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Considering various optimization model of energy storage in wind power load auxiliary trading game

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Abstract: *In winter heating period, the heating mode of "setting electricity by heat" in northeast China causes a large number of wind abandoning, and the wind abandoning absorption rate can be improved by absorbing heat and absorbing wind. The operation of the traditional heat storage system is not linked with the wind farm, and there are still many wind curtailment. In order to track the purchase of wind curtailment in real time, based on the pre-evaluation of short-term power of wind curtailment, a day-before market centralized transaction mode of wind power curtailment reported by wind farms and demand function reported by heat storage enterprises was proposed in the market of auxiliary peak shaving service for wind power storage. By establishing the multi-party game optimal demand function model of heat storage enterprises, the unified clearing price and wind abandoning subscription situation are obtained, and the intra-day settlement method is proposed for intra-day unbalanced electricity quantity.*

Keywords: *Electric heat storage, Wind abandoning pre-assessment, Centralized trading, Demand function*

1. Introduction

In recent years, wind power generation has witnessed rapid development. In 2018, the accumulative grid-connected installed capacity in China reached 184 million kW, accounting for 9.7% of the total installed power generation capacity. However, wind abandoning phenomenon is very serious in China, and the wind abandoning power in 2018 was about 27.7 billion KWH [1]. There are many wind abandoning in The Three North regions of China, and most of them occur in the winter heating period. The main reason is that the cogeneration units in the three North regions generally work in the mode of "setting power by heat" in winter. At this time, the peak regulation capacity of the system is significantly reduced and the wind power acceptance space is reduced [2].

At present, there are a lot of research results on wind power consumption. Wind abandon heating can improve the wind power acceptance capacity in off-peak hours [3-4]. Literature [5-6] analyzes that wind power consumption rate can be improved by configuring heat storage devices. In addition, foreign studies have shown that electric power system equipped with electric boiler can improve the acceptance capacity of wind power [7-8]. In northeast China, solid phase change heat storage device is used to absorb wind abandoning, that is, when there is a large amount of wind abandoning in the power grid, the heat storage device uses wind abandoning to store heat for heating users [9].

The scheme of solid phase change heat storage absorbing wind abandoning has obvious emission reduction benefits and is environmentally friendly, but the large-scale promotion of this scheme needs to solve the transaction pricing problem of wind farms and heat storage enterprises. Literature [10] analyzes the price mechanism and economy of wind electric heating under different operating modes. Literature [11] studies the peak-adjustment pricing mechanism of thermal power plants and wind farms equipped with heat storage, and puts forward the pricing method of power generation rights in two stages: recovery period and beyond the recovery period.

Large-scale electric heat storage facilities can participate in peak shaving service transactions as interruptible loads [12]. Centralized trading is one of the main ways of interruptible load trading. Literature [13] designs centralized bidding trading rules based on declared price clearing according to the market structure characteristics of "bilateral monopoly" in Yunnan electricity market. Literature [14] constructed an inter-provincial centralized trading platform model based on intelligent agent. Literature [15] simulates the relevant rules of the domestic monthly electricity centralized bidding market based on

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the multi-agent simulation system of JADE framework. Literature [16] established the centralized bidding model of the power market through research to predict the balance point of supply and demand of future transactions.

There are two modes of using heat storage to improve the acceptance capacity of wind power :(1) fixed period and output mode of heat storage system; (2) The heat storage system follows the wind abandon power mode in real time. The existing heat storage system mostly adopts the medium absorption mode of (1), less consideration is given to the coordination and optimization scheduling. The large capacity heat storage system adopts the heat storage in the off-peak period of load or all day, and then continues to release heat, and carries out electricity subsidy transaction with the wind farm. In this mode, the electric heating power of the heat storage system is not linked with the wind farm, and only a small part of the electric power used by the heat storage system comes from wind abandoning power, while most of the electric power used is thermal power from the grid. A large amount of wind abandoning power will still be generated in the time period when there is a lot of wind abandoning power.

To solve the above problems, this paper proposes a centralized transaction model for heat storage to participate in peak-shaving based on wind abandoning pre-evaluation. Through the day-ahead assessment of wind power abandoned by the dispatching center, wind farms report short-term wind abandoning sequence, and heat storage enterprises report demand function by using multi-party game optimization model, and the transaction center conducts unified clearing. According to intra-day ultra-short-term wind abandoning power correction, intra-day compensation and intra-day subscription are adopted for intra-day settlement of unbalanced wind abandoning power.

