Research on Interactive Trading Mode between Thermal Storage Electric Boiler and Wind Power Based on Dynamic Time Sharing

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Abstract. As a typical heating equipment with energy storage function, the regenerative electric boiler has great flexibility potential. How to guide it to participate in power trade by market-oriented means to absorb new energy efficiently, it is a challenging technical problem to realize the green and low-carbon transition of energy and electricity. In view of this, this paper analyzes the current situation of clean heating in our country, and explores the interactive characteristics between the load of regenerative electric boiler and wind power, a time-division transaction model based on wind power prediction is designed, and an example of a provincial source network charge-storage interaction demonstration project is analyzed, the results show that the proposed method can fully guide the thermal storage electric boiler to participate in the power market transactions, effectively mitigate the impact of wind power fluctuations on the grid, and further promote the wind power consumption.

Keywords: Clean heating; electric boiler; electricity market; trading mode

1 Introduction

In 2020, China made a solemn commitment to the world to "strive to peak carbon by 2030 and achieve carbon neutrality by 2060." In terms of the main areas of carbon emissions, carbon emissions are mainly concentrated in power, industry and transportation, and the carbon emissions of power and industry account for 41% and 29% of the total global emissions respectively[1-2]. Low-carbon transformation of the power industry is the key to achieve the dual-carbon goal, and accelerating the development and utilization of clean energy is an important means to promote the low-carbon transformation of the energy industry. By the end of 2022, China's renewable energy power generation capacity will become the third largest power supply after coal power and hydropower [3-4]. However, due to the randomness and volatility of clean energy power generation output, its large-scale grid connection has brought serious impact on the security and stability of power system. With the conventional power regulation capacity approaching exhaustion, it is difficult to meet the growing clean energy grid connection demand only by relying on the flexibility resources on the power generation

ICEMME 2023, November 17-19, Beijing, People's Republic of China

DOI 10.4108/eai.17-11-2023.2342711

side[5], so it is necessary to effectively mobilize the demand-side resources to participate in grid regulation.

At the same time, as a typical heating equipment with energy storage function, regenerative electric boiler has greater flexibility potential, and plays a great role in the construction of safe, economic and environmental protection intelligent power system. Scholars at home and abroad have conducted extensive and in-depth research on the participation of thermoelectric storage boilers in the power market. Literature [6] puts forward the concept of distributed electric boiler network, and the proposed optimization strategy can fully respond to the peak and valley electricity price, and can indirectly respond to the peak cutting and valley filling of the power grid while achieving economic operation. Literature [7] analyzed various characteristics of the operation of regenerative electric boiler system, and established a comprehensive energy system operation optimization scheduling model of implicit thermal electric boiler. Reference [8] evaluates the potential of electric heating load users to jointly participate in demand response using dynamic methods. Reference [9] proposes a demand side resource perception technique. Reference [10] proposes that the power grid side can quickly conduct transactions with the generation side or user side according to the distributed matching trading system process.

To sum up, the above work focuses on the study of the model and method of regenerative electric boilers participating in power trading and the strategy of participating in power grid interaction at the micro level, while it rarely involves the study of the mode of regenerative electric boilers participating in power market trading at the macro level. The resulting technical problem is: how to promote the regenerative electric boiler to participate in the electricity market trading, so as to promote the development of low-carbon green economy in the power system. Focusing on the above problems, this paper, starting from the complementary characteristics of regenerative electric boilers and wind power, analyzes the mechanism and shortcomings of traditional regenerative electric boilers' participation in power market trading, designs a time-sharing trading model based on the time-shifting characteristics of regenerative electric boilers to adapt to the volatility of wind power, and builds a benefit model of market entities under different modes. The validity and correctness of the proposed method are verified by an example analysis. It provides important theoretical support for the orderly and efficient participation of regenerative electric boilers in power market trading.

2 Characteristic analysis of electric boiler and wind power

In order to ensure the safe and economic operation of the power grid, the control center makes the power generation plan of each unit by predicting the user's load in advance. However, with the continuous increase of the installed proportion of renewable energy, due to the volatility and randomness of renewable power generation, it is difficult to meet the needs of safe and economic operation of the power grid through power generation planning and scheduling instructions, so the flexible adjustment ability of the power system is increasingly required. Figure 1 shows the typical daily wind power output curve of a city in China. It can be seen from the figure that the daily characteristics of wind power are large at night and small during the day. The annual characteristics are large in spring and winter and small in summer.

