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Research on the Carbon Emission Reduction Effect and Trading Mechanism of Load Aggregator and Users Based on Stackelberg Game

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Abstract:

The integration of wind power into the power grid has important strategic significance to achieve carbon neutrality, but it affects the safe and stable operation of the power grid. This paper aims to establish a trading mechanism of load aggregator and users based on the Stackelberg game to achieve wind power accommodation, improve the effect of carbon emission reduction, and maintain the safe and stable operation of the power grid. Firstly, a trading mechanism of load aggregator and users is proposed. Secondly, the Stackelberg game model is established considering carbon emission limit and penalty coefficient. Finally, the particle swarm algorithm is introduced to solve the model. Results show that the load aggregator guides users to adjust power consumption through the trading mechanism, realizes wind power accommodation, improves carbon emission reduction effect, and maintains the safe and stable operation of the power grid.

Keywords: *Trading mechanism, Carbon emission reduction, Load aggregator, Stackelberg game, Particle swarm algorithm.*

I. INTRODUCTION

In recent years, many countries have put forward the strategic goal of carbon emission peak and carbon neutrality. As one of the main sources of carbon emission in China, the transformation of the power industry is crucial to achieving carbon emission peak and carbon neutrality goals. [1-3] A high proportion of wind power can contribute to carbon emission reduction goals in the energy transition. The uncertainty of wind power grid integration will seriously affect the security of power grid operation.[4] Demand-side management plays a vital role in maintaining the security and economy of power grid operation. [5-6] On the demand side, users have the following characteristics [7]: the small capacity of loads, the high degree of fragmentation, and the difficulty of control lead to obstacles in scheduling small-scale load resources in the power grid. To effectively utilize the scheduling potential of these dispersed load resources, the load aggregator has emerged in developed countries, which can explore load resources with response value through professional technical means. Load aggregator aggregates dispatchable users' power resources

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within a specific range and participates in grid dispatch as a whole, increasing the opportunity for users' participation in the market. Therefore, the load aggregator acts as a bridge between the power grid and users, effectively using idle and scattered load resources. [8] The load aggregator fully taps load resources by formulating an appropriate demand response strategy, positively impacting the power grid's peak shaving. [9-10]

Currently, scholars have conducted a lot of research on the participation of load aggregators in carbon emission reduction and the realization of wind power accommodation. Shi et al. [11] establish a low carbon economic dispatch model for multiple independent load aggregators. Mei et al. [12] establish a day-ahead scheduling model of the load aggregator with carbon emission limit. The above researches mainly consider the problem from the load aggregator without considering users. However, with the gradual development and improvement of the power market, users will become more interactive and proactive. Users can also become market players to optimize the power grid. [13] Wu et al. [14] establish an incentive price customization model for different comfort levels. He et al. [15] construct a satisfaction function of power consumption to reduce the uncertainty of demand response. Zhang et al. [16] formulate different price menus considering the users' needs and preferences. Cao et al. [17] classify users' load according to users' load sensitivity. Wind power accommodation is improved through the hierarchical scheduling method of microgrid, load aggregator, and residential users. The above researches consider the influence of users' satisfaction and preferences, which increases the initiative of users to participate in the response. However, the above researches lack the interaction between load aggregator and users.

Game theory can better describe the interaction between multiple players and has been applied to improve load aggregators' profit. Xiang et al. [18] establish a transaction decision-making model between supply and demand sides based on game theory. Chen et al. [19] prove through the Stackelberg game that load aggregator aggregates users to participate in auxiliary services, and both load aggregator and users could benefit economically. Among game theories, the Stackelberg game is a classic game that can solve the dynamic interaction problem of the master-slave structure. The load aggregator sets the price according to peak cutting and valley filling during the trading process, and the users adjust power consumption based on the price. The game process has a sequence, which is in line with the master-slave dynamic interaction situation, and the Stackelberg game model should be used.

The remainder of this paper is organized as follows. A trading mechanism of load aggregator and users is proposed in section I; A Stackelberg game model considering carbon emission limit and penalty coefficient is established in section II, and the existence and uniqueness of the game equilibrium solution are verified; A particle swarm algorithm is introduced to solve the Stackelberg game model in section III; An example analysis is carried out in section IV.

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II. TRADING MECHANISM OF LOAD AGGREGATOR AND USERS CONSIDERING CARBON EMISSION REDUCTION

This paper assumes that the microgrid system has wind power equipment and users. When the wind power cannot meet the users' power, the microgrid dispatch center can purchase power from the power grid to ensure the reliability of the users' power. The microgrid dispatch center forecasts the users' power and wind power, determines the power amount in each peak cutting and valley filling time, and informs the load aggregator of information such as power, price, and carbon emission reduction. As an intermediary between the microgrid dispatch center and users, the load aggregator guides users to participate in peak cutting and valley filling through economic incentives to achieve wind power accommodation and improve carbon reduction effect. Users adjust the power consumption by participating in demand response or executing an interruption contract to minimize the cost. The trading mechanism of the load aggregator and users is shown in Fig.1.