2. Pre-assessment of wind abandoning

1) Abandon wind forecast assessment

Wind abandoning in this paper is defined as follows: on the premise that the grid topology, peak load adjustment capacity of power supply, load prediction and wind power prediction are determined, the capacity of power grid to accept wind power in a future period of time is evaluated by establishing a whole-network optimization model, and the difference between predicted power and accepted power is wind abandoning.

The theoretical wind power P_{wp}^t of the wind farm can be obtained through the characteristic fan method, etc., and it is taken as the maximum theoretical output of the wind farm at time t . The difference between the theoretical power of wind power generation and the wind power P_{ane}^t absorbed by the grid is wind abandon power $P_{w,av}^t$:

$$P_{w,av}^t = \begin{cases} P_{wp}^t - P_{ane}^t & P_{wp}^t \ge P_{ane}^t \\ 0 & P_{wp}^t < P_{ane}^t \end{cases} \tag{1}$$

In practical operation, wind power short-term power forecast is mainly used in the formulation of the next day generation plan of dispatching institutions and the arrangement of wind turbine maintenance plan. According to the working principle of wind power forecasting system and the specific requirements of power generation planning by power grid dispatching department, the time parameters of wind power short-term power forecasting are required to predict the output power in the next day (24h) with a time resolution of 15 minutes.

At the day-ahead level, the start-stop and output of all units that can be started in the system are optimized according to the information of the current operation status of the power grid, the predicted output of wind power and load prediction. Based on day-ahead wind power, load power forecast and power system operation state, the power system time series production simulation was carried out to evaluate the wind power consumption capacity.

2) Intraday curtailment correction

Compared with short-term wind power prediction, ultra-short-term wind power prediction mainly provides real-time scheduling basis for dispatching institutions. According to the working principle of the wind power forecasting system and the specific requirements of the real-time dispatching operation of the power grid dispatching department, the time parameter requirements of the ultra-short-term wind

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power forecasting are as follows: the output power of 0~4 hours in the future is predicted rolling every 15 minutes, and the time resolution is 15 minutes.

In the Functional Specification for Wind Power Prediction released by State Grid Corporation of China in 2011, it is pointed out that the monthly root mean square error of ultra-short-term prediction should be less than 15%[17], and many literatures continuously improve the accuracy of ultra-short-term prediction of wind power by improving prediction methods [18-20]. On the basis of short-term wind power prediction, rolling correction of wind power output prediction results through ultra-short-term wind power prediction is an effective method to improve the wind abandonment pre-evaluation results. The rolling correction method process of wind abandonment pre-evaluation is shown in Figure 1.

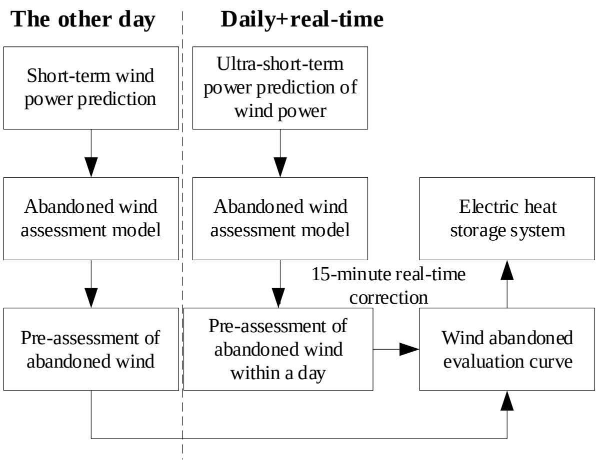

Fig.1 Day abandonment wind correction process

3. Heat storage participates in peak regulation auxiliary centralized transaction model

1) Centralized exchange market quotation framework

Wind curtailment is characterized by randomness and low price elasticity, while heat storage demand is characterized by controllable size and high price elasticity. Therefore, in the transaction market of heat storage and wind curtailment, the nature of wind curtailment is similar to load in general power market, while the heat storage demand is similar to traditional power generation.

