Operation control strategy of load aggregator based on new energy consumption in power grid

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Abstract—Managing the scattered small and medium-sized load by the existing ternary market model of regenerative electric heating is difficult. In this paper, the load aggregator is introduced on the basis of the traditional ternary market, transforming the existing ternary market model into the quaternary market transaction mode of new energy, power grid, load aggregator and regenerative electric heating users. The coupling relationship of four parties' interests is studied for the win-win solution limited by the goal of obtaining the maximum income and assuming the minimum risk. A case of Northeast China is carried out and the results show that the maximum profit point is 0.5 yuan/kWh, 0.3 yuan/kWh and 0.1 yuan/kWh respectively.

1. Introduction
Under the background of carbon peak in 2030 and carbon neutral in 2060, the renewable proportion of the energy consumption in China will continue to increase, making power grid face the impact of large-scale photovoltaic, wind power and other unstable renewable energy. Electric heating, as a safe, clean and comfortable heating method, can further enhance the interaction between the load side and the power grid, stabilize the peak valley impact of the power grid, and improve the environment, which has a significant effect on the control of urban air pollution and the improvement of residents' quality of life[1-3].
Electricity market mode, heating market mode and thermal storage market mode offer the possibility for the realization of regenerative electric heating load participating in market-oriented transaction. The current regenerative electric heating market is mainly composed of new energy, power grid, and users heated by electric boiler with thermal storage. Through the effective control of the load side, the renewable energy consumption can be realized, which has been carried out by lots of researchers.

As in [4], the economic analysis of a pilot project of heating using wind power was carried out. In order to save the operation cost, the pilot project was operated at full load at the time of low electricity price, which could not make the best of the ability of regenerative electric heating to absorb "abandoned wind power". With the opening of Chinese electricity sale market, DSM (demand side management) will change from the orderly power consumption mode dominated by administrative means to the mode dominated by economic means, and the demand response considering interruptible load will become the mainstream in the power auxiliary service market [5]; Reference [6] proposed that according to different types of contracts, including long-term contracts and medium-term contracts, users of interruptible load were compensated on the basis of a certain fixed unit price. As in [7], With the minimum daily electricity cost as the goal, taking temperature demand of users, outdoor temperature, time-of-use price and compensation price into account, the optimal control model for air source heat pump as the electric heating equipment widely used in rural areas was established. Also, optimal control strategies were proposed in this paper.

Guiding users to participate in electricity market transaction and regulation is difficult for the traditional ternary market model. In order to solve this problem, this paper studies the realization methods of market-oriented transaction about regenerative electric heating. On the basis of the traditional ternary market, the load aggregator is introduced to obtain the maximum profit point under the constraint of ensuring that all parties' interests are not reduced. The optimal pricing strategy is proposed to find the subsidy mode with the highest income for users.

2. System description
In this paper, the information interaction model of new energy, power grid, load aggregator and regenerative electric heating users is constructed. In the actual process of regenerative electric heating supply, the load aggregator is the core of the quaternary market, which relies on the information interaction with all parties to maximize the overall benefit. At time i, the information interaction structure among the four parties is shown in Fig 1.

Power grid usually uses peak-valley electricity price to encourage users to shave peak and fill valley independently. However, shaving peak and filling valley by electricity price is very random which will not completely reach the goal of power grid. While further reduction is needed, the existence of load aggregator becomes particularly important. According to the peak shaving subsidy price given from the power grid, the load aggregator encourages the users to participate in load response and controls heat release of heat storage of the regenerative electric heating boiler for auxiliary peak shaving. Wind power plants have the characteristics of reverse peak shaving, and its peak period of wind power usually coincides with the valley period of power grid. In order to promote the consumption of wind power, wind power plants can sign power sale contracts with load aggregator, and sell wind power to load aggregator with lower price in a specified period of time. In this period, load aggregator can use preferential electricity for heating supply and heat storage.
3. Model description
Regenerative electric heating can make all participants gain benefits. However, the income of four parties can be affected by the bundled electricity price of wind power $P_{W,i}$, the subsidy price of peak shaving $P_{R,i}$ and the price of user subsidy $P_{B,i}$. Therefore, determining the impact of various price factors on the benefits of all parties is the key to a multi-party win-win mechanism.