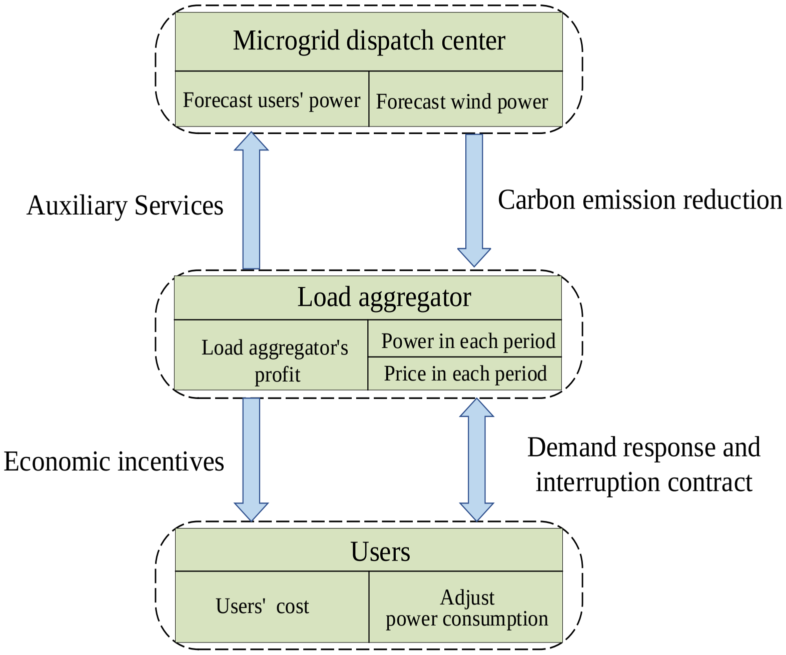

Fig.1: Trading mechanism of the load aggregator and users

2.1 Load Aggregator's Profit

Due to the randomness and volatility of wind power, wind power accommodation has become a difficult problem, which seriously threatens the safe and stable operation of the power grid. The microgrid dispatch center determines the peak period threshold, valley period threshold, and the load aggregator's total power to peak cutting and valley filling in each period according to forecast wind power and users' power. The microgrid dispatch center and the load aggregator sign a contract for peak shaving and valley filling to promote wind power accommodation and improve the carbon reduction effect. The load aggregator guides users to adjust power consumption through demand response and interruption contracts.

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The load aggregator signs an interruption contract with the users, including the interruption power and price. Meanwhile, the load aggregator publishes demand response prices to encourage users to participate in demand response. The revenue of the load aggregator consists of peak cutting and valley filling revenue; the cost includes interruption compensation fee, demand response fee, deviation penalty fee, and carbon emission penalty fee.

$$\max F_{LA} = \sum_{t=1}^{24} \sum_{i=1}^{I} \left(F_t^S - F_{i,t}^{IL} - F_{i,t}^{DR} - F_{i,t}^P - F_t^C \right) \tag{1}$$

Where: F_{LA} is the profit of the load aggregator; I is the total number of users; F_t^S is the peak cutting and valley filling revenue of the load aggregator at time t; $F_{i,t}^{IL}$ is the interruption compensation fee paid by the load aggregator to the user i at time t; $F_{i,t}^{DR}$ is the demand response fee paid by the load aggregator to the user i at time t; $F_{i,t}^P$ is the deviation penalty fee for the load aggregator at time t; F_t^C is the carbon emission penalty fee at time t.

2.1.1 Peak cutting and valley filling revenue

The microgrid dispatch center publishes peak shaving and valley filling to the load aggregator in a contract. The contract includes peak cutting and valley filling time, power, price, etc.

$$\begin{gathered} F_t^S = \lambda_t^S P_t^S = \lambda_t^S \left(P_t^w + P_t \right) \\ \begin{cases} P_{t,\min} \le P_t \le P_{t,\max} \\ P_{t,\min}^w \le P_t^w \le P_{t,\max}^w \end{cases} \end{gathered} \tag{2}$$

Where: λ_t^S is the peak cutting and valley filling price at time t; P_t^S is the peak cutting and valley filling power at time t; P_t^w is the wind power at time t; $P_{t,\min}^w$ and $P_{t,\max}^w$ are the minimum and maximum wind power at time t, respectively; P_t is the thermal power at time t; $P_{t,\min}$ and $P_{t,\max}$ are the minimum and maximum thermal power at time t, respectively.

2.1.2 Interruption compensation fee

The load aggregator signs interruption contracts with users, incentivizing users to interrupt power and giving users interruption compensation.

$$F_{i,t}^{IL} = \lambda_t^{IL} P_{i,t}^{IL} \tag{3}$$

Where: $P_{i,t}^{IL}$ is the interruption power provided by the user i at time t.

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2.1.3 Demand response fee

The demand response fee comprises the demand response price and the demand response power.

$$F_{i,t}^{DR} = \lambda_t^{DR} P_{i,t}^{DR} \tag{4}$$

Where: $P_{i,t}^{DR}$ is the demand response power by the user i at time t; λ_t^{DR} is the demand response price given by the load aggregator to users at time t.

2.1.4 Deviation penalty fee

The load aggregator guides the users to adjust the power consumption by interruption contract and demand response. If the adjusted power cannot complete the peak shaving and valley filling, the load aggregator will receive a deviation penalty fee.

$$F_{i,t}^{P} = \lambda_t^{P}\left(P_{i,t}^{S} - P_{i,t}^{AD}\right) = \lambda_t^{P}\left(P_{i,t}^{S} - P_{i,t}^{IL} - P_{i,t}^{DR}\right) \tag{5}$$

Where: $F_{i,t}^{P}$ is the deviation penalty fee at time t; λ_t^{P} is the deviation penalty price received by the load aggregator at time t; $P_{i,t}^{AD}$ is the adjusted power by the user i at time t.

2.1.5 Carbon emission penalty fee

Under the background of an in-depth reform of the power market, load aggregator is not only the main organization that directly provides power to users but also an important carrier of energy conservation and emission reduction. The carbon emission penalty fee of the load aggregator is:

$$F_t^{C} = \begin{cases} \eta\left[\sum_{i=1}^{I}\left(\theta P_{i,t} + P_{i,t}^{w}\right) - C_t^{L}\right], \sum_{i=1}^{I}\left(\theta P_{i,t} + P_{i,t}^{w}\right) > C_t^{L} \\ 0, \sum_{i=1}^{I}\left(\theta P_{i,t} + P_{i,t}^{w}\right) \le C_t^{L} \end{cases} \tag{6}$$

Where: η is the carbon emission penalty coefficient; C_t^{L} is the carbon emission limit of the load aggregator at time t; θ is the median carbon emission intensity of thermal power; $P_{i,t}^{w}$ is the wind power purchased by user i at time t; $P_{i,t}$ is the thermal power purchased by user i at time t.