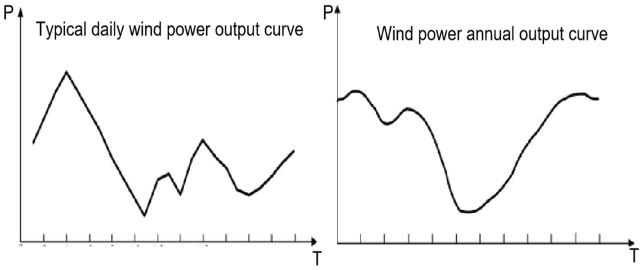

Figure 1. Daily and annual output characteristic curve of wind power

The regenerative electric boiler is put into the spring and winter festival, and runs in the form of night heat storage and all-day heating. The typical regenerative electric boiler can meet the needs of the whole day by storing heat for 4-6 hours at night. It has the characteristics of adjustable running time and running power, and has high flexibility value. At the same time, the characteristics of regenerative electric boilers and wind power are highly consistent with the actual power supply and demand, and have the complementarity in time and space. By using the load time-shift characteristic of regenerative electric boiler, three combination strategies of time splicing, power splicing and flexible splicing can be designed to adapt to the fluctuating output of wind power, so as to further absorb new energy.

3 Electric boilers participate in market trading mechanism

Based on the time-shifting characteristics of electric boilers, the time-segment trading mode adapted to the volatility of wind power is based on in-depth consideration of the characteristics of both supply and demand, with the goal of realizing the "load follows the source". By maximizing the market dividend space, the value creation and resource allocation of both supply and demand sides are realized, and the consumption of clean energy is further promoted and a win-win market environment is created. The mechanism is shown in Figure 2 below.

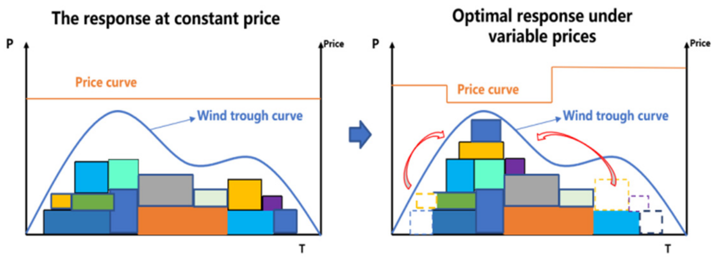

Figure 2. Mechanism of regenerative electric heating participating in market-oriented trade

Based on the time-shifting characteristics of electric boilers, the time-sharing trading process adapted to wind power volatility is as follows:

Transaction organization. The trading center organizes electric boiler users and wind power enterprises to carry out listing, bilateral and other medium and long-term transactions, one is to clarify the total electricity consumption in the heating season, and the second is to lock the price reduction space of wind power enterprises to ensure the overall interests.

Time division. On the basis of fully learning from the typical practices of other industries, on the basis of considering the market price elasticity, relying on the wind power curve to divide the time period and price, that is, appropriately reduce the price during the period of large wind power, and appropriately increase the price during the period of small wind power.

User response. After obtaining daily time-segment price information, electric boiler users take into account the economic operation of electric boiler load, and under meeting their own heating needs, take the initiative to change their power consumption habits, rationally arrange the load operation plan, and encourage users to adopt the operation mode that ADAPTS to the wind power output, so as to obtain maximum benefits.

Transaction settlement. The decoupling settlement on both sides of the power generation is adopted, that is, the settlement on the power generation side is settled according to the medium and long term trading price of power, and the electric boiler user is settled according to the segmented price.

4 Electric Boiler and Wind Power Trading Model

4.1 Dynamic period division and price formation model

In view of the prediction accuracy of D-1 daily wind power prediction as high as 95%, a four-stage quotation algorithm model based on the wind power prediction curve was constructed to divide the low period (21:00- 7:00 the next day) into periods, and different periods correspond to different prices.

Benchmark price. Calculate the average delisting price of all wind power plants participating in the medium and long term transaction of electricity.

$$\overline{p_f} = \frac{\sum_{i=1}^{n} p_{fi}}{n} \tag{1}$$

In formula (1), n indicates the number of wind power plants participating in the interactive transaction of source load, p_{fi} indicates the price at which the i wind power plant participates in the medium - to long-term transaction, $\bar{p}$ represents the average price of all wind farms participating in medium - to long-term transactions

Sectional model of wind power plant. Total wind power forecast output curve.

$$P_k^z = \sum_{i=1}^{n} P_k^i \tag{2}$$

In formula (2), P_k^z represents the total predicted output value of wind power during period k, P_k^i represents the predicted output value of wind power during period k of wind power plant i. Time slot from 21:00 PM to 7:00 AM, a total of 40, K=1,2,⋯,40.

