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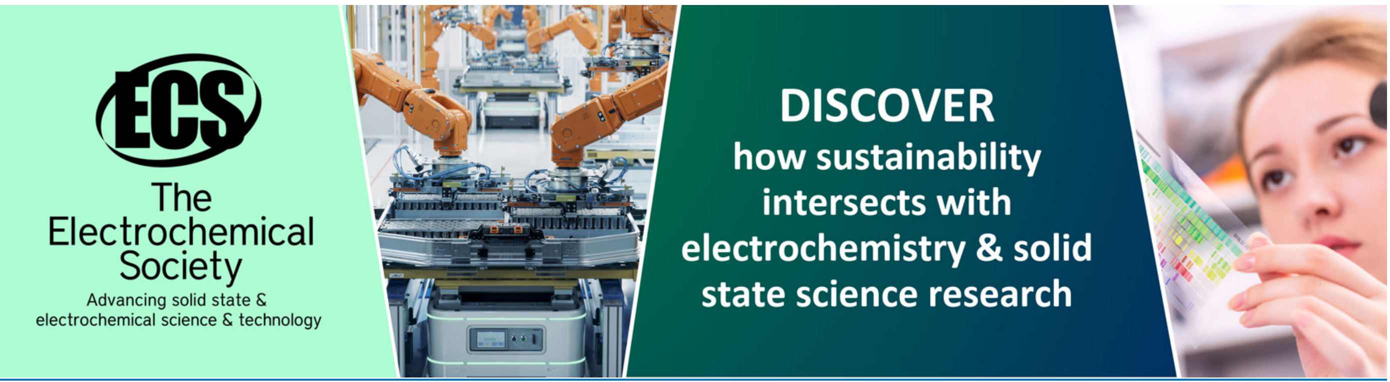

Quotation Strategy of Combined-Cycle Gas Turbine Considering Flexibility and Start-Stop Peak Shaving

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Abstract: This paper proposes a bilevel optimal scheduling model considering the flexibility and peak shaving benefits of gas-steam combined cycle units, which realizes "thermoelectric decoupling" and the flexibility of the unit by configuring electric boilers, and adds the benefit of peak shaving to the upper model to maximize the profit of the unit. Among them, the upper model is the unit optimal bidding model considering flexibility and peak shaving benefits, and the lower model is the power market-clearing model considering the maximization of social welfare. The bilayer model is transformed into a mixed-integer linear programming problem through KKT conditions and other solution methods. The effectiveness and rationality of the model are verified by the analysis of examples. The results of examples show that "thermoelectric decoupling" and start-stop peak shaving can effectively improve the profit of the gas-steam combined cycle unit and the wind power consumption capacity of the system. Finally, the strategic bidding behavior of gas-steam combined cycle units in different periods of the power market is explored.

1.Introduction

With the continuous increase in energy demand, haze weather has appeared in the three northeast provinces of China for many years, which puts forward new demands for the local power energy structure, namely reducing the use of coal and finding clean energy to replace coal. In recent years, some cities in the north have been actively promoting the development of "coal to gas" technology. Using combined-cycle gas turbines (CCGT) to replace coal-fired units. CCGT has many advantages such as good peak shaving performance, fast peak shaving speed, low carbon emission level, and high thermal efficiency[1-2]. However, due to the high-power generation cost of units, they do not have an advantage in the current reformed power market. Therefore, in order to adapt to the transformation of the energy field, it is urgent to study the bidding strategy of CCGT.

At present, the relevant theories of the power market are relatively mature, and a lot of research has been done on unit quotation strategy, mainly including four methods, cost analysis[3], electricity price prediction[4], estimation of bidding behavior of other power producers[5], and game theory[6]. Among them, the bilevel model optimization method based on game theory can solve the equilibrium problem of the power market, which essentially takes profit maximization as the upper model and social welfare maximization as the lower model. There are mainly two methods to solve the bilevel optimization problem. One method is to replace the lower-level problem with the KKT condition, so that the bilevel optimization problem can be transformed into an equivalent single-level MPEC problem. The influence of the assessment weight of renewable energy consumption responsibility weighting system, green card price, and renewable energy penetration on the market equilibrium point was studied through the MPEC model[7]. Some scholars[8] constructed a market equilibrium MPEC model considering power to gas and analyzed the ability of power to gas in improving wind power consumption. The other is to solve the market equilibrium point through a heuristic algorithm. Past research[9] solves the bilevel model of market clearing through the combination of particle swarm optimization and CPLEX.