The traditional quotation methods are: ①wind farm quotation, heat storage enterprises reported volume; ②Both wind farms and heat storage enterprises offer prices.

Suppose point 1 is the optimal equilibrium point in the market, at which curtailment is absorbed as much as possible. Under the quotation method ①, the demand reported by heat storage enterprises is difficult to be consistent with the amount of abandoned air in the market; Under the quotation method ②, point 2 is the intersection of the two quotation curves, and represents the cleared electric quantity and cleared electricity price of the transaction between the wind farm and the heat storage enterprise. That is to say, in the traditional way of quotation ①②, point 2 in the figure is difficult to close to point 1.

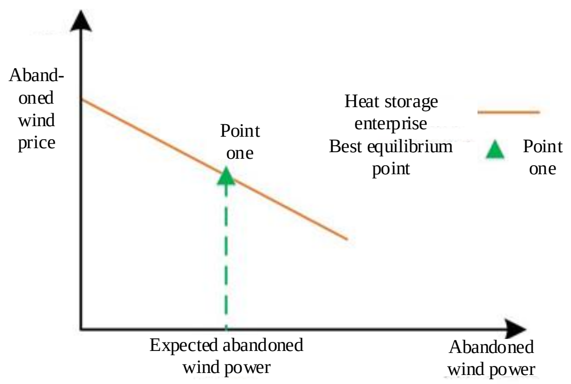

Fig.2 Wind farm quotes amount, heat storage quotes price

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Considering the special nature of heat storage and wind curtailment, in the centralized trading market designed in this paper, the wind farm only reports the bid quantity according to the pre-evaluation results of wind curtailment, which is different from the traditional power-generation side quotation (the bid price is reported at the same time when the bid quantity is reported). Heat storage adopts dynamic inverse demand function to influence the price, which is different from the common load only reporting demand. The market clearing situation is shown in Figure 2. The wind farm reports the expected amount of wind abandoning power, and the heat storage enterprise reports the demand curve. The intersection point of the two is the optimal equilibrium point in the market. Therefore, the quotation method proposed in this paper is more suitable for the power market with heat storage and wind abandoning than the traditional quotation method.

The market model of heat storage and wind abandonment adopts day-ahead centralized trading market for unified clearing. Day-ahead optimization wind abandoning consumption method based on wind abandoning pre-evaluation is as follows:

a) The dispatching center conducts pre-evaluation of wind abandoning before the day, and the data of wind abandoning before the day is delivered to the trading platform that stores heat and consumes wind abandoning;

b) The heat storage enterprise shall formulate the optimal heat storage plan for the next 24 hours according to the wind curtailment situation and its own heat storage demand, and subscribe the corresponding wind curtailment power in the wind curtailment trading center;

c) The wind abandoning trading center clears the wind abandoning trading quantity according to the wind abandoning sequence and the wind abandoning demand function;

d) The dispatching center confirms the power purchase plan of the heat storage enterprise and reduces the wind abandoning power of the corresponding wind farm.

2) Optimization subscription model for heat storage enterprises

According to the pre-evaluation sequence of day-ahead wind abandoning and the relevant operation rules of the heat storage and absorption market, the heat storage enterprises optimize the heat storage and release power, determine the optimal absorption and abandonment sequence, and report the demand function of wind abandoning to the trading center. Wind curtailment subscription is made every 15 minutes, as shown in Figure 3. The wind curtailment subscription amount from t_0 to t_0+T and the wind curtailment price already subscribed by the heat storage enterprise are known, and the wind curtailment electricity quantity from t_0+T to t_0+T+1 needs to be subscribed.

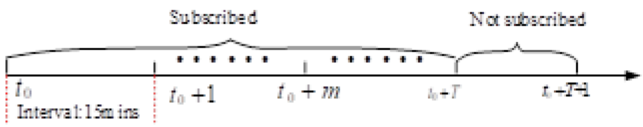

Fig.3 Abandoned wind subscription timeline

The utilization of abandoned wind power has the greatest social and environmental benefits. Heat storage enterprises mainly use abandoned wind power for heating. When heating is insufficient, coal boiler heat source is purchased to ensure heating. The price of coal boiler heat source is known, and the quotation of heat storage enterprises will not be higher than the price of coal boiler heat source when buying abandoned wind power. The heat supply quantity that the heat storage enterprise needs to meet is known, and its heating income is determined. Therefore, the goal of maximizing the income of the heat storage enterprise is to maximize the utilization of wind curtailment. The optimization objective function of heat storage enterprise is as follows:

$$\max\ f_{TSi}= \sum_{t=T-1}^{T}\left[p_{\text{heat}}^{t}P_{\text{hload}}^{t}-p_{\text{w}}^{t}P_{\text{wi}}^{t}-p_{\text{bo}}^{t}P_{\text{bo}}^{t}+p_{\text{w,mean}}(H_{\text{TSi+}}^{t}-H_{\text{TSi-}}^{t})\right]\Delta t -C_1-C_2 \quad (2)$$

In the formula: p_{heat}^{t} and P_{hload}^{t} are heating unit price and heating quantity of heat storage enterprise respectively; p_{w}^{t} is wind curtailment price; P_{wi}^{t} is the subscribed abandoned air volume; p_{bo}^{t} and P_{bo}^{t} are heating price and heating quantity of supplementary heat source respectively; $p_{\text{w,mean}}$ is the average

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purchase price of heat stored in the heat storage system; $H^t_{\mathrm{TSi+}}$ and $H^t_{\mathrm{TSi-}}$ are respectively the heat storage power and heat release power of the heat storage system; C_1 is the apportioned cost of the total investment cost of the heat storage system; C_2 is the operation and maintenance cost of the heat storage system [21].

Its constraint conditions are as follows:

a) The heat storage and heat release process of the heat storage system should satisfy the energy conservation without considering the heat dissipation.

$$E^{t+1}_{\mathrm{TS}} = E^t_{\mathrm{TS}} + \Delta T(H^t_{\mathrm{TSi+}} - H^t_{\mathrm{TSi-}}) \tag{3}$$

In the formula: E^t_{TS} is the energy level of the heat storage system at time t.

b) There is loss in electric conversion heat of heat storage system.

$$H^t_{\mathrm{TSi+}} = \eta_{\mathrm{EHi}} P^t_{wi} \tag{4}$$

In the formula: η_{EHi} is the thermoelectric conversion coefficient.

c) The combined heating of heat storage system and coal-fired boiler should meet the restriction of heating balance.

$$H^t_{\mathrm{TSi-}} + P^t_{\mathrm{bo}} = P^t_{\mathrm{hload}} \tag{5}$$

d) Controllable abandoned wind power constraints.

$$0 \le P^t_{\mathrm{wi}} \le P^t_{\mathrm{w,av}} \tag{6}$$

In the formula: $P^t_{\mathrm{w,av}}$ is the maximum controllable wind curtailment.

e) Maximum heating constraints for coal-fired boilers.

$$0 \le P^t_{\mathrm{bo}} \le \overline{P_{\mathrm{bo}}} \tag{7}$$

f) Power constraints and capacity constraints exist in the heat storage system.

$$0 \le H^t_{\mathrm{TSi+}} \le \overline{H_{\mathrm{TS}i+}} \tag{8}$$

$$0 \le H^t_{\mathrm{TSi-}} \le \overline{H_{\mathrm{TSi-}}} \tag{9}$$

$$0 \le E^{t+1}_{\mathrm{TS}} \le \overline{C_{\mathrm{TS}}} \tag{10}$$

In the formula: $\overline{H_{\mathrm{TSi+}}}$ and $\overline{H_{\mathrm{TSi-}}}$ are the upper limits of heat storage power and heat release power of the heat storage system; $\overline{C_{\mathrm{TS}}}$ is the capacity of heat storage system.

3) Curtailment trading center clearing model

The market clearing results need to determine the transaction wind power and wind power price. When the wind abandoning power is cleared, the wind abandoning power trading center should not only consider the maximum adjustable wind abandoning power, but also consider the maximum capacity of the heat storage enterprise to absorb the wind abandoning power. As the maximum capacity of heat storage enterprise i to absorb abandoned wind power at moment t, $P^t_{avail\_i}$ is affected by the maximum heat storage power $\overline{H_{\mathrm{TSi+}}}$ and the remaining capacity of heat storage device $(\overline{C_{\mathrm{TS}}} - E^{t-1}_{\mathrm{TS}})$:

$$P^t_{avail\_i} = \min\left\{\overline{H_{\mathrm{TSi+}}}, 4*(\overline{C_{\mathrm{TS}}} - E^{t-1}_{\mathrm{TS}}) + P^t_{hload}\right\} \tag{11}$$