2.2 Users' cost

The users' cost is the difference between the power purchase fee and users' revenue. The users' revenue

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consists of the interruption compensation revenue, the demand response revenue, and the users' utility.

$$\min F = \sum_{t=1}^{24}\sum_{i=1}^{I}\left(F_{i,t}^{B} - F_{i,t}^{IL} - F_{i,t}^{DR} - F_{i,t}^{U}\right) \tag{7}$$

Where: F is the users' cost; $F_{i,t}^{B}$ is the power purchase fee of the user i at time t; $F_{i,t}^{U}$ is the utility of the user i at time t.

2.2.1 Power purchase fee

As an essential measure of power demand-side management and a power price mechanism that effectively reflects the power supply cost in different periods of the power grid, time-of-use power price has been widely used in various countries. The user's power purchase fee consists of the time-of-use price and the purchased power.

$$\begin{gathered} F_{i,t}^{B} = \lambda_t P_{i,t}^{B} \\ P_{i,t}^{B} = P_{i,t}^{0} - P_{i,t}^{IL} - P_{i,t}^{DR} = P_{i,t} + P_{i,t}^{w} \end{gathered} \tag{8}$$

Where: λ_t is the time-of-use price at time t; $P_{i,t}^{B}$ is the power purchased by the user i at time t; $P_{i,t}^{0}$ is the initial power of the user i at time t.

2.2.2 Interruption compensation revenue

Users sign interruption contracts with the load aggregator and receive interruption compensation by providing interruption power. The user's interruption compensation revenue consists of interruption power and interruption price.

$$F_{i,t}^{IL} = \lambda_t^{IL} P_{i,t}^{IL} \tag{9}$$

Where: $F_{i,t}^{IL}$ is the interruption compensation revenue of the user i at time t.

2.2.3 Demand response revenue

The load aggregator publishes the demand response price to the users. The users adjust power consumption based on the demand response price to maximize their revenue. The demand response revenue comprises the demand response price and the demand response power.

$$F_{i,t}^{DR} = \lambda_t^{DR} P_{i,t}^{DR} \tag{10}$$

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Where: $F_{i,t}^{DR}$ is the demand response revenue obtained by the user i at time t.

2.2.4 Users' utility

In microeconomics, the utility function generally describes the degree of satisfaction from consuming a given combination of commodities. [20] With the continuous development of wind power and the improvement of users' awareness of environmental protection, users will pay more attention to the impact of carbon emissions on the environment. Since wind power does not produce carbon emissions, especially for users with stronger environmental awareness and social responsibility, users will be more and more inclined to purchase wind power. The lower the carbon emissions in power purchased by the user, the greater the utility the user obtains. The utility of user i at time t is expressed as follows:

$$F_{i,t}^{U} = \omega\left(P_{i,t}^{B} - \theta P_{i,t}\right)^{2} \tag{11}$$

Where: $F_{i,t}^{U}$ is the utility of the user i at time t; ω is utility coefficient; θ is the carbon emission coefficient of thermal power.

III. STACKELBERG GAME MODEL OF LOAD AGGREGATOR AND USERS

The load aggregator is the leader and sets price as strategies; users are followers and set the power consumption as strategies. To achieve wind power accommodation and improve carbon emission reduction, the load aggregator guides users to adjust power consumption through demand response price:

$$\max F_{LA} = \sum_{t=1}^{24}\sum_{i=1}^{I}\left(F_t^{S} - F_{i,t}^{IL} - F_{i,t}^{DR} - F_{i,t}^{P} - F_{i,t}^{C}\right)$$
$$s.t.\begin{cases} \lambda_{t,\min}^{S} \le \lambda_t^{S} \le \lambda_{t,\max}^{S} \\ \lambda_{t,\min}^{IL} \le \lambda_t^{IL} \le \lambda_{t,\max}^{IL} \\ \lambda_{t,\min}^{DR} \le \lambda_t^{DR} \le \lambda_{t,\max}^{DR} \\ Eq.(2)\text{-}(6) \end{cases} \tag{12}$$

Where: $\lambda_{t,\min}^{S}$ and $\lambda_{t,\max}^{S}$ are the minimum and the maximum peak cutting and valley filling price at time t, respectively; $\lambda_{t,\min}^{IL}$ and $\lambda_{t,\max}^{IL}$ are the minimum and the maximum interruption price at time t, respectively; $\lambda_{t,\min}^{DR}$ and $\lambda_{t,\max}^{DR}$ are the minimum and the maximum demand response price at time t, respectively.

Based on the demand response price of the load aggregator, users can minimize the cost by adjusting power consumption:

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$$\min F=\sum_{t=1}^{24}\sum_{i=1}^{I}\left(F_{i,t}^{buy}-F_{i,t}^{IL}-F_{i,t}^{DR}-F_{i,t}^{U}\right)$$
$$s.t.\begin{cases}P_{i,t,\min}^{IL}\le P_{i,t}^{IL}\le P_{i,t,\max}^{IL}\\P_{i,t,\min}^{DR}\le P_{i,t}^{DR}\le P_{i,t,\max}^{DR}\\Eq.(8)\text{-}(11)\end{cases}\tag{13}$$

Where: $P_{i,t,\min}^{IL}$ and $P_{i,t,\max}^{IL}$ are the minimum and the maximum interruption power of the user i at time t, respectively; $P_{i,t,\min}^{DR}$ and $P_{i,t,\max}^{DR}$ are the minimum and the maximum demand response power of the user i at time t, respectively.