3.1. Profit model for all parties
The new revenue of wind power plants comes from the electricity consumed by the load aggregator during the contract period and from the heat storage of the regenerator. The wind power plant revenue at time $i$ is:

$$E_{W,i} = P_{W,i} \cdot L_{C,i}$$  \hspace{1cm} (1)

In the formula, $L_{C,i}$ is the aggregator’s heat storage at time $i$ (kWh). $P_{W,i}$ is the preferential wind power price (yuan/kWh).

The income of the aggregator comes from the subsidy rewards of the power grid and the heat storage income of the heat storage body. The expenditure part is the subsidy to the user and the heat storage cost of the regenerator. The income of the load aggregator at time $i$ is:

$$E_{LA,i} = P_{R,i} \cdot L_{A,i} + P_{i} \cdot L_{DC,i} - P_{B,i} \cdot L_{X,i} - P_{W,i} \cdot L_{C,i}$$  \hspace{1cm} (2)

In the formula, $L_{A,i}$ is the total load reduction in the area under the load aggregator (kWh). This part includes the total load $L_{X,i}$ (kWh) actively reduced by the user and the heat $L_{DC,i}$ (kWh) released by the thermal storage body of the thermal storage electric boiler. $P_{R,i}$ is the peak cut subsidy price (yuan/kWh). $P_{i}$ is the peak and valley electricity price (yuan/kWh). $P_{B,i}$ is the subsidy price given to users by the aggregator (yuan/kWh).

Part of the user’s revenue comes from the subsidies given by the aggregator, as well as the reduced load and heat savings. The income of the user at time $i$ is:

$$E_{U,i} = P_{B,i} \cdot L_{X,i} + P_{i} \cdot \sum_{m=1}^{M} L_{X,m,i}$$  \hspace{1cm} (3)

3.2. The impact of price parameters on multi-party revenue
According to the profit model of each party, a multi-party total profit calculation model can be obtained.

$$\begin{cases}
E_{all,i} = \alpha E_{W,i} + \beta E_{LA,i} + \gamma E_{U,i} \\
\alpha + \beta + \gamma = 1
\end{cases}$$  \hspace{1cm} (4)
In the formula, $E_{W,i}$ represents the income of the wind power plant, $E_{LA,i}$ represents the income of the load aggregator, $E_{U,i}$ represents the user income, and $E_{ail,i}$ represents the weighted total income of three parties.

The above formula does not include the peak shaving income of the power grid. The reason is that this income is not an economic parameter, so it will be analyzed separately. $\alpha$, $\beta$, $\gamma$ are weight coefficients, representing the importance of each party’s income.

Further analysis of the above formula, substituting various income models into (1) can obtain:

$$E_{ai,i} = \beta [P_{B,i} \cdot L_{X,i}(P_{B,i}) + (P_{B,i} + P_i) \cdot L_{C,j}] + (\alpha - \beta) P_{B,i} \cdot L_{C,j} + (\gamma - \beta) P_{B,i} \cdot L_{X,i}(P_{B,i}) - \gamma P_i \cdot \sum_{m=1}^{M} N_{m,i}(L_{m,i} - L_{m,i}(P_{B,i}))$$  \(\text{(5)}\)

In the formula, $L_{X,i}(P_{B,i})$ indicates that the amount of load reduction is a function of the user subsidy price $P_{B,i}$.

It can be found from the above formula that the price of municipal electric heating $P_i$ is regulated by the government and usually can’t be changed. But the changes in the peak shaving subsidy price $P_{R,i}$, user subsidy price $P_{B,i}$, and wind power bundled electricity price $P_{W,i}$ will affect the total income of multiple parties. Observing this formula further, it can be found that after determining the weight coefficients of all parties, the size of the wind power price $P_{W,i}$ will only affect the distribution of benefits between the aggregator and the wind power plant, and will not affect the interval where the maximum profit of the multiple parties exists.