Forecast reference value of total wind power output.

$$\bar{P} = \frac{\sum_{k=1}^{40} P_k^z}{40} \tag{3}$$

In formula (3), $\overline{P}$indicates the forecast reference value of total wind power output.

$$\Delta P = \max\{P_k^z\} - \min\{P_k^z\} \tag{4}$$

In formula (4), ΔP indicates the maximum change in wind power output.

Period division. According to the total power "peak and valley level", ABC is divided into three periods, A is the peak segment, B is the flat segment, and C is the valley segment.

The value range of segment A is shown in formula (5).

$$P_k^z > \bar{P} + 20\%\Delta P \tag{5}$$

The value range of segment B is shown in formula (6).

$$\bar{P} - 20\%\Delta P \leq P_k^z \leq \bar{P} + 20\%\Delta P \tag{6}$$

The value range of segment C is shown in formula (7).

$$P_k^z < \bar{P} - 20\%\Delta P \tag{7}$$

Time segment price.

$$p_f(t) = \overline{p_f} + \Delta p_f(t) \tag{8}$$

In formula (8), $p_f(t)$ is the time segment spread, $\Delta p_f(t)$ is the price change during t.

$$\Delta p_f(t) = -\overline{p_f} \times \frac{1}{\mathrm{Ed}} \times \frac{\Delta P_k(t)}{\bar{P}} \tag{9}$$

$$\Delta P_k(t) = \begin{cases} 0 & t = A \\ \max\{P_k^z\} - \bar{P} & t = B \\ \max\{P_k^z\} - \min\{P_k^z\} & t = C \end{cases} \tag{10}$$

In formula (9) and (10), Ed represents the price elasticity coefficient, which is temporarily set as 1 at the initial stage of the market; Δp_{uk} represents the price change in period k; p_c indicates the directory price, p_{uk} indicates the price for period k.

4.2 Market subject benefit model

In order to effectively analyze the economy of the traditional trading mode and the time-sharing trading mode, this paper compares and analyzes the benefits of the two different trading modes from four dimensions: user side, power generation side, power grid side and environment side.

User-side benefit. User-side benefits are mainly expressed in terms of reduced electricity costs. It specifically refers to the electricity cost saved after the load of regenerative electric boiler participates in the power grid regulation. Can be expressed by formula (11) .

$$W_s = (Q_1 - Q_2) \times p \tag{11}$$

Where, W_S represents the reduced electricity cost, Q_1 represents the actual daily electricity consumption before demand-side resources are not involved in power grid regulation. Q_2 indicates the actual daily electricity consumption after demand-side resources participate in power grid regulation; p indicates the power purchase price.

Generation side benefit. The benefit of power generation side is mainly expressed by the increased consumption of clean energy, which specifically refers to the renewable energy consumption that may be abandoned after the load of the regenerative electric boiler is involved in the grid regulation.

Grid side benefits. After the heat storage electric boiler load participates in the power grid regulation, the users are encouraged to use off-peak power during the peak period, thus reducing the load peak-valley difference, and the reduction of load peak-valley difference is conducive to the more economical and safe operation of the power grid.

Environmental Benefits. Environmental benefits are mainly expressed by the reduction of carbon dioxide emissions, specifically refers to the thermal storage electric boiler load participation in the power grid regulation, can reduce the power generation of coal-fired units of power generation enterprises, thereby reducing CO_2 emissions.

5 Example analysis

In order to effectively verify the feasibility of the interactive market-based trading mechanism proposed in this paper to promote the consumption of clean energy, a demonstration project of interactive market-based clean energy consumption of a provincial source-net and charge-storage was taken as an example. Among them, the total transaction scale of regenerative electric boilers is 380 million KWH, a total of 40 wind power plants and 70 users participate, and the load side capacity is about 480,000 kW. As shown in Table 1 below.

Table 1. main economic parameters

Type	Price	Type	Price
Wind power feed-in tariff	0.3731CNY /KWh	Wind power yields average profits	0.063CNY /KWh
Valley list price	0.28CNY /KWh	Market elasticity coefficient	1

5.1 Period division under fixed market price elasticity

The wind power curve of two typical days in 2019 was selected for example analysis, and it was divided into three periods according to the trough wind power prediction curve, and the corresponding prices of the three periods were calculated by the over-model algorithm.