3.1 Model Analysis

The Stackelberg game model starts from the cost minimization problem of followers and derives the response function of the demand response power to the demand response price through its first-order partial derivative. Then, the demand response price is solved by substituting the solution of the follower's response function into the first-order partial derivative of the leader's objective function.

The load aggregator is the leader and chooses a demand response price to publish to the users; users are followers and choose the optimal demand response power according to the demand response price. To minimize the users' cost, find the first-order partial derivative of Eq. (13):

$$\frac{\partial F}{\partial P_{i,t}^{DR}}=\lambda_t^{DR}+2\omega\left(P_{i,t}^{0}-P_{i,t}^{IL}-P_{i,t}^{DR}-\theta P_{i,t}\right)-\lambda_t\tag{14}$$

Let Eq. (14) equal zero. The load aggregator obtains the optimal demand response power of the users:

$$P_{i,t}^{DR,*}=\frac{\lambda_t-\lambda_t^{DR}}{2\omega}-P_{i,t}^{0}+P_{i,t}^{IL}+\theta P_{i,t}\tag{15}$$

Where: $P_{i,t}^{DR,*}$ is the optimal demand response power of the user i at time t.

The load aggregator receives the optimal demand response power from users:

$$P_{t}^{DR,*}=\frac{\lambda_t-\lambda_t^{DR}}{\omega}-P_{t}^{0}+P_{t}^{IL}+\theta P_{i,t}\tag{16}$$

To maximize the load aggregator's profit, find the first-order partial derivative of Eq. (12), and substitute Eq. (16) into the first-order partial derivative:

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$$\frac{\partial F_{LA}}{\partial \lambda_t^{DR}} = \frac{\lambda_t - \lambda_t^{DR}}{\omega} - P_t^0 + P_t^{IL} + \theta P_t \tag{17}$$

Let Eq. (17) equal zero. The users can get the optimal demand response price of the load aggregator:

$$\lambda_t^{DR,*} = \lambda_t + \omega\left(P_t^0 - P_t^{IL} - \theta P_t\right) \tag{18}$$

Repeat the above game process until the following conditions are met:

$$\begin{cases} F_{LA}\left(\lambda_t^{DR,*}, P_t^{DR,*}\right) \geq F_{LA}\left(\lambda_t^{DR}, P_t^{DR,*}\right) \\ F\left(\lambda_t^{DR,*}, P_{i,t}^{DR,*}\right) \leq F\left(\lambda_t^{DR,*}, P_{i,t}^{DR}\right) \end{cases} \tag{19}$$

Where: $\left(\lambda_t^{DR,*}, P_t^{DR,*}\right)$ is the game equilibrium solution.

When the Stackelberg game reaches equilibrium, the load aggregator can't increase the profit by adjusting the demand response price; users also can't reduce cost by adjusting power consumption.

3.2 Existence and Uniqueness of Game Equilibrium Solution

According to the Stackelberg game theory (Fabiana et al. 2022), verifying the existence and uniqueness of a game equilibrium solution requires the Stackelberg game model to satisfy three conditions simultaneously:

Condition 1: The strategy space of the load aggregator and the users are a nonempty compact convex set: Eq. (12) and (13) are both nonempty compact convex sets satisfying condition 1;

Condition 2: When the demand response price is fixed, the users have unique optimal demand response power: According to the users' cost, find the second-order partial derivative of Eq. (13);

$$\frac{\partial^2 F}{\partial\left(P_{i,t}^{DR}\right)^2} = -2\omega \tag{20}$$

Since $\omega > 0$, Eq. (20) is always negative, Eq. (13) is strongly concave. Therefore, the optimal demand response power is the only optimal solution that satisfies condition 2.

Condition 3: When demand response power is fixed, the optimal demand response price of the load aggregator is unique: Substituting Eq. (18) into Eq. (12) and obtaining the second-order partial derivative of the Eq. (12);

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$$\frac{\partial^2 F_{LA}}{\partial\left(\lambda_t^{DR}\right)^2} = -\frac{1}{\omega} \tag{21}$$

Since $\omega > 0$, Eq. (21) is always negative, Eq. (12) is strongly concave. Moreover, the load aggregator's strategy space Eq. (12) is a convex set, so the load aggregator has a unique optimal demand response price for the users' optimal demand response power.

To summarize, the Stackelberg game model satisfies the above three conditions simultaneously. Therefore, the game equilibrium solution exists and is unique.

IV. MODEL SOLUTION OF LOAD AGGREGATOR AND USERS UNDER CARBON EMISSION REDUCTION

In the Stackelberg game, the decision-making process of each market participant is an optimization process. A particle swarm algorithm is introduced to improve the efficiency and accuracy of optimization. Fig.2 shows the process of the particle swarm algorithm to solve the Stackelberg game model.

Firstly, the particle swarm parameters are initialized. Input primary data such as peak cutting and valley filling time, power, carbon emission limit, etc.

Secondly, solve the users' cost. Users' demand response power and cost are obtained according to the demand response price given by the load aggregator. If the users' cost is less than the previous cost, update the users' optimal demand response power and optimal global demand response power, simultaneously feedback on the optimal demand response power to the load aggregator; if the users' cost is not less than the previous cost, continue to iterate.

Then, solve the load aggregator's profit. The load aggregator's demand response price and profit are obtained according to the demand response power given by users. If the load aggregator's profit is more than the previous profit, update the load aggregator's optimal demand response price and optimal global demand response price simultaneously the optimal demand response price is fed to users; if the load aggregator's profit is not more than the previous profit, continue to iterate.