When CCGT supplies heat independently, the complex operation mode and the constraints of "determining electricity by heat" limit its flexibility and regulation ability on the power side, which seriously affects the quotation and income of units in the power market. Therefore, many types of research are devoted to realizing "thermoelectric decoupling" and reasonable unit combinations to release the flexibility of the power side. In terms of "thermal power decoupling", references[10] took thermal power plants with a variety of thermal power decoupling equipment as the object and studied the bidding strategy of thermal power plants participating in the day-ahead market. Some researchers[11] considered that heat and power units can be combined to formulate real-time heat prices in the heat market for load management to release the flexibility of units in the power market. In terms of unit commitment, researchers[12] put forward a unit commitment formula that considers the transition process between different operation modes of CCGT. Reference[13] proposed a new compact mixed-integer linear formula for CCGT modeling which can be used for unit commitment problems or power market bidding problems.

In this paper, a CCGT bilevel decision-making model considering both "thermoelectric decoupling" and start-stop peak shaving is proposed. Compared with the traditional bilevel model of the power market, the model proposed in this paper fully considers the flexibility and operation characteristics of units. Through the comparison of clearing results under different scenarios, the effectiveness and rationality of the model are verified, which has a certain reference value for the development path of the future power market and the bidding decision of CCGT.

2.The bilevel decision model considering CCGT flexibility and peak shaving benefits

2.1.Mathematical model of CCGT

The mathematical model of the unit mainly includes the internal output model, cost model, and start-stop peak shaving model. For CCGT, its power generation output is the sum of the output of the gas turbine and steam turbine. The output relationship between gas turbine and steam turbine can be expressed as follows.

$$P_2 = bP_1 + c - P_{2s} = bP_1 - dQ_H + c \tag{1}$$

Where, P_1, P_2, and P_{2s} are gas turbine power, steam turbine power, and steam turbine power lost due to heat supply. Q_H is heating power of the steam turbine, and b, c, d are fitting coefficients.

Under the condition of stable natural gas prices, the variable cost of CCGT is mainly determined by gas consumption. The natural gas consumption of the unit is mainly related to the power generated by the gas turbine.

$$V_f = a_1P_1^2 + a_2P_1 + a_3 \tag{2}$$

Where, V_f is natural gas consumption, and a_1, a_2, a_3 are fitting coefficients.

The cost of CCGT mainly includes variable costs and fixed costs. This paper simplifies the calculation of fixed cost and converts it according to its proportion to the total cost. Therefore, the total cost of CCGT can be expressed as follows.

$$C_{RL} = 1/(1-\gamma)\ pV_f \tag{3}$$

Where, C_{RL} is the total cost of CCGT, γ is the conversion coefficient, and p is the natural gas price.

For the CCGT participating in start-stop peak shaving, the operation cost in the start-stop peak shaving section mainly depends on the number of starts and stops of the gas turbine. Each start and stop of CCGT will consume a certain amount of natural gas, and its cost can be expressed as follows.

$$C_{tf} = \sum_{t=1}^{T}\sum_{ct=1}^{CT_i}(y_{t,i}^{ct} + z_{t,i}^{ct})V_{tf}\,p \tag{4}$$

Where, C_{tf} is the start-stop peak shaving cost, and $y_{t,i}^{ct}$, $z_{t,i}^{ct}$ are 0-1 variables of whether the gas turbine ct in unit i starts or stops in t period. V_{tf} is start-stop gas consumption. CT_i is the number of gas turbines in the unit i. T is the number of periods.

In order to make up for the loss of peak load regulation auxiliary services provided by CCGT, the unit needs to be economically compensated. The peak shaving benefits are related to the gas turbine capacity and compensation price, which is generally formulated by local relevant institutions.

