Research of Unit Bidding Strategy and Earnings Analysis in the Peak Regulation Ancillary Service Market

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Abstract. With the gradual development of electricity market reform, the peak load ancillary service market has been built in many regions of China. It is necessary to analyse the bidding strategies and earnings of thermal power units in different bidding modes and settlement modes. First of all, according to the cost of thermal power units, the cost of participating in peak ancillary services is studied. Then, based on the accurate prediction of the market clearing price in peak shaving, the bidding strategy and profit of thermal power units under the corresponding market rules are studied. Finally, considering the prediction error of the market clearing price in peak load regulation, the bidding price in peak regulation is taken as a random variable to study the optimal bidding strategy and the maximum expected return of thermal power units. The research results show that thermal power enterprises can improve their own profits by choosing the optimal strategy. Different bidding modes have little effect on the efficiency of market operation, while different settlement modes have obvious effect on the total market peak regulating cost and the peak regulating income of thermal power enterprises.

1. Introduction
With the rapid development of clean energy such as wind power, its installed capacity accounts in various provinces among the total capacity are becoming more and more. The state has adopted a policy that the elimination of clean energy has priority, it is necessary for the thermal power unit to operate at low load rate due to the obvious anti-peak characteristics of clean energy such as wind power. The cost of coal consumption per unit of thermal power generation increase significantly with the decrease of load ratio as in refers [1-3], the peak power is not enough for enterprises, the dispatching centre endured enormous pressure at the low load time period, it is only arranged the thermal power running at low load rate according to dispatching procedures, and it is still difficult to avoid the widespread abandonment of wind. In 2015, the General Office of the CPC Central Committee issued a document( Zhongfa [2015] No. 9), It has become an important means for various regions to solve the problem of peak adjustment by means of market, and many provinces began to build peak regulation auxiliary service market. There are also many research achievements on peak regulation auxiliary service market in China. In refer [4] it has studied the peak regulation compensation model of common thermal power units and put forward a depth peak regulation model which takes into account the host-guest factors of peak adjustment. In refer [5], it analysed the depth peak regulation capability of existing thermal power units in China, which is based on large scale wind power connected to gird, and the goal is made the total power cost of thermal units under dispatching period turning to minimum, it established the economic dispatching model based on the graded deep peak. The refer [6] is deduced a new peak regulation model based on the
effectiveness analysis of peak regulation and the trade principle of social welfare maximization. The problem of wind abandonment in Northeast power grid has improved, which based on the analysis of the situation before and after the operation of the peak regulation auxiliary service market in Northeast Power Grid, and the peak power ability has improved, but there still some problems, then in refer [7], it has analysed the peak regulation auxiliary service market of Northeast Power Grid in detail. The refer [8] has analysed the effect of Jilin Power Grid taken part in the Northeast peak regulation auxiliary service market. Refer [9] has studied the peak capacity of Northeast Power Grid can be greatly increased by the test of the lowest steady combustion load performance of power plant. It proposed a method to reduce peak regulation cost of thermal power plant to enhance the competitiveness of thermal power enterprises in peak regulating market in refer [10]. The refer [11] put forward a multiple types of power supply jointed peak method contained grid and province dispatch grade level. Here we introduced the commonly used quotation mode and clearing mode of peak regulation auxiliary service market with thermal units. Then, it analysed the quotation strategy and profit of thermal power unit under two different declaration mode when under the marginal price settlement. Later, it made analysis of examples according to the settlement model.

2. Introduction of peak regulation auxiliary service market of thermal units

2.1. Declaration mode of thermal unit peak market
In the peak regulation auxiliary service market of thermal unit, the paid peak regulating is identified when the thermal load rate lower than the specified ratio, and it is proceed in market. A thermal unit rated capacity is set of \( P_{\text{cap}} \), \( P_{\text{min}} \) is the minimum output, the benchmark power of paid peak regulating specified by market is \( \alpha P_{\text{cap}} \), that the unit declaration mode of peak regulating is adopt one or multistage under the period of \( (0, \alpha P_{\text{cap}} - P_{\text{min}}] \), and the price is single-track without declining.it is required that each 5% of the rated power of peak regulating benchmark power for thermal unit is a bidding period, and it is only to bid each period price. The typical bidding curve is shown in Figure 1. The figure shows that the unit minimum output is \( 30\% P_{\text{cap}} \), \( 60\% P_{\text{cap}} \) is the base power of paid peak regulating. The paid peak regulating range is divided into six sections for bidding. If the unit bidding quantity is \( X \) after market clearing, it means the unit power generation scheduling is \( \alpha P_{\text{cap}} - X \).