When the wind abandoning power is cleared by the wind abandoning trading center, the maximum power $P^t_{\mathrm{w\,max}}$ can be cleared is:

$$P_{\mathrm{wmax}}^{t} = \min\left\{P_{\mathrm{w,av}}^{t}, \sum_{i=1}^{N} P_{avail\_i}^{t}\right\} \tag{12}$$

Electric quantity constraint when clearing is:

$$\sum_{i=1}^{N} P_{wi}^{t} = P_{\mathrm{w\,max}}^{t} \tag{13}$$

In the formula: N is the number of heat storage enterprises; P_{wi}^{t} is the wind abandon electricity subscribed by heat storage enterprise i at time t.

The wind abandoning price at the time of clearing is the unified clearing price, which is determined by the demand function of each heat storage enterprise and has the following constraints:

$$p_w = \rho_{0i} - \alpha_i P_{wi} \tag{14}$$

In the formula: p_w is unified clearing price; ρ_{0i} and α_i are the demand function coefficients of heat storage enterprise i.

4) Solution of model

Optimizing the centralized market equilibrium model for heat storage enterprises to participate in curtailment subscription requires solving a game problem of multiple market players, including a two-layer optimization model. The upper model is the profit maximization model of each heat storage enterprise, as shown in Section 2.2. The underlying model is the clearance condition of wind abandon trading center, as shown in Section 2.3. The optimization problem can be summarized as follows:

$$\begin{aligned} &\min_{x_i} - f_{TSi}(x_1, x_2, ..., x_{N-1}, x_N) \\ &s.t. \begin{cases} g_i(x_1, x_2, ..., x_{N-1}, x_N) \le 0 \\ h_j(x_1, x_2, ..., x_{N-1}, x_N) = 0 \end{cases} \end{aligned} \tag{15}$$

In the formula: $x_i = \{P_{wi}^{t}, P_{bo}^{t}, E_{TS}^{t+1}, H_{TSi+}^{t}, H_{TSi-}^{t}, \alpha_{TSi}^{t}\}$ is the variable to be optimized of heat storage enterprise i; g_i and h_j are the constraints of heat storage enterprises and the constraints of the clearing model of wind abandon trading center.

The single-layer optimization model of multiple heat storage enterprises is obtained by substituting the clearance conditions of wind curtailment trading center into the upper optimization model of each market member. On this basis, the first-order KKT optimal conditions of the single-layer optimization model of each market member are obtained as follows:

$$\begin{aligned} &(\rho_{0i} - 2\alpha_i P_{wi})\Delta t - \lambda_{i2}\eta_{EHi} - \mu_{i1,\min} + \mu_{i1,\max} - \lambda_{i4}\alpha_i \\ &+\lambda_{i5} + \mu_{i6,\min}\alpha_i - \mu_{i6,\max}\alpha_i = 0 \end{aligned} \tag{16}$$

$$\rho_{0i}\Delta t + \lambda_{i3} - \mu_{i2,\min} + \mu_{i2,\max} = 0 \tag{17}$$

$$\lambda_{i1} - \mu_{i5,\min} + \mu_{i5,\max} = 0 \tag{18}$$

$$-p_{w,mean}\Delta t - \lambda_{i1}\Delta t + \lambda_{i2} - \mu_{i3,\min} + \mu_{i3,\max} = 0 \tag{19}$$

$$p_{w,mean}\Delta t + \lambda_{i1}\Delta t + \lambda_{i3} - \mu_{i4,\min} + \mu_{i4,\max} = 0 \tag{20}$$

$$-P_{wi}^{2}\Delta t - \lambda_{i4}P_{wi} + \mu_{i6,\min}P_{wi} - \mu_{i6,\max}P_{wi} = 0 \tag{21}$$

$$\begin{cases} \mu_{i1,\min}P_{wi} = 0 \\ \mu_{i1,\max}(P_{wi} - P_{wav}) = 0 \end{cases} \tag{22}$$

$$\begin{cases} \mu_{i2,\min}P_{boi} = 0 \\ \mu_{i2,\max}(P_{boi} - \overline{P_{boi}}) = 0 \end{cases} \tag{23}$$