2.2. Upper-level model - bidding model of power producers based on profit maximization

The objective function of the upper CCGT optimal bidding model is to maximize the profits of power producers, and the constraints are CCGT operation mode conversion constraints, unit output, and ramp constraints, heat balance constraints, and market rules constraints. This paper assumes that CCGT can only switch between "two gas turbines+ one steam turbine" (2GT+1ST) and "one gas turbines+ one steam turbine" (1GT+1ST).

$$\max\ F = \sum_{t=1}^{T}(\alpha_{t,k}^{e}P_{t,i}^{SD} + \alpha_{t,k}^{r}Q_{t,i} + S_{com} - C_{RL} - C_{tf}) \tag{5}$$

$$\sum_{t=1}^{T}\sum_{ct=1}^{CT_i}(y_{t,i}^{ct} + z_{t,i}^{ct}) \le N_i \tag{6}$$

$$y_{t,i}^{ct} - z_{t,i}^{ct} = u_{t,i}^{ct} - u_{t-1,i}^{ct} \tag{7}$$

$$y_{t,i}^{ct} + z_{t,i}^{ct} \le 1 \tag{8}$$

$$u_{t,i}^{ct}P_{\min}^{S,ct} \le P_{t,i}^{S,ct} \le u_{t,i}^{ct}P_{\max}^{S,ct} \tag{9}$$

$$u_{t,i}^{gt}P_{\min}^{S,gt} \le P_{t,i}^{S,gt} \le u_{t,i}^{gt}P_{\max}^{S,gt} \tag{10}$$

$$u_{t,i}^{ct}P_{s\min}^{S,ct} \le P_{t,i}^{S,ct} \le P_{\max}^{S,ct}u_{t,i}^{ct} \tag{11}$$

$$-DR_i^{ct} \le P_{t,i}^{S,ct} - P_{(t-1),i}^{S,ct} \le UR_i^{ct} \tag{12}$$

$$-DR_i^{gt} \le P_{t,i}^{S,gt} - P_{(t-1),i}^{S,gt} \le UR_i^{gt} \tag{13}$$

$$Q_H^{\min} \le Q_{t,i} \le Q_H^{\max} \tag{14}$$

$$\sum_{i\in\varphi_k}Q_{t,i} + \sum_{x\in\phi_k}Q_{t,m,x}^{e} = Q_{t,m}^{load} \tag{15}$$

$$\alpha_t^{\min} \le \alpha_{t,i}^{S} \le \alpha_t^{\max} \tag{16}$$

Where, F is the profit of CCGT. $\alpha_{t,k}^{e}$ and $\alpha_{t,k}^{r}$ are clearing prices of the power market and selling heat price at node k in t period. $P_{t,i}^{SD}$ is bid winning power of CCGT i in the power market in t period. S_{com} is peak shaving income. $u_{t,i}^{ct}$ and $u_{t,i}^{gt}$ are 0-1 variables of the operating state of gas turbine ct and steam turbine gt in the period t in CCGT i. N_i is the maximum number of starts and stops. $P_{t,i}^{S,ct}$, $P_{\max}^{S,ct}$, and $P_{\min}^{S,ct}$ are generation powers of gas turbines and their upper and lower limits. $P_{t,i}^{S,gt}$, $P_{\max}^{S,gt}$, and $P_{\min}^{S,gt}$ are generation powers of steam turbines and their upper and lower limits. $P_{s\min}^{S,ct}$

is the minimum technical output of start-stop peak shaving. DR_i^{ct} and UR_i^{ct} are sliding and climbing speeds of gas turbines. DR_i^{gt}, UR_i^{gt} are sliding and climbing speeds of steam turbines. $Q_{t,i}$, $Q_H^{\min}$, and $Q_H^{\max}$ are heating outputs of CCGT and its upper and lower limits. $Q_{t,m,x}^{e}$ is the heating output of an electric boiler. $\alpha_{t,i}^{S}$, $\alpha_t^{\min}$, and $\alpha_t^{\max}$ are the quotations of CCGT and its upper and lower limits.