Another common declaration mode is bid the electricity quantity and the price at the same time, that is bid more than three period under the range of \( (0, \alpha P_{\text{cap}} - P_{\text{min}}] \) and the price is single-track with increase.

![Figure 1. Typical bidding curve of peak shaving market.](image)

2.2. Clearing model of thermal unit in peak regulating market
The common market clearing mechanism include two model, one is cleared by marginal price, the other is by bidding price. When set the unit i bidding price with \( D_{i,k} \) in period k, \( M_{X,y} \) is the highest
bidding price called in the market clearing. It is cleared by marginal price $M_{xy}$ of all the winning biding electricity with all winning unit in the marginal price clearing model. In the bidding price clearing model, all the winning electricity quality is cleared by bidding price $D_{ik}$ with all the winning units.

2.3. Peak regulating cost analysis of thermal unit

The figure below shows the typical average cost of generating with the thermal unit, the abscissa represent the generating power point, and the ordinate represent average cost of generation. $P_{\min}$ is the minimum output of unit, $P_{cap}$ is unit rated capacity, $P_{sta} = \alpha P_{cap}$ is the unit paid regulating base power.

In the operation of the peak regulating market, the dispatching operation still ensure that the annual utilization hours of all thermal power units are basically the same. If there is a peak regulating demand in the market at a certain time, it start the peak regulating market, when a unit does not participate the market, then the unit generating power is $P_{sta}$, the generating cost is show as follows:

$$F_{sta} = C_{sta}P_{sta}\Delta t$$  \hspace{1cm} (1)

In the formula, $C_{sta}$ is average cost under the condition of output at peak regulating base power, $\Delta t$ is the duration moment.

If the unit participated in the market, the winning bidding energy is $\Delta p$, then the generating power is $P_{sta} - \Delta p$, the generating cost during the peak regulating period is as follows:

$$F'_{sta} = C_{sta}(P_{sta} - \Delta p)\Delta t$$  \hspace{1cm} (2)

In the formula, $C_{sta}$ is the average cost of output clearing corresponding to generating power. Based on the “three public” dispatching requirements, if the unit participated in the peak regulating market, the less generating power compared with the nonparticipation will catch up on the behind, the patch generating output range is above the peak base power, and the average cost of patch generation can be calculated briefly according to the typical power generating curve of same month, and the formula for calculating the cost of power generation for this part is as follows:

$$F_{ap} = (\sum_{i=1}^{N} c(P_t)) / N)\Delta p\Delta t$$  \hspace{1cm} (3)

In the formula, $P_t$ is the historical power generation power of unit in this month, we remove the data below the peak regulating base power, the remaining number is $N$. The $c(P_t)$ is the average cost corresponding to generating power $P_t$.

![Figure 2. Average cost curve of generating units for thermal power units](image)

The generating power cost of unit winning in peak regulating market increased compared with not participating in peak regulating market, that is the cost unit participated in peak regulating market. When the winning bidding of peak regulating is $\Delta p$, the total cost of participating in the peak market is given in follows:
In the formula, \( C_p = \sum_{i=1}^{N} c(P_i) / N \), when the peak winning bidding take different values, it can calculate the corresponding total cost of peak regulating.

If the unit peak regulating range is \((0, \alpha P_{\text{cap}} - P_{\text{min}}]\), the minimum bidding power unit is 1MW, then we can calculate the \( c_m(E) = c_s(E) - c_s(E - 1) \) which is the marginal cost of the unit participated in peak regulating successively. The details as marginal cost of unit participated peak regulating is shown as follows, it is different from most common goods which marginal cost is increased.

![Figure 3. Thermal power unit peak shaving marginal cost](image)

3. Thermal unit bidding strategy and earnings analysis under marginal price clearing model

Each figure should have a brief caption describing it and, if necessary, a key to interpret the various lines and symbols on the figure.

3.1. Bidding strategy and earnings based on forecast marginal price

It is established appropriate prediction models according to the data of peak regulating requirements in historical data, system load and historical clearing prices, it can predict the peak regulating market start in which period of the next day, and the market clearing price is \( M \). It is analysed the unit bidding strategy and earnings based on forecasting price under two declaration mode.

The analysis of market declaration mode is only on bidding price, a unit can have \( N \) bidding periods if specified each 5% of rated power is a bidding period, the \( I \) period corresponding bidding peak range is \((5\% (i-1)P_{\text{cap}}, 5\% iP_{\text{cap}}]\). If \( M \geq c_m(1) \), the bidding strategy of unit is all bidding price not exceed the \( c_m(1) \) in all bidding periods, the earnings is as follows:

\[
R = (\alpha P_{\text{cap}} - P_{\text{min}})M - c_s(\alpha P_{\text{cap}} - P_{\text{min}})
\]

If \( M \leq c_m(\alpha P_{\text{cap}} - P_{\text{min}}) \), the unit bidding strategy is bidding more than price \( M \), it is to prevent winning the bid.