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$$\begin{cases} \mu_{i3,\min} H_{TSi+} = 0 \\ \mu_{i3,\max} (H_{TSi+} - \overline{H_{TSi+}}) = 0 \end{cases} \tag{24}$$

$$\begin{cases} \mu_{i4,\min} H_{TSi-} = 0 \\ \mu_{i4,\max} (H_{TSi-} - \overline{H_{TSi-}}) = 0 \end{cases} \tag{25}$$

$$\begin{cases} \mu_{i5,\min} (-E_{TS} + 20) = 0 \\ \mu_{i5,\min} (E_{TS} - \overline{C_{TS}}) = 0 \end{cases} \tag{26}$$

$$\begin{cases} \mu_{i6,\min} (-\rho_{0i} + \alpha_i P_{wi}) = 0 \\ \mu_{i6,\max} (-\alpha_i P_{wi}) = 0 \end{cases} \tag{27}$$

$$\begin{cases} \mu_{ij,\min} \geq 0 (j = 1, 2, ..., 6) \\ \mu_{ik,\max} \geq 0 (\mathrm{k} = 1, 2..., 6) \\ \lambda_{ir} \neq 0 (r = 1, 2..., 6) \end{cases} \tag{28}$$

By combining the above formulas from 16 to 28, the equilibrium solution of the multi-party game problem can be obtained by using the optimization software CPLEX, and the optimal subscription demand function of the heat storage enterprise and the clearing result of the wind abandoning trading center can be obtained.

4. Intra-day settlement

There is an error between the wind farm's evaluation of wind abandoning day and the actual power of wind abandoning day. When the wind abandoning sequence within the day is less than the pre-evaluated wind abandoning sequence, the heat storage enterprise will raise the heating cost due to the shortage of wind abandoning resources. In this case, the wind farm should subsidize the insufficient wind abandoning. In the market, the unified clearing electricity price is p_w, the unit price of boiler heating used by the heat storage enterprise to supplement the heat source is ρ_{0i}, the penalty coefficient of negative deviation of the wind farm is ρ_{p-}, and the unfinished wind abandoning electricity is compensated to the heat storage enterprise by unit price $(p_w + \rho_{p-})$, so it should meet the following requirements:

$$p_w + \rho_{p-} \geq \rho_{0i} \tag{29}$$

In the formula: ρ_{p-} is negotiated between the wind farm and the heat storage enterprise.

When the wind curtailment sequence within the day is greater than the pre-evaluated wind curtailment sequence, the heat storage enterprise is still willing to absorb this part of electric quantity when there is still room to accept the abandoned wind power. Considering the time needed for actual scheduling and operation, real-time bidding is no longer carried out for this part of wind curtailment, and the price of wind curtailment is stipulated uniformly. Heat storage enterprises only need to report the maximum wind abandonment power subscription, and the dispatching center will allocate the power according to the maximum subscription power of each heat storage enterprise in the following way:

$$P_{drwi} = \varpi_i (P_{rw,av} - P_{w,av}) \tag{30}$$

In the formula: P_{drwi} and ϖ_i are the distributed power and distribution coefficient of the heat storage enterprise, $\varpi_i = \overline{P_{rwi}} / \sum_{i=1}^{N} \overline{P_{rwi}}$; $\overline{P_{rwi}}$ is the maximum power that heat storage enterprise i continues to subscribe when the intra-day wind curtailment sequence is greater than the pre-evaluated wind curtailment sequence.

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5. The example analysis

1) Basic data

The grid structure of the test example in this paper is shown in Fig. 4. There are eleven nodes, each of which is loaded, including three cogeneration units, three conventional units, one wind farm and three electric heat storage enterprises.