2.3.Lower-level model - clearing model of power market based on the maximization of social welfare
The lower level is the power market-clearing model with the maximization of social welfare as the objective function, which comprehensively considers the constraints of market-clearing power, system-safe operation, and unit bid winning power.

$$\max\ F_{dl} = \sum_{t=1}^{T}(\sum_{d=1}^{D} P_{t,d}^{load}\alpha_t^{yh} - \sum_{i=1}^{I} P_{t,i}^{SD}\alpha_{t,i}^{S} - \sum_{j=1}^{J} P_{t,j}^{OD}\alpha_{t,j}^{O}) \tag{17}$$

$$\sum_{i\in\varphi_k} P_{t,i}^{SD} + \sum_{j\in\varphi_k} P_{t,j}^{OD} + \sum_{w\in\zeta_k} P_t^{w} - \sum_{l|sl=k} f_{l,t} + \sum_{l|rl=k} f_{l,t} = \sum_{d\in\xi_k} P_{t,d}^{load} \tag{18}$$

$$0 \le P_{t,d}^{load} \le P_{t,d,\max}^{load} \tag{19}$$

$$f_{l,t} = B_l(\theta_{sl,t} - \theta_{rl,t}) \tag{20}$$

$$-P_l^{\max} \le f_{l,t} \le P_l^{\max} \tag{21}$$

$$\theta_{k,t} = 0 \tag{22}$$

$$-\pi \le \theta_{k,t} \le \pi \tag{23}$$

$$P_{t,i,\min}^{SD} \le P_{t,i}^{SD} \le P_{t,i,\max}^{SD} \tag{24}$$

$$P_{t,j,\min}^{OD} \le P_{t,j}^{OD} \le P_{t,j,\max}^{OD} \tag{25}$$

$$0 \le P_t^{w} \le p_t^{w} \tag{26}$$

$$-P_l^{\max} \le \sum_k GSF_{l-k}(P_{t,k} + P_w^{t} - P_{t,k}^{load}) \le P_l^{\max} \tag{27}$$

In the formulas above, F_{dl} is social welfare. $P_{t,d}^{load}$ and $P_{t,d,\max}^{load}$ are the bid-winning powers of the user d and its upper limit. α_t^{yh} is the bidding price of the user. $\alpha_{t,j}^{O}$ is the quotation for the thermal power unit j. $P_{t,j}^{OD}$ is the bid-winning power of the thermal power unit j. P_t^{w} is the actual output of wind power. $f_{l,t}$ is the transmission power of the branch l. $\theta_{ls,t}$ and $\theta_{lr,t}$ are voltage phase angles of nodes at both ends of the branch l. $\theta_{k,t}$ is the voltage phase angle of the node k. B_l is susceptance of the branch l. $P_l^{\max}$ is the maximum transmission power of the branch l. $P_{t,i,\min}^{SD}$ and $P_{t,i,\max}^{SD}$ are the minimum and maximum generating powers of CCGT i. $P_{t,j,\min}^{OD}$ and $P_{t,j,\max}^{OD}$ are the minimum and maximum generating powers of the thermal power unit j. p_t^{w} is the predicted output of wind power. GSF_{l-k} is generation transfer factor. $l|sl=k$ and $l|rl=k$ are branches with the node k as the head and endpoint. $n\in\varphi_k(n=i,j)$, $w\in\zeta_k$, $d\in\xi_k$, and $x\in\phi_k$ are the collection of generator units, wind farms, power loads, and electric boilers associated with the node k.

2.4.Model solving
In operations research, the dual variable of Equation (18) is the marginal price of the electric energy market. For the solving steps of bilayer optimization problems, generally, the lower-level problem is replaced by the KKT condition, so that the bilayer optimization problem can be transformed into an equivalent single-layer MPEC problem. And then it is transformed into the MILP model by using the big-m method and strong duality theory. Finally, the optimization toolbox such as CPLEX is used to

solve the model. The specific conversion process can be referred to in the old studies[11].

3.Case study

3.1.Parameter Setting

This case analyzes the modified PJM 5 nodes system, and the network topology is shown in Figure 1. The transmission capacity of B-C and C-D is set to be 180MW, and the rest lines are 400 MW. At the same time, it is assumed that each power plant has one generator. The generator parameters are shown in Table 1. Among them, G1, G2, G4, and G5 are coal-fired generators, and G3 is CCGT. In addition, the load demand and predicted wind power are shown in Figure 2. To ensure the preferential consumption of wind power, the cost of wind turbines is not considered in this case. Non-strategic units are quoted at their own marginal cost. With the day-ahead market serving as an example, this case divides a day into 24 periods and takes one hour as an application period for the market quotation.