When \( c_m(\alpha P_{\text{cap}} - P_{\text{min}}) < M < c_m(1) \), If all bidding periods are bid as \( M \), the winning bid amount is \( \alpha P_{\text{cap}} - P_{\text{min}} \), the earnings is the area that the right shadow area minus the left shadow area as shown the below figure. In the range of \((0, \alpha P_{\text{cap}} - P_{\text{min}}]\), we can find the average peak cost as follows:

\[
C_{\text{ave}} = c_s(\alpha P_{\text{cap}} - P_{\text{min}}) / (\alpha P_{\text{cap}} - P_{\text{min}})
\]
The optimal bidding strategy is that all the bidding is \( C_{\text{ave}} \) in their bidding periods, and the earning is shown in below:

\[
R = \begin{cases} 
(a P_{\text{cap}} - P_{\text{min}}) M - c_m(a P_{\text{cap}} - P_{\text{min}}), M > c_m(E_k) \\
0, M \leq c_m(E_k) 
\end{cases}
\]  

(7)

Figure 4. Schematic diagram of revenue for thermal power units in the peak shaving market

Considering the above three situations, the clearing is calculated according to marginal price, thus the bidding strategy can be unified that all the bidding periods are the same value of \( C_{\text{ave}} \).

It analysed the situation that the market declaration mode declared the electric quantity and price at the same time. The bidding price can be analysed when divided into three bidding period at most according to set rules.

Since it is cleared according to the margin price, then as long as the bidding price meet the condition \( M > c_m(a P_{\text{cap}} - P_{\text{min}}) \), the bidding quantity is the bigger the better, so the best offer strategy is bidding in range of \( (0, a P_{\text{cap}} - P_{\text{min}}] \) according to the first bidding price \( C_{\text{ave}} \), and the earing is the same as the model which only bidding price.

3.2. Bidding strategy and earning considering price forecast error

According to the historical accuracy, the marginal price of the day-ahead clearing market can be regarded as a random variable \( M \) that obeys a certain distribution, the probability density function is set as \( f(m) \).

All the bidding price is \( C_{\text{ave}} \) at all bidding period at the condition that only declare price at the market declaration mode. In the mode that declared electric quantity and price, the bidding price is according to the price \( C_{\text{ave}} \) in the range of \( (0, a P_{\text{cap}} - P_{\text{min}}] \). The peak regulating expected earnings are the same under the two modes, the probability with market clearing price calculated in the range of \( [C_{\text{ave}}, +\infty) \) is given as follows:

\[
p = \int_{c_{\text{ave}}}^{+\infty} f(m)dm
\]  

(8)

The expectation of market clearing marginal price interval \( [C_{\text{ave}}, +\infty) \) is shown in follows:

\[
\mu = \frac{\int_{c_{\text{ave}}}^{+\infty} mf(m)dm}{p}
\]  

(9)

The expected earnings of unit under this bidding strategy is given below.
4. Thermal unit bidding strategy and earnings analysis under bidding price mode

4.1. Bidding strategy and earnings based on the highest forecast winning bid price
Setting the highest forecasting winning price of day-ahead market as $M$, we analysed the market declaration mode which is only declared price. When meet the condition $M \geq C_{ave}$, it can obtained the maximum benefit when declared price adopt the forecasting price $M$, the peak regulating earnings is as follows:

$$ R = (\alpha P_{cap} - P_{min})(M - C_{ave}) $$

(10)

When meet the condition $M < C_{ave}$, the bidding price is $C_{ave}$ in each periods, which not win the bid, the peak regulating earnings is zero. The bidding strategy and peak earnings is the same when the mode is declared electric quantity and price.

4.2. Bidding strategy and earnings considering price forecasting errors
According to the historical forecasting accuracy, the marginal price of the day-ahead clearing market can be regarded as a random variable $M$ that obeys a certain distribution, the probability density function is set as $f(m)$.