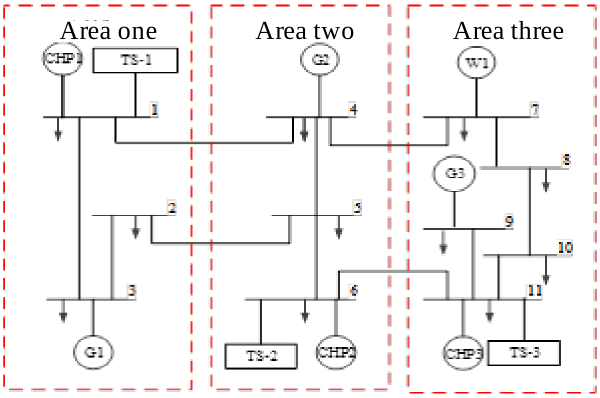

Fig.4 7 machine 11 node example

Specific parameters of the test system unit are shown in Table 1. Specific parameters of the heat storage unit are shown in Table 2. The heating price of auxiliary coal boiler is 220 RMB/MW. Thermoelectric conversion coefficient of heat storage device is 0.99.

Table 1 Basic parameters of test system units

Unit	Unit	Minimum power /MW	Maximun power /MW	Up and down climbing limits/MW
CHP1	1	40.3	131.2	45.0
CHP2	6	42.5	123.0	60.0
CHP3	11	62.1	155.8	60.0
G1	3	21.0	81.4	45.0
G2	4	28.3	102.5	50.0
G3	9	34.6	118.9	55.0
W1	7	0.0	300.0	100.0

Table 2 Basic parameters of test system thermal storage units

Heat stora-ge unit	Maximu-n power/MW	Maximum heat releas-e power/MW	Heat storage capacity/MWH	User's heat demand/MW	Average price of initial storage heat/(RMB/MW)
TS1	70	50	300	40	140
TS2	65	40	240	30	130
TS3	65	40	260	35	135

The heating areas of the three cogeneration units are independent of each other. 15-minute thermal load of each region is shown in Figure 5, and 15-minute electrical load and wind power are shown in Figure 6.

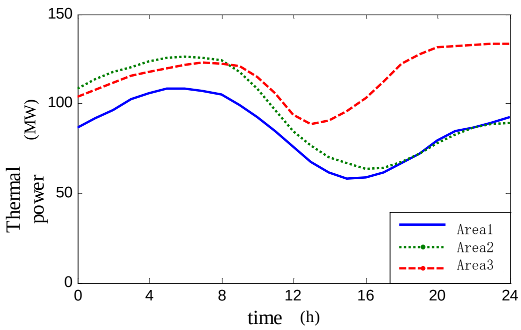

Fig.5 Heat load of different areas

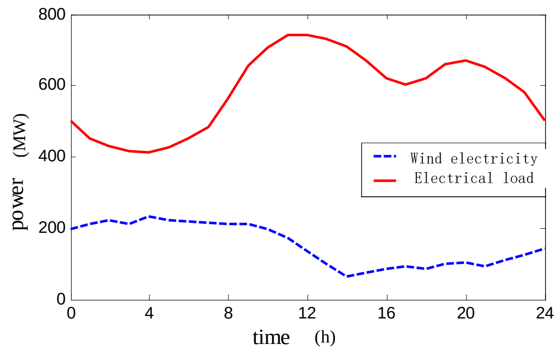

Fig.6 Wind power and electric load

2) The result of clearing

In order to illustrate the positive effect of heat storage on improving wind power consumption, two examples are designed as follows: Example 1: The heat storage system does not participate in wind abandoning consumption; Example 2: The heat storage system participates in wind abandoning.

The operation of each unit in example 1 is shown in Figure 7. During the period from 0:00 to 8:00 in the evening, the coGENERATION unit has forced force due to thermoelectric coupling constraints. Even though the conventional unit runs at the minimum technical output, the system still has a large amount of wind abandoning. The total wind abandoning power was 1288MWh, accounting for 33.91% of the total wind power on that day.

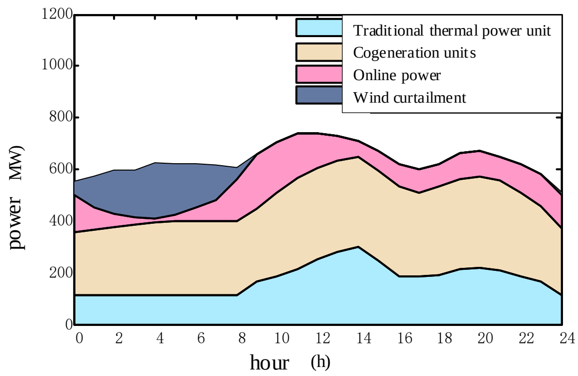

Fig.7 Electric power balance (without heat storage)

The heat storage system is used to absorb abandoned wind in example 2. The clearing price and the result of the clearing quantity in the wind abandon market are shown in Figure 8 and 9. The price range of wind curtailment is 103 yuan /MW~220 yuan /MW, and the amount of wind curtailment is 1270MWh. Due to the heat storage power constraint of the heat storage system, the wind abandoning power that has not been traded is only 18MWh, accounting for 1.39% of all the wind abandoning power, which is relatively small.