Finally, if peak cutting and valley filling are complete and carbon emission reductions are achieved, output game equilibrium solution; otherwise, the Stackelberg game is repeated.

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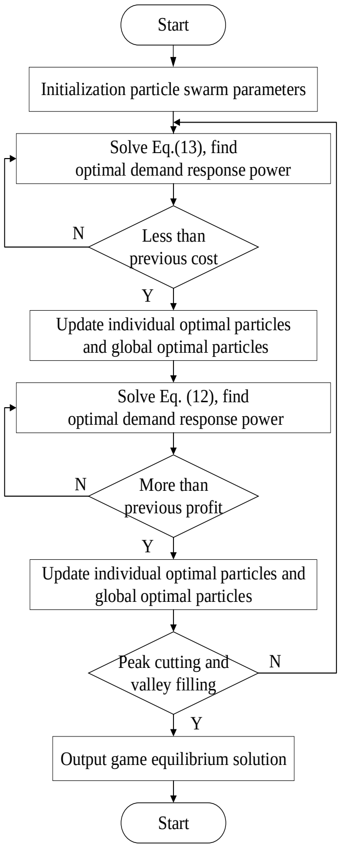

Fig 2: Flowchart of particle swarm optimization algorithm

V. EXAMPLE ANALYSIS

5.1 Basic Data

A region in China was selected as the research object, in which market participants include the microgrid dispatch center, the load aggregator, and users. The peak period threshold, valley period threshold, and the users' initial power are shown in Fig.3.

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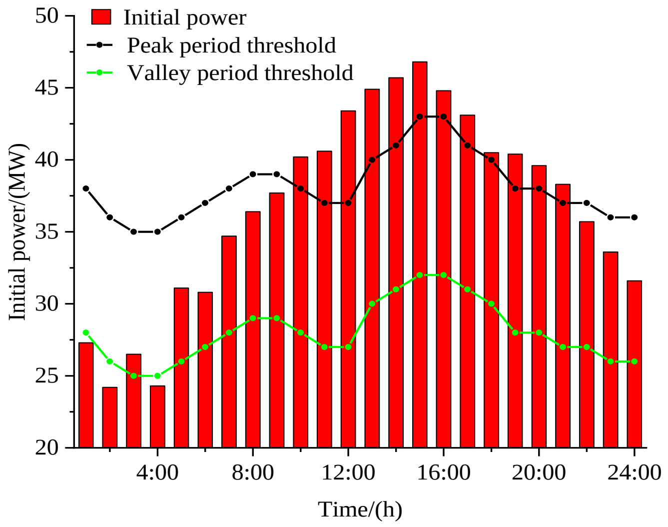

Fig 3: Users' initial power

The users' initial power is unevenly distributed, and the power is concentrated to form peak periods, affecting the power grid's safe and stable operation. The microgrid dispatch center publishes the power higher than the peak period threshold or lower than the valley period threshold to the load aggregator as the peak cutting and valley filling contract. TABLE I shows the minimum power to be adjusted at each period.

TABLE I. Minimum power to be adjusted at each period

Time quantum	Power /(MW)	Time quantum	Power /(MW)	Time quantum	Power /(MW)
1:00	0.7	2:00	1.8	4:00	0.7
10:00	-2.2	11:00	-3.6	12:00	-6.4
13:00	-4.9	14:00	-4.7	15:00	-3.8
16:00	-1.8	17:00	-2.1	18:00	-0.5
19:00	-2.4	20:00	-1.6	21:00	-1.3

The microgrid dispatch center sets the time-of-use price. TABLE II shows time division and time-of-use price. TABLE III shows the parameters for the users' interruption contract.

TABLE II. Time-of-use price

Time division	Time quantum	λt / (¥ /(kW·h))
Peak period	10:00-21:00	1.08

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Flat period	6:00-9:00; 22:00-23:00	0.72
Valley period	24:00-6:00	0.34

TABLE III. Users' interruption contract parameters

Time division	λtIL/ (¥ /(kW·h))	λtS/ (¥ /(kW·h))
Peak period	1.36	1.95
Flat period	0.92	1.32
Valley period	0.34	0.46

5.2 Analysis of Optimization Results

Suppose the number of users in the load aggregator's jurisdiction is 1,000. In this section, to compare the economy and effect of users' adjusted power, the users adjust power through three scenarios. Scenario one: the users only participate in the interruption contract; scenario two: the users only participate in the demand response; scenario three: the users both participate in the interruption contract and demand response.

The Stackelberg game model is solved, and the users' cost, the load aggregator's profit, etc., in three scenarios are calculated. TABLE IV shows the optimization results.

TABLE IV. Optimization results

	Scenario one	Scenario two	Scenario three
Adjusted power /(MW)	36.6	56	70.4
Interruption compensation / ¥	52056	0	47056
Demand response compensation / ¥	0	76345	36289
Deviation penalty / ¥	7595	3885	0
Users' cost / ¥	723504.8	673535.0	608469.8
Load aggregator's profit / ¥	19238.8	21059.0	41025.8

In scenario one, the load aggregator and users participate in the Stackelberg game by interruption contract. As a result, scenario one provides 36.6 MW of adjusted power, and some users tend to maintain power consumption without considering the cost. Although the interruption contract cannot complete the peak cutting and valley filling, as shown in Fig.4, the fluctuation of the overall power decreases in different degrees compared with the initial power. The users' cost is 723,504.8 ¥, and the load aggregator's profit is 19,238.8 ¥.

In scenario two, the load aggregator and users participate in the Stackelberg game by demand response. As shown in TABLE IV, the adjusted power increased from 36.6 MW to 56 MW. The adjusted power of scenario two is much higher than scenario one. As shown in Fig.4, the users' power is further optimized.