It is analysed the declaration mode which only declared price, and set each 5% of rated power as a bidding period., here we set the bidding price is $D_k$ in period $k$, the mathematic model is established as follows:

$$ \max \sum_{k=1}^{T} R_k $$

(12)

$$ C_k = (c_s(5\%kP_{cap}) - c_s(5\%(k-1)P_{cap}))/ (5\%P_{cap}) $$

(13)

$$ R_k = 5\%P_{cap}(D_k - C_k) \int_{D_k}^{+\infty} f(m)dm $$

(14)

$$ D_1 \leq D_2 \leq \ldots \leq D_T $$

(15)

$$ 1 \leq k \leq T $$

(16)

In the formula, $T$ is the total bidding periods of this unit, $R_k$ is the expectation earnings in $k$ bidding price period.

It is analysed the declaration mode both declared electric quantity and price, it can only divided into three period to declare price according to the rule. The three divided grade is $(0,E_1]$, $(E_1,E_2]$ and $(E_2,60\%P_{cap} - P_{min}]$, the corresponding bidding price is $D_1$, $D_2$ and $D_3$, the established mode is shown as below:

$$ \max R_1 + R_2 + R_3 $$

(17)

$$ C_1 = c_s(E_1)/E_1 $$

(18)

$$ R_1 = E_1(D_1 - C_1) \int_{D_1}^{+\infty} f(m)dm $$

(19)

$$ C_2 = (c_s(E_2) - c_s(E_1))/(E_2 - E_1) $$

(20)

$$ R_2 = (E_2 - E_1)(D_2 - C_2) \int_{D_2}^{+\infty} f(m)dm $$

(21)

$$ C_3 = (60\%P_{cap} - P_{min} - E_2)/(60\%P_{cap} - P_{min} - E_2) $$

(22)

$$ R_3 = (60\%P_{cap} - P_{min} - E_2)(D_3 - C_3) \int_{D_3}^{+\infty} f(m)dm $$

(23)

$$ D_1 \leq D_2 \leq \ldots \leq D_3 $$

(24)

$$ D_{i+1}, i = 1,2 $$

(25)
When solving this mode, we should refer to \( f(m) \) and its domain of definition, we can adjust the integral range and bidding price range in the function, then increase the efficiency.

5. Calculating example

5.1. Calculation of peak regulating cost

A thermal generation unit has a rated capacity of 300MW and a technical minimum output of 120MW. According to the market rules, the compensation reference power is 180MW which means this unit would get compensation if the output is lower than 180MW. The average cost fitting curve of the coal consumption for this unit can be calculated by the following equation.

\[
y = 0.002x^2 - 1.1064x + 487.01
\]

(25)

In this formula, \( y \) is the average cost with the unit of kg/MWh. And \( x \) is the output with the unit of MW. According to the latest data published by China Electricity Council, the indexed price of electricity-coal is ¥0.6/kg. And the average cost for power generation of this unit can be calculated by the following equation.

\[
z = 0.0012x^2 - 0.66384x + 292.206
\]

(26)

\[
F_p = -0.0012\Delta p^2 - 0.01584\Delta p + 38087.064
\]

(27)

For instance, if this unit quit the peak regulating market as the market has a certain demand. It would have to reduce the output to the reference output of 180MW. And the generation cost is 38087.064 per hour. Otherwise, if this unit participated in the peak regulating market, and won \( \Delta p \) regulation power. The generation cost can be calculated by the following equation.

\[
\begin{align*}
\text{Table 1} & \quad \text{Unit 24 typical power (MW)} \\
\text{Moment} & \quad 1\text{AM} & \quad 2\text{am} & \quad 3\text{am} & \quad 4\text{am} & \quad 5\text{am} & \quad 6\text{am} & \quad 7\text{am} & \quad 8\text{am} \\
power & \quad 190 & \quad 180 & \quad 175 & \quad 166 & \quad 170 & \quad 177 & \quad 185 & \quad 195 \\
\text{Moment} & \quad 9\text{am} & \quad 10\text{am} & \quad 11\text{am} & \quad 12\text{am} & \quad 13\text{pm} & \quad 14\text{pm} & \quad 15\text{pm} & \quad 16\text{pm} \\
power & \quad 215 & \quad 230 & \quad 220 & \quad 210 & \quad 215 & \quad 220 & \quad 225 & \quad 230 \\
\text{Moment} & \quad 17\text{pm} & \quad 18\text{pm} & \quad 19\text{pm} & \quad 20\text{pm} & \quad 21\text{pm} & \quad 22\text{pm} & \quad 23\text{pm} & \quad 24\text{pm} \\
power & \quad 240 & \quad 250 & \quad 240 & \quad 225 & \quad 220 & \quad 210 & \quad 202 & \quad 195 \\
\end{align*}
\]

The typical power of 24 hours is listed in Table 1. The cost of the subsequent regenerative power generation in the market can be obtained by the following equation.

\[
F'_{sp} = 205.3907\Delta p
\]

