative change in its cost term (-45.159%) illustrates the necessity for optimal distribution of load. The deep coordination of thermal power and energy storage can not only improve the AGC frequency regulation gain, but also reduce the total cost, shorter the return period of investment.

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