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The period exceeding the peak period threshold and below the valley period threshold is further reduced, which improves the safety of power grid operation. The users' cost is reduced from 723504.8 ¥ to 673535.0 ¥, and the load aggregator's profit is increased from 19238.8 ¥ to 21059.0 ¥. Compared with scenario one, scenario two can further adjust the users' power consumption and increase the load aggregator's profit while reducing users' costs.

In scenario three, the load aggregator and users participate in the Stackelberg game by interruption contract and demand response. As shown in TABLE IV, the adjusted power for users increased from 56 MW to 70.4 MW. The adjusted power of scenario three is much higher than scenario two. As shown in Fig.4, the users' power is further optimized to complete peak shaving and valley filling, ensuring the safety of power grid operation. Compared with scenario two, the users' costs are reduced from 673535.0 ¥ to 608469.8 ¥, and the load aggregator's profit is increased from 21059.0 ¥ to 41025.8 ¥. Scenario three can complete peak cutting and valley filling, maximize load aggregator's profit and minimize users' costs.

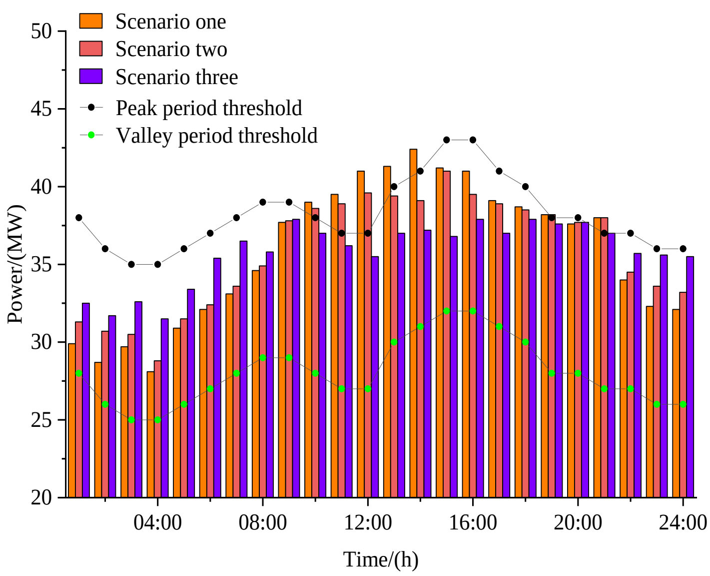

Fig 4: Users' power purchase under different scenarios

5.3 Sensitivity Analysis of Carbon Emission Limit and Penalty Coefficient

As shown in Fig.5, the carbon emission limits are 10t, 10.7t, and 11.0t. When the carbon emission limit is fixed, if the carbon emission exceeds the carbon emission limit, the load aggregator will reduce the carbon emission according to the incremental penalty coefficient until it reaches the standard. That is, the carbon emission is equal to the carbon emission limit. As shown in the curve with a carbon emission limit of 11.0t, when the penalty coefficient is more significant than 1500 ¥/t, the emission and the limit are equal to 11.0t. However, when the fee is too high, it is difficult to motivate the load aggregator to reduce carbon emission even if the penalty coefficient increases. The carbon emission is always more than the carbon emission limit, such as the carbon emission limit is 10t and 10.7t curves shown. It can be seen that when

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the profit of the load aggregator is large, a small penalty coefficient cannot achieve a good carbon emission reduction effect.

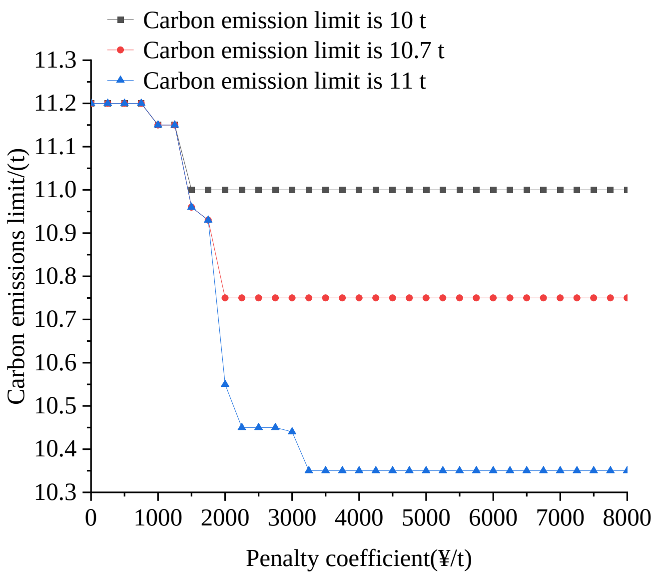

Fig 5: Sensitivity analysis of penalty coefficient

As shown in Fig.6, the carbon emission penalty coefficients are 1200¥/t, 1800 ¥/t, and 2100 ¥/t. When the penalty coefficient is fixed, the carbon emission "follows" the reduction of the carbon emission limit. Still, there is a limit value (the carbon emission equals the carbon emission limit). The larger the penalty coefficient, the smaller the theoretical minimum carbon emissions can reach within a reasonable range. However, once this minimum value is reached, it is difficult to reduce the carbon emissions even if a lower carbon emission limit is set. The theoretical minimum values of the carbon emissions corresponding to the above three penalty coefficient values are about 11.15t, 10.95t, and 10.54t, respectively.

