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Original Article

A Study of Electricity Market Trading Mechanism Considering Demand Response Mechanism and Peak Regulation Mechanism

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Abstract:
In order to guide the sellers and users to make reasonable peak regulation and ensure the stable and orderly power supply, a peak regulation mechanism based on incentive demand response and considering user behavior factors was proposed. This mechanism also considers the peak and off-peak power load, encourages users to transfer part of the demand electricity during the peak by guiding the sellers to formulate compensation standards, and considers the impact of user behavior factors on their own utility, and finally establishes a double-layer programming model between the sellers and users for analysis. Among them, the upper sellers aim to maximize their own profits, and the lower users aim to maximize the total utility. Through solving, the optimal pricing strategy, compensation standard and the optimal power consumption of users are obtained when the sellers adopt the peak load mechanism. The numerical simulation results show that the peak balancing mechanism can improve the profit and the total utility of users, and the profit can be improved by appropriately increasing the base value and compensation rate. The optimal power consumption of the user is not related to the jealousy coefficient and guilt coefficient of the user, but is related to the product of the dissatisfaction coefficient. In addition, the proposed peaking mechanism can effectively reduce the load of the power system during the peak period, guide users to adjust their own consumption habits and off-peak consumption, so as to ensure the stability of the power system.
Key words: Incentive demand response ; Peak regulation mechanism ; User behavior ; Electricity market

1. Introduction

With the economic development and the improvement of living standards, the electricity load of industry and commerce and residents is increasing. According to the data released by the National Energy Administration, in July 2022, the highest power load in the country reached 1.26 billion kilowatts, and the daily power generation reached 28.5 billion KWH [1]. Especially in the daily power consumption process, in the case of high temperature, cold and other bad weather, it is more necessary to use a large number of refrigeration and heating appliances, which will produce a large amount of electricity demand in the short term, and it is easy to produce security risks for the power system. Therefore, how to meet the demand for electricity and alleviate the contradiction between supply and demand has become a major problem in the operation of the power system, so the demand response, which plays a role in coordinating the balance between supply and demand in the power market transaction, has become a major problem. The DR Mechanism came into being [2-4]. DR Is a power supply and power supply mode provided by e-commerce companies to guide power users to actively adjust power load with the power grid according to the power supply and demand situation and ensure the stable and reliable operation of power [5]. Domestic and foreign scholars have conducted a lot of research on demand response mechanism, which is generally divided into incentive based demand response (IBDR) and price based demand response (price based demand response). PBDR)[6]. Since excessively high electricity price will not only increase market costs, but also inhibit domestic consumption and reduce social welfare, while excessively low electricity price will also hinder the development of the electric power industry [7], PBDR has been widely concerned by scholars [8,9].