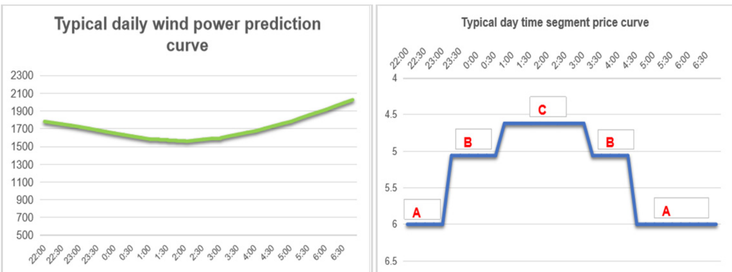

Figure 3. Typical day time segment price curve

As shown in Figure 3. Due to the different daily wind conditions, the daily division of time and price are different. If electric boiler users want to obtain the maximum dividend, they need to actively adjust their own electricity consumption habits according to the time-segment price curve to achieve accurate energy use, that is, as much electricity as possible in the A period.

5.2 Time division under different market price elasticity

Taking typical day 2 as an example for analysis, the results are shown in the figure below. Under different market price elasticity coefficients, the price fluctuation amplitude of different periods is different. According to the forecast situation of wind power, the price adjustment can be made by appropriately adjusting the market price elasticity coefficient, so as to effectively mobilize the enthusiasm of electric boiler users. As shown in Figure 4.

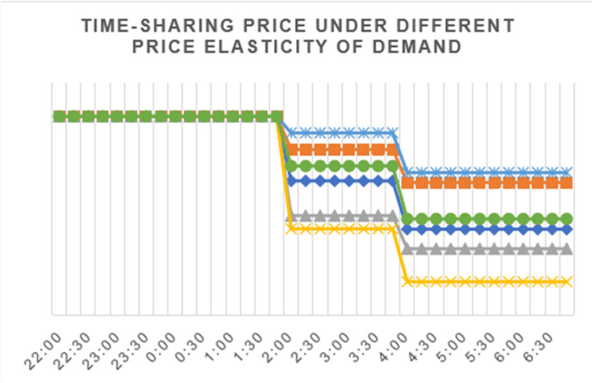

Figure 4. Time-sharing price under different price elasticity of demand

5.3 Benefit analysis of time-sharing interaction between regenerative electric boiler and wind power

Under the guidance of the time-segment price, the electric boiler user increased the electricity consumption during the high generation of new energy from 21:00 to 7:00 the next day, compared with the time segment trading before, the maximum load of the valley segment increased from 120,000 kilowatts to 180,000 kilowatts, an increase of about 50%, the polymerization effect was obvious, and the goal of "load with the source" was achieved.

Through the market mechanism, the price signal is released, and the electric boiler users are promoted to participate in the interaction of the source and network load and storage, and the flexible adjustment is given full play. To achieve new energy enterprises increased revenue of 93.03 million yuan, the average price reduction of users 0.063 yuan/KWH, saving electricity cost 13.86 million yuan, creating a win-win market environment. At the same time, the practice of green and low-carbon development, to achieve a saving of 11,700 tons of standard coal, sulfur dioxide emission reduction of 2,233.81 tons, carbon dioxide emission reduction of 29.04 tons, effectively contributing to the carbon neutral development goal.

6 Conclusions

On the basis of in-depth analysis of the mechanism of load-storage synergy-interaction in the source and network, and relying on the medium and long-term market system of electric power, this paper proposes an interactive trading mechanism for the source and network load-storage to promote the consumption of clean energy based on the load characteristics of electric boilers. It fulfills the work requirements of "six contracts" in the medium and long term, embodies the time value of electricity, and fully taps the flexibility potential of flexible load. Further promote the large-scale consumption of clean electricity. The practice shows that the market mechanism proposed in this paper can lay a foundation for companies to build the power market system under the energy Internet.

In terms of market players, with the continuous deepening of the development of energy Internet, the demand side will show diversified development, emerging market players continue to enter the market, on the one hand, it is necessary to continuously optimize the user response effect, further promote the consumption of new energy, improve the income of wind power enterprises, promote wind power enterprises to expand the price reduction space, and encourage high-quality users. On the other hand, continuously expand the market scale; Guide market players to diversify their development, and bring interactive resources such as photovoltaic and electric vehicles into the market scope.

In terms of market mechanism, gradually build a "who benefits who bears" rights and responsibilities mechanism, combined with the current market practice of power demand response, actively explore demand response and renewable energy power direct trading scheme, form a dynamic balance with renewable energy response mechanism, form a market-led price incentive mechanism, and effectively mobilize the willingness of market players to participate.

Acknowledgments. This work was financially supported by the Science and Technology Project of State Grid Corporation of China (Research on Trading Mechanism and Key Technology of Energy Block with Time Scale for Diversified Trading Demand, 5108-202225032A-1-1-ZN).

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