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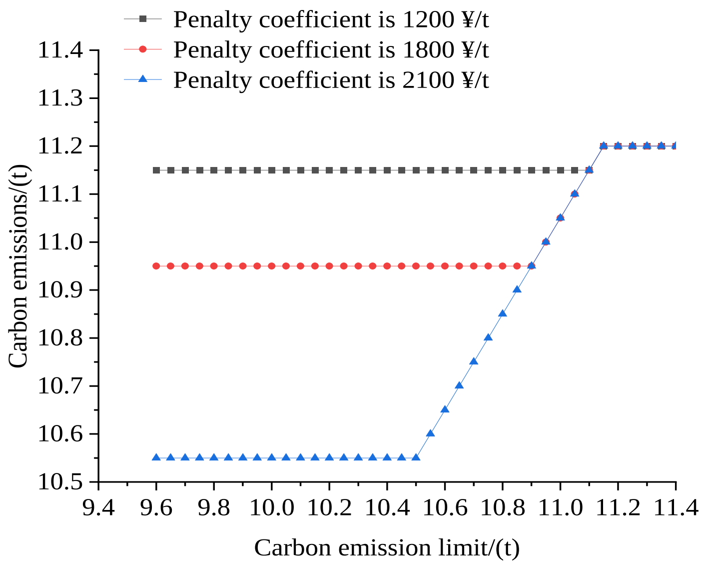

Fig 6: Sensitivity analysis of carbon emission limit

5.4 Carbon Emission Reduction Effect Analysis under Different Scenarios

Under three scenarios, the carbon emission reduction effect of the load aggregator is verified, and the operation results are shown in TABLE V. The carbon emission limit is 11t, and the penalty coefficient is 1800 ¥/t.

TABLE V. Carbon emission reduction effect analysis

	Carbon emission /t	**Carbon emission penalty fee/¥**	**Load aggregator's profit/¥**
Scenario one	15.95	8910	19238.8
Scenario two	13.3	4140	21059.0
Scenario three	10.95	0	41025.8

It can be seen from TABLE V that in scenario one, the carbon emission of the load aggregator is 15.95t. The load aggregator needs to pay a carbon emission penalty of 8910 ¥. Scenario one cannot fully guide users to adjust power consumption and participate in wind power accommodation, resulting in more carbon emissions and carbon emission fees, which compresses the profits of the load aggregator. In scenario two, the carbon emission of the load aggregator is 12.3t. The load aggregator needs to pay a carbon emission penalty of 4140 ¥. Compared with Scenario one, scenario two can reasonably guide users to adjust power consumption and participate in wind power accommodation. Scenario two improves the carbon reduction effect of the load aggregator. Substantially reduce carbon emission and carbon emission penalty fees while further increasing the load aggregator's profits. In scenario three, the carbon emission of the load aggregator is 11.08t. The carbon emission generated is below the carbon emission limit and has no

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carbon emission penalty fee. In contrast, scenario three can achieve a better carbon emission reduction effect, making the carbon emission close to the theoretical minimum carbon emission of 10.95t. Meanwhile, the load aggregator can maximize its profit.

5.5 Particle Swarm Iterative Analysis

The number of users who participated in the response is shown in Fig.7. During the first 12 iterations, all users participate in the iterations and are compensated by adjusting the power consumption. When the iteration reaches the 13th time, some users do not participate in the iterations, and users' power consumption cannot be adjusted. When the number of iterations continues to increase, at the 20th iteration, all users no longer participate in the iteration, indicating that all users' power consumption cannot be adjusted.

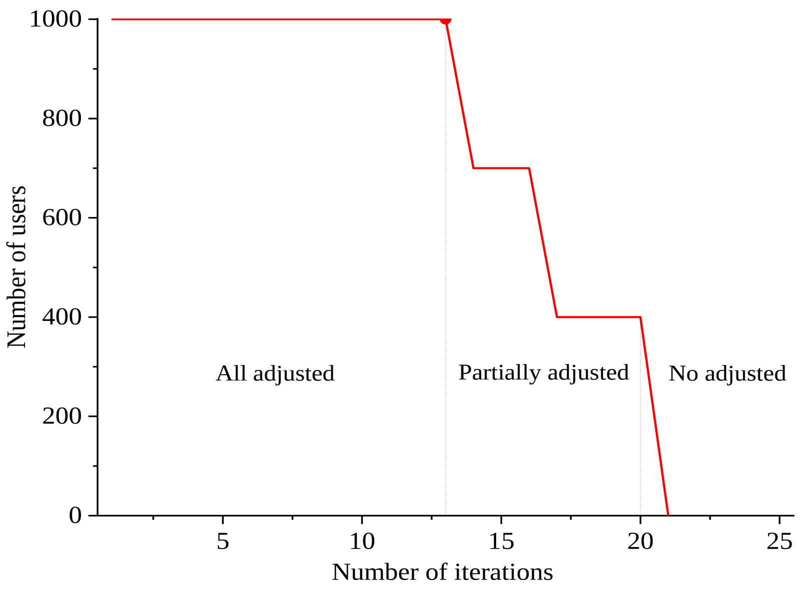

Fig 7: The number of users who participated in the response

Fig.8 shows the curve of the user's cost and the load aggregator's profit with the number of iterations. In the iteration, the increase in the number of iterations is the price adjustment of the load aggregator. At the beginning of the iteration, the users' cost is high, and the load aggregator's profit is low. As the iteration progresses, the load aggregator continuously adjusts the price, and the users adjust the power consumption according to the price. The load aggregator's profit increases while the users' cost decreases. When the iteration reaches the 13th time, the load aggregator's profit is maximized while the users' cost is minimized. When the iteration goes further, the users' cost is no longer reduced, and the load aggregator's profit no longer increases. It shows that in the 13th time, the game equilibrium solution is reached.