Although PBDR can flexibly adjust the user load, it is limited to the optimization of user load scheduling and lacks the improvement of the reliability and economy of power grid operation [10], while IBDR usually guides users to adjust and optimize their own power consumption behavior by means of subsidy incentives. It mainly includes direct load control, interruptible load, demand-side bidding, adjustment incentive mechanism and other response methods [11]. Compared with PBDR, IBDR has the advantages of higher implementation accuracy and stronger load regulation ability. In terms of direct load control, Ericson et al. [12] studied direct load control of residential water heaters to evaluate the potential of different demand-side measures that may help reduce peak load. Fattahi et al. [13] studied how public utility companies manage peak load energy through direct load control contracts, thereby reducing user electricity consumption to achieve peak regulation. In terms of interruptible load, Aalami et al. [14] built a demand response model of interruptible load based on demand price elasticity and user utility, and evaluated the model through numerical simulation. In order to guide users with interrupted load to participate in bilateral transactions, Chu Shuai et al. [15] proposed a dynamic settlement method of bilateral transactions based on "volume pricing", aiming at the problems of users blindly signing transaction prices and falsely high signing power, and compared the settlement results with traditional bilateral transactions, thus verifying the effectiveness of the dynamic settlement method of bilateral transactions. In terms of demand-side bidding, Yin Shangrui et al. [16] based on the improved rolling optimization mechanism, proposed a demand-side integrated energy station bidding strategy that conforms to the multi-time scale cooperative operation relationship and verified the economic benefits of the proposed strategy by combining the two-stage robust optimization algorithm. In terms of adjusting the incentive mechanism, Shahryari et al. [17] found when studying the IBDR model that the compensation to the user depends not only on the electricity price, but also on the duration of electricity consumption and the type of customers. The incentive value paid to the participating consumers is not a fixed value, but related to the peak intensity per hour. Liu et al. [18] proposed an incremental incentive mechanism based on incentive demand response, that is, consumers get different incentives according to the incremental response, so that incentives can change with the change of consumers' marginal cost. However, direct load control is a way to interrupt or cycle the user's power consumption through the remote control system during peak periods according to the contract between the supply and demand parties in the demand response plan [19], which usually causes a lot of inconvenience costs on the user side [20]. Interruptible load and demand-side bidding are both demand-side management methods for users to participate in the operation of the power market. Although they can reduce network losses and power supply costs, a large number of users' participation will lead to instability of the power market, reduced operating efficiency and uncertainty of power supply and demand [21]. Therefore, it is necessary to design a new load transfer control mechanism for peak demand adjustment to increase the profit of e-commerce sellers and the utility of users, so as to promote a more stable and orderly electricity market transaction.

Through the demand response of transfer load control, that is, the peak load balancing mechanism, its core idea is to transfer part of the electricity demand during the peak period to the off-peak period, and the inconvenience cost caused by the user's transfer of electricity demand is compensated by the e-commerce supplier. As a kind of IBDR, the peak load balancing mechanism is conducive to the stability of power market transactions, improve the reliability, stability and economy of the power system, and solve the problem of excessive peak load. At present, there are few researches on the mechanism of peak load regulation. Xu Bo et al. [22] constructed a hybrid demand response mechanism, dividing the power consumption period into peak hour and valley hour, and solving the problem of "peak-valley upside down" by analyzing the equilibrium solution. Agrawal and Yucel et al. [23]

designed a new demand response mechanism, taking the historical electricity demand of users as the baseline to measure the electricity consumption of users in a certain period, and adjusting the electricity consumption by transferring the electricity consumption in the peak period, and studied the impact of user compensation and baseline on the utility of users and the profits of power grid companies. However, the power cycle is not considered comprehensively.

The implementation of the above demand response mechanism is mainly reflected in the power sale side, but the user behavior will also affect the stability of the power market due to the impact of participation in peak regulation. In fact, in the process of electricity consumption, there is often a difference between the actual and expected electricity consumption of users, resulting in user satisfaction falling short of expectations, which has an impact on their own utility [24-26]. At the same time, users will also compare their electricity consumption by communicating with others, thus further influencing their own utility [27,28]. For example, Wang Yi et al. [29] put forward the concept of power user behavior model, analyzed it from five aspects, such as agent and environment, and then expounded the research significance of the user behavior model and analyzed the theoretical research framework of power user behavior modeling. Peng Dajian et al. [30] proposed a data-driven modeling method of user demand response behavior, which combined with deep short and long term memory network method to achieve effective characterization of complex response features of user aggregates. Kwag et al. [31] established a demand response reliability model considering user behavior factors to evaluate system and load reliability indicators. Therefore, the introduction of user behavior preference and other factors in the power market research can help improve the power market trading mechanism and improve the reliability, stability and economy of the power system.

To sum up, based on the literature [23], this paper designs a new peak-regulating mechanism, which considers the total utility of users and the profit of e-commerce sellers in the peak period and off-peak period respectively, instead of being limited to the peak period, and carries out peak regulating by transferring the power demand during the peak period to the off-peak period. At the same time, in order to further guide the user's demand response, this paper also considers the user's behavior preference factors, and describes the user's utility more accurately. Finally, the influence of the new peak regulation mechanism on the power market trading mechanism is studied.