Therefore, the follow-up will first focus on the impact of the peak-shaving subsidy price $P_{R,i}$ and the user subsidy price $P_{B,i}$ on the total income of multiple parties. Then, according to the changes of different bundled electricity price of wind power $P_{W,i}$, the impact of the distribution of benefits between aggregator and wind power plants on the total revenue is analyzed.

3.3. Multi-party income analysis under variable price parameters
In regenerative electric heating, the aggregator has the highest weight as the heat provider and coordination center, and the user as the main body of heat is the second most important. As a renewable energy generator, wind power plants rely on wind curtailment to obtain income, which has the least impact on operations and therefore has the least weight. In this study, the weighting coefficients of aggregator, users and wind power plants are taken as 0.5, 0.3 and 0.2 respectively.

4. Results and discussion
According to the survey, the paid demand response subsidy in the Northeast region ranges from 0-0.4 yuan/kWh. To obtain revenue, the subsidy given to users by aggregator should not be higher than this price. The pilot electricity price for wind curtailment is 0.07-0.328 yuan/kWh. In order to facilitate the analysis of the impact of the three on the total revenue, the study unified the change range of the three to 0.1-0.5 yuan/kWh. According to the win-win income model, the changes in the total income of the region can be calculated as follows:

As in Fig.2, with the price of wind power increasing, the total revenue of the region is on a downward trend. The reason is that the new revenue of wind power plants has a lower weight in the total revenue. Therefore, after the wind power plant obtains higher revenue, it will encroach on the revenue of the aggregator and cause the total revenue to decrease. With the increase in peak-shaving subsidies, the total revenue of the region is on the rise. The reason is that the peak-shaving subsidies come from outside the regenerative electric heating system, so the increase in this value is equivalent to injecting funds into the system. With the increase in user subsidies, the total revenue of the region has first increased and then decreased. The reason is that appropriate user subsidies can increase the enthusiasm of users to participate in demand response, but excessive subsidies will damage the income of aggregator with higher weights. As a result, the revenue of the entire region has fallen.
Figure 2 Changes in regional total income under multiple influencing factors

In order to make the probability of obtaining higher multi-party income greater, the optimal pricing interval is shown in table 1:

| Category                      | Revenue                           |
|-------------------------------|-----------------------------------|
| Load aggregator revenue       | 99.44 Ten thousand yuan            |
| Grid load reduction ratio     | 26.23 %                           |
| New revenue from wind power   | 36.04 Ten thousand yuan            |
| Total expenditure of user 1   | 6603.42 yuan                      |
| Total expenditure of user 2   | 6603.42 yuan                      |
| Total expenditure of not responding user | 7272.58 yuan      |

The load aggregator as the core of the quaternary market, gets the highest income of 99.44 ten thousand yuan and total expenditure of responding user is less than that of not responding user.

5. Conclusion
The promotion and market application of electric heating storage equipment involve power grid, new energy, load aggregator, electric heating users and other multiple parties. Considering that the individual
electric heating boiler cannot participate in the market transaction effectively due to the heat capacity limit, it is necessary to set up a reasonable market-oriented transaction path to realize the interaction with the power grid through the third-party load aggregator. Also, it can realize the optimal management of the affiliated regenerative electric heating storage equipment, so as to meet the multiple constraints of the upstream and downstream parties. In the final deep interaction and win-win situation among power grid, new energy, load aggregator, electric heating users will be reached.

According to the above example, the maximum profit point is the peak shaving subsidy price of 0.5 yuan/kWh, the user subsidy price of 0.3 yuan/kWh, and the wind power price of 0.1 yuan/kWh.

Also, the following strategy recommendations can be obtained: Wind power plants can dynamically adjust electricity prices based on fluctuations in wind power output, but excessively high prices will affect overall revenue. User subsidies are affected by the characteristics of user response. High subsidies can incentivize users to participate in the response, but excessive subsidies will affect overall revenue. The peak-cutting subsidy support provided by the finance is one of the keys to maintaining high profits for many parties. To increase enthusiasm, it should not be too low.

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