(28)

The additional cost of peak regulation is:

\[
c_c(\Delta p) = -0.0012\Delta p^3 - 0.01584\Delta p + 35.5271\Delta p
\]

(29)

The average cost of peak regulation is:

\[
c_s(\Delta p)/\Delta p = -0.0012\Delta p^2 - 0.01584\Delta p + 35.5271
\]

(30)

The marginal cost of peak regulation for 1MW is:

\[
c_m(\Delta p) = c_s(\Delta p) - c_s(\Delta p - 1)
\]

\[
= -0.0036\Delta p^2 - 0.02808\Delta p + 35.54174
\]

(31)

The cost curve of peak regulation is shown in Fig 5.
5.2. Bidding strategy and revenue under the marginal price settlement mode

The marginal price of peak regulating market is ¥40/MWh, ¥32/MWh, ¥24/MWh in the cases of different demand prediction. Within the output range of \((0, \alpha \alpha_{\text{cap}} - P_{\text{min}}]\) the average cost of peak regulation is ¥30.2567/MWh. Therefore in case of price-offer only mode, the bidding strategy is to offer ¥30.2567/MWh in every gear. In case of price-quantity-offer mode, the bidding strategy is to offer ¥30.2567/MWh in the gear of \((0, \alpha \alpha_{\text{cap}} - P_{\text{min}}]\).

The revenue of the unit in peak regulating market is listed in Table 2.

| clearing price | Peak regulating earnings |
|----------------|--------------------------|
| 40             | 584.598                  |
| 32             | 104.598                  |
| 24             | 0                        |

The case is further analysed considering the prediction error. Hypothetically the market marginal price \(M\) obey the uniform distribution in the interval \([28,38]\). The probability density function of the distribution is:

\[ f(m) = 0.1, 38 \leq m \leq 42 \]  

(32)

In case of price-offer only mode, the quotation strategy is to offer ¥30.2567/MWh in every gear. In case of price-quantity-offer mode with a maximum gear number of 3, the bidding strategy is to offer ¥30.2567/MWh in one grade of \((0, \alpha \alpha_{\text{cap}} - P_{\text{min}}]\).

The expected revenue can be calculated with equation 8–10. And the expected revenue of this generation unit is ¥179,8761.

5.3. Bidding strategy and revenue under the offered price settlement mode

The maximum price of peak regulating market is ¥40/MWh, ¥32/MWh, ¥24/MWh in the cases of different demand prediction. The bidding strategy and revenue of the unit is listed as follows.

If \(M = 40\), the quotation strategy is to make an offer of ¥40/MWh in every gears in both modes and the revenue is ¥584.598.

If \(M = 40\), the quotation strategy is to make an offer of ¥32/MWh in every gears in both modes and the revenue is ¥104.598.
If \( M = 40 \), the bidding strategy is to make an offer of ¥30.2567/MWh in every gear in both modes and the revenue is ¥0. The case is further analysed considering the prediction error. Hypothetically the market marginal price \( M \) obey the uniform distribution in the interval \([28,38] \).

In case of price-offer only mode, the offer data can be calculated by equation 12–16 and the result is shown in Table 3. The expected revenue of this unit in peak regulating market is ¥89.93804.

| Bidding period | Peak regulating quantity | Bidding price(yuan/MW) |
|-----------------|--------------------------|------------------------|
| 1               | (0,15]                   | 34.12835               |
| 2               | (15,30]                  | 34.12835               |
| 3               | (30,45]                  | 34.12835               |
| 4               | (45,60]                  | 34.12835               |

In case of three-gear price and power offer mode, the offer data can be calculated by equation 17–24. If the price is ¥89.93804/MWh, the power can be divided into any gears. The expected revenue of this unit in peak regulating market is ¥89.93804.

6. Conclusion

In thermal peak regulating market, the thermal generation enterprises as participants should analysed the bidding strategy to gain more earnings in the market. The analysis should be made based on the bidding and settlement method. The optimized bidding strategy can be solved with suitable mathematic model with reference to the predicted market price. And using the optimized strategy the generation company could gain more earnings in the peak regulating market and improve the competitiveness. In peak regulating market, the peak marginal cost curve of thermal unit is monotonously decreasing. The common two bidding methods in peak regulating market have little influence on the bidding strategy and the market earnings to the generation units. While the settlement method of using marginal price is more likely to increase the total cost of peak regulating service than the settlement of using offered price, however, it is more in line with the original intention of stimulating of peak potential of thermal generation enterprises.

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Acknowledgments
The authors wish to thank cooperators and other co-workers. This work was supported in part by a grant number of DZ71-18-002.