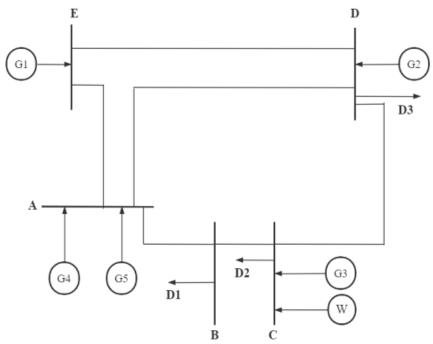

Figure 1 Modified PJM5 node network topology

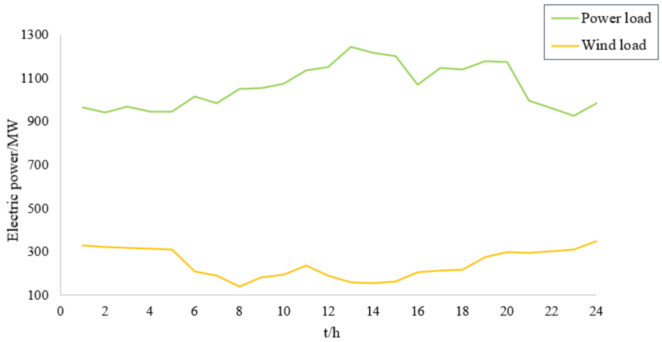

Figure 2 Load curve

Table 1 Technical parameters of the generator

Generator number	$P_{G,\max}$ /MW	$P_{G,\min}$ /MW	Marginal cost/yuan
1	600	200	307
2	200	80	335
3	520	180	366
4	100	40	345
5	110	45	340

3.2.Influence analysis of thermoelectric decoupling and start-stop peak shaving

In order to analyze the impact of thermoelectric decoupling and start-stop peak shaving on the clearing results of combined cycle units and wind power consumption efficiency, the following four cases are analyzed in this section.

Case 1: Thermoelectric decoupling and peak load regulation are not considered.

Case 2: thermoelectric decoupling is considered but not the start-stop peak shaving.

Case 3: The start-stop peak shaving is considered but not the thermoelectric decoupling.

Case 4: Thermoelectric decoupling and peak load regulation are both considered.

The results of the four cases are shown in Table 2. The comparison of wind power output, combined-cycle unit operation mode, and LMP of node C is shown in Figures 3~5. In Figure 4, operation mode 2 represents “2GT+1ST”, and operation mode 1 represents “1GT+1ST”.

Table 2 Comparison of results in different cases

Case	Profit /yuan	Amount of abandoned wind /MW	Wind power consumption rate
1	153473.4	1732.98	49.81%
2	949111.7	17.55	99.49%
3	841955.2	449.17	86.99%
4	1031276.9	0.45	99.98%