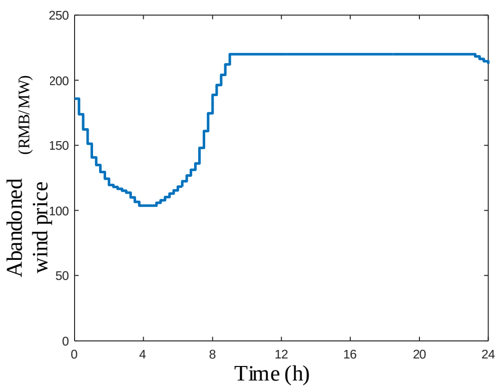

Fig.8 Abandoned wind transaction price

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At about 4:00 PM, the maximum wind abandoning power exceeds 200MW, which exceeds the maximum capacity of the heat storage system to absorb the wind abandoning power. At this time, the heat storage enterprise will naturally reduce the offer, so that the final transaction price is lower. When there is less wind curtailment or no wind curtailment in the system, the heat storage enterprise will raise the price to obtain more wind curtailment power. Therefore, the wind curtailment trading mechanism proposed in this paper can well show the impact of wind curtailment resources on the price, which is relatively consistent with the actual situation.

The average purchase price of heat storage system is shown in Figure 9. From 00:00 to 1:30 in the evening, there is less wind abandoning in the system, the transaction price of wind abandoning is higher, and the average purchase price of heat stored in the heat storage system is increased. From 1:30 to 6:00 in the evening, there are more wind curtailment in the system, the transaction price of wind curtailment is low, and the average purchase price of heat stored in the heat storage system decreases. From 6:00 to 8:00 in the morning, there is less wind abandoning in the system, the transaction price of wind abandoning is high, and the average purchase price of heat stored in the heat storage system rises again. From 8:00 to 24:00, there is basically no wind abandoning in the system, and the average purchase price of heat stored in the heat storage system remains unchanged.

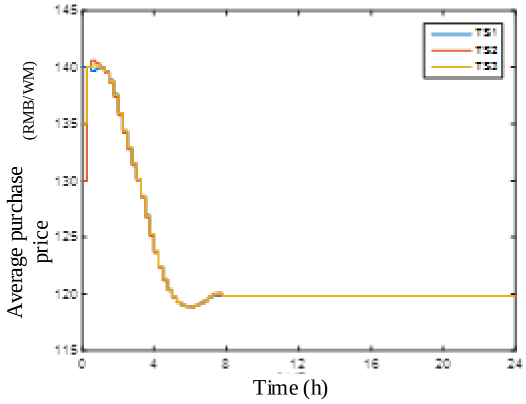

Fig.9 Average purchase price of heat stored in the heat storage system

6. Conclusion

This paper proposes a centralized transaction model for heat storage to participate in peak-shaving auxiliary services based on wind curtailment pre-evaluation, and mainly draws the following conclusions:

1) This paper proposes that wind farms report wind abandoning sequence based on day-ahead wind abandoning pre-evaluation, and heat storage enterprises report demand function based on optimized subscription model. In a typical day, the unabsorbed abandoned air volume accounts for 1.39% of all abandoned air volume, and the effect of absorbed abandoned air is good.

2) The profit of heat storage enterprises participating in the peak shaving auxiliary service market is related to the volume of air abandoning. When the wind abandoning is sufficient, the investment return years of heat storage enterprises are within 5 years.

3) There is a deviation between the actual wind abandoning in the trading day and the pre-estimation. This paper proposes the intra-day settlement method, in which the excess wind abandoning is distributed by the dispatching center and the insufficient wind abandoning is compensated by the wind farm to the heat storage enterprise.

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