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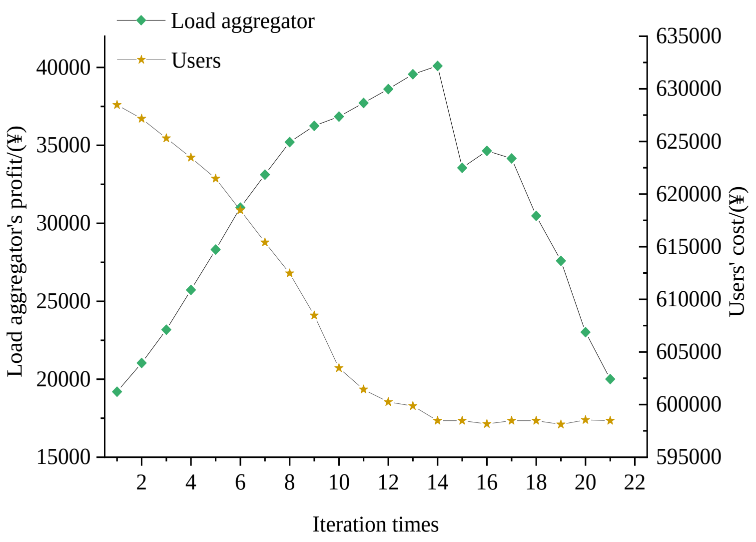

Fig 8: User's cost and load aggregator's profit

5.6 Users' Utility and Revenue

Users' utility and revenue under different scenarios are shown in Fig.9. When scenario one is only adjusted by interruption contract, the users get the least revenue, and the users' utility is the lowest. When scenario two is only adjusted by demand response, the revenue received by the users and users' utility is greatly improved. When scenario three is adjusted by combining interruption contract and demand response, the users get the most revenue, and the users' utility is the highest. Therefore, the users' revenue is inversely proportional to the utility.

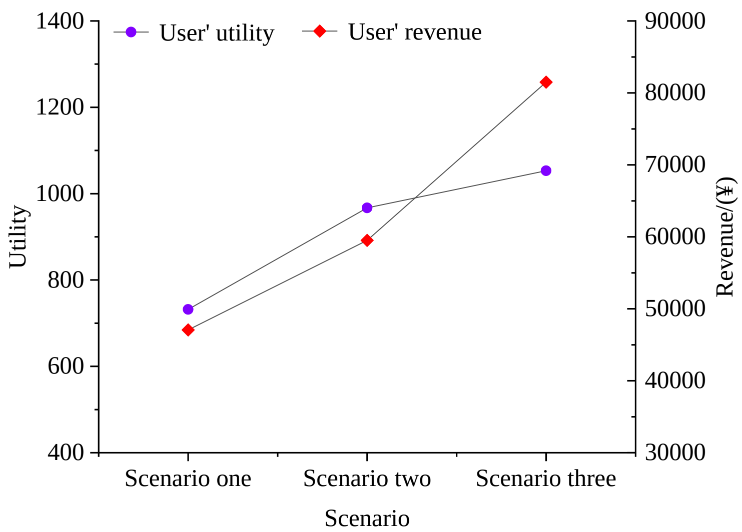

Fig 9: Users' utility and revenue

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5.7 Comparison of Different Algorithms

This paper also uses the genetic algorithm to solve the Stackelberg game model, and users adjust power consumption in scenario three. The comparison of the optimization results is shown in Fig.10. After optimizing the particle swarm algorithm, the users' power consumption is in the threshold range. After optimization using the genetic algorithm, the users' power consumption is higher than the valley period threshold during valley periods; the users' power consumption is higher than the peak period threshold during peak periods. Compared with the genetic algorithms, the particle swarm algorithm has a strong optimization ability. So that the users' power consumption is in the threshold range, completing peak cutting and valley filling, maintaining the safe and stable operation of the power grid.

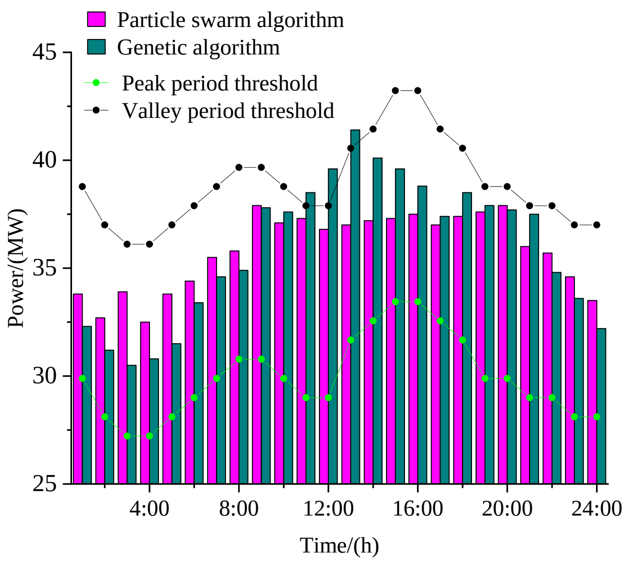

Fig 10: Optimization results of different algorithms

VI. CONCLUSION

This paper establishes the carbon emission reduction effect and trading mechanism between load aggregator and users based on Stackelberg game. The Stackelberg game model is solved by a particle swarm algorithm and draws the following conclusions:

1) The trading mechanism considering carbon emission limit can effectively mobilize load aggregator to participate in carbon emission reduction, which has the advantage of promoting wind power accommodation and improving carbon emission reduction effect.

2) The load aggregator guides users to adjust power consumption through a trading mechanism, participate in wind power accommodation, and maintain the stable operation of the power grid.

3) The Stackelberg game model is established to realize the dynamic game between the load aggregator and users, improve the initiative of users to adjust power consumption, maximize the load aggregator's profit and minimize users' cost.

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