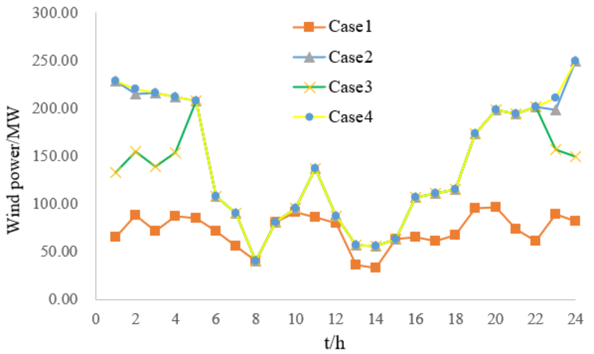

Figure 3 Comparison of wind power output

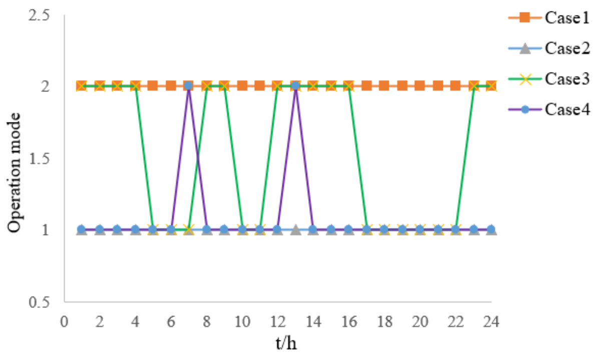

Figure 4 Comparison of operation modes

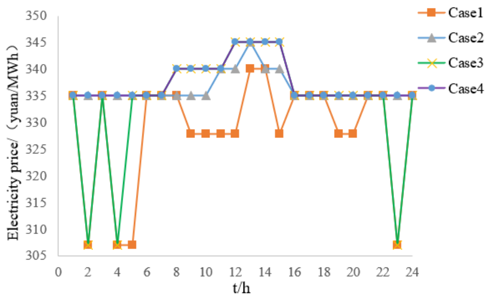

Figure 5 LMP comparison of node C

Firstly, thermoelectric decoupling is analyzed. From the comparison between Figure 4 and Figure 5, it can be seen that the CCGT of case 1 and case 2 operate in the “2GT+1ST” and “1GT+1ST” modes respectively, and the LMP of node C in case 3 is greater than or equal to the LMP of case 2. This is because before the electric boiler is configured, the two gas turbines of CCGT work near the minimum technical output, and the output of the electric boiler makes the combined cycle unit no longer subject to the limitation of “determining power by heat”. It is not necessary to run two gas turbines at the same time to ensure heat supply. CCGT can shut down a gas turbine to let unit 2 and unit 5 with higher quotations obtain the bidding power, so as to obtain a higher LMP. It can be seen from Table 2 that the profit of CCGT in case 2 is higher than that in case 1 because CCGT in case 2 operates in the “1GT+1ST” mode, and the unit output is lower than that in case 1. When LMP is lower than marginal cost, higher LMP and smaller output make CCGT lose less and obtain higher profit. From the perspective of promoting wind power consumption, the comparison between Table 2 and figure 3 shows that the wind power consumption rate of case 2 is 99.46%, higher than that of case 1. The amount of abandoned wind in case 2 is only 17.55MW which produces a good effect on waste air consumption. This is because the CCGT operation mode is switched from “2GT+1ST” to “1GT+1ST”, which reduces the output of the unit and provides more space for wind power consumption.

Then, start-stop peak shaving is analyzed. It can be seen from Table 2 that compared with case 1, case 3 not only improves the profit of the combined cycle unit but also reduces the amount of abandoned wind. This is because CCGT reduces the minimum technical output after participating in start-stop peak shaving, which firstly provides some space for wind power consumption. Secondly, wind abandonment is serious in the periods of 5~7, 10~11, and 17~22. CCGT switches from "2GT+1ST" to "1GT+1ST" mode, which provides more space for wind power consumption. At this time, the LMP is still less than the marginal cost of CCGT, and the small output reduces the power generation loss of the unit. At the same time, the start-stop peak shaving compensation also further increases the profit of the unit. Comparing Figure 3 and Table 2, it can be seen that compared with case 2, the total profit and wind power consumption rate of case 3 are lower, and the abandoned wind power is mainly concentrated in the two periods of 1~4 and 23~24. This is mainly because the heat load in these two periods is higher, and CCGT is still limited by "determining power by heat". CCGT must keep two gas turbines running at the same time, which makes it impossible for start-stop peak shaving. At this time, the unit output is more than that of "1GT+1ST", and the power generation loss is also more. Compared with Figure 5, the LMP of case 3 in the three periods of 2, 4, and 23 is lower than that of case 2. This is also because CCGT cannot reduce its output due to the limitation of "determining power by heat", resulting in only unit 1 and CCGT winning the bid. Therefore, thermal power decoupling has more advantages in improving unit revenue and wind power consumption rate than start-stop peak shaving.

3.3.Analysis of model validity and CCGT quotation strategy

To further prove the effectiveness of the strategic quotation based on the double-layer model for CCGT, this section compares the bilevel model with the single-layer model. Among them, the single-level model is $\max\ (5)+(17)\ \text{s.t.}\ (6\text{-}16),(18\text{-}27)$. The cost of the bilevel model is 8628678 yuan, which is lower than the 9849081 yuan of the single-level model. The wind power consumption rate of the single-level model is 81.86%, which is lower than the 99.98% of the bi-level model. The results show that the bilevel model is more effective than the single-level model in both improving the unit revenue and wind power consumption efficiency. In addition, the CCGT quotation curves of the two models and different cases are shown in Figures 6~7.

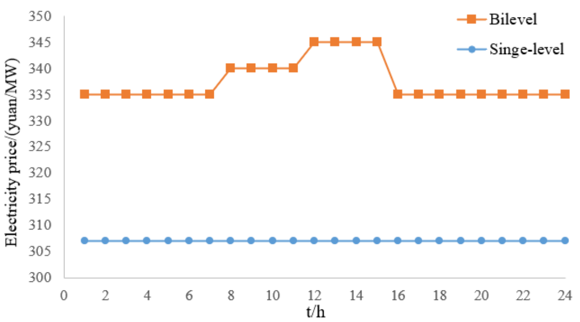

Figure 6 CCGT quotation under two models

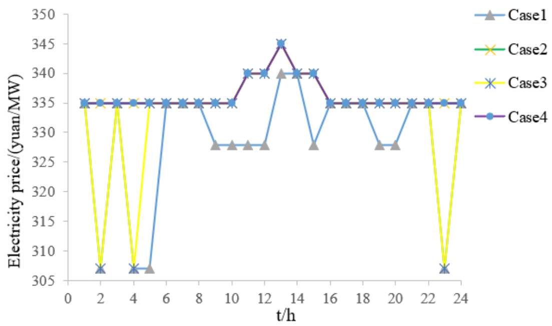

Figure 7 CCGT quotation under different cases

It can be seen from Figure 8 that the single-layer model only adds the objective functions and constraints of the upper and lower layers without considering the coupling relationship between the upper and lower layers. It is difficult to consider the economy of the upper and lower levels at the same time during optimization, which results in the conservative quotation of CCGT. To obtain the minimum power output to ensure heating, the quotation of CCGT is lack strategy. At the same time, CCGT in the single-level model obtains more bid-winning power due to its low quotation, which not only increases the power generation loss of the unit but also occupies the space of wind power consumption. The above results prove the rationality of the bilevel model proposed in this paper, and also prove the effectiveness of the quotation strategy.

The comparison between Figure 5 and Figure 7 shows that CCGT becomes the marginal unit in market clearing due to its high marginal cost. Comparing the load curves in Figure 7 and Figure 2, it can be seen that the CCGT quotation is low in different cases during the low power load period. Power load reduction and high quotation may lead to bid failure. To ensure the minimum output under the condition of the heating, CCGT can adopt the strategy of low prices and large quantities to obtain basic heating income. During the peak period of power load, CCGT offers higher prices in different cases. At this time, the low thermal load will lead to the reduction of unit output. CCGT can adopt the strategy of high price and a small amount to reduce the power generation loss through high clearing price and low power generation output on the premise of ensuring the basic heating income.

4.Conclusion

This paper analyzes the CCGT quotation strategy considering “thermal power decoupling” and peak load regulation in detail and compares the unit profit and system wind power consumption capacity under different cases. The following conclusions are drawn.

(1) “Thermoelectric decoupling” effectively releases the power flexibility of the CCGT power side, which reduces the output and provides a bid-winning opportunity for other units with a higher quotation. CCGT takes the opportunity to improve its quotation, and the unit profit and wind power consumption rate are significantly improved.

(2) During the period of low heat load, the start-stop peak shaving effectively reduces the output of CCGT and provides space for wind power consumption. Through strategic quotation and peak shaving compensation, the profit of CCGT is further improved. However, in some periods of high heat load, CCGT is still affected by “determining power by heat”, and the unit revenue and wind power consumption rate are not ideal, which needs to be coordinated with “thermal power decoupling”.

(3) Through the comparison of single-level and bilevel models, it is proved that the model proposed in this paper can effectively improve the profit and wind power consumption efficiency of CCGT and provide a useful reference for the bidding of CCGT in the power market.

Acknowledgments

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