2. Problem description

In this paper, the user's electricity consumption period is divided into peak and off-peak periods, and the two periods are carried out alternately. In case of severe weather such as high temperature and cold, a large amount of electricity demand is generated, that is, in the peak period, the e-commerce supplier can consider adopting the peak regulation mechanism, of course, it may not. Therefore, the daily electricity consumption period is t ($t \in \mathrm{H}$, H is an electricity consumption cycle, that is, 24 hours a day), and the electricity consumption cycle H includes the following four situations: 1) The peak period of the peak adjustment mechanism $\mathrm{H}_{offpeak}^{ado}$ adopted by the e-commerce supplier; 2) The peak period $\mathrm{H}_{offpeak}^{unado}$ when the e-commerce supplier does not adopt the peak adjustment mechanism; 3) Off-peak $\mathrm{H}_{offpeak}^{ado}$ containing power demand transfer during peak period; 4) Does not contain the off-peak $\mathrm{H}_{offpeak}^{unado}$ of power demand transfer during the peak period.

When the peak load mechanism is adopted, the e-commerce supplier needs to set the benchmark value of the user's electricity consumption as the compensation standard, that is, the fixed value of the average electricity consumption based on the historical electricity consumption data of the user is the benchmark value b [23]. If the actual electricity consumption q_i^t of the user $i(i=1,2,\ldots,n)$ after the transfer at the t time period is lower than the base value, the seller will give corresponding compensation to its difference $s_i^t = b - q_i^t$, that is, the part of compensated electricity, and set the fixed value of each unit of compensation as r. The inconvenience cost generated by the user is expressed as $c(s_i^t)^2/2$, where c is the transfer cost constant [23,32]. If the remaining actual electricity consumption q_i^t after the transfer is still higher than the benchmark value, it will not be compensated.

Therefore, when the peak load mechanism is adopted, the electricity consumption transferred from the peak period will be completely transferred to the off-peak period of the next stage, which does not consider the partial transfer of electricity from the peak period to the off-peak period after several cycles, nor does it consider the partial transfer of electricity from the peak period may be dispersed to the off-peak situation after two or more cycles.

3. Model preparation

Let the user i purchase electricity q_i^t from the seller at the t period, that is, the actual electricity consumption of the user i at the t period, and $q_i^t \in [q_i^{t,\min}, q_i^{t,\max}]$ $q_i^{t,\min}$, $q_i^{t,\max}$ are respectively the lower limit and upper limit of the power consumption of user i during the t period.

When $t \in H_{peak}^{ado}$, that is, when the e-commerce supplier adopts the peak load mechanism during the peak period and the actual electricity consumption q_i^t of user i after the transfer at the t period is lower than the reference value b, the e-commerce seller will compensate the difference $s_i^t = b - q_i^t$ per unit r. If the actual electricity consumption q_i^t after the transfer is still higher than the benchmark value, there will be no compensation. The utility obtained by user i after participating in the peaking mechanism is $[rs_i^t - c(s_i^t)^2/2]^+$, $t \in H_{peak}^{ado}$, $i \in N$ indicates a set of n users, $[x]^+$ indicates that $[x]^+ = x$ when $x \geq 0$, When $x \prec 0$, $[x]^+ = 0$ [23].

3.1. Total User Utility

3.1.1. Customer Purchase Cost

If the unit price of electricity purchased by user i from the e-commerce vendor is p^t, then the $C_i^t(q_i^t)$ of power purchased by user i in the t period is:

$$C_i^t(q_i^t) = p^t q_i^t, t \in H, i \in N \quad (1)$$

3.1.2 Users are Not Satisfied with the Cost

The dissatisfaction of user i is affected by the electricity consumption q_i^t, $\varphi_i(q_i^t)$ can be used to measure the dissatisfaction with electricity consumption, m_i^t is the dissatisfaction threshold of user i in the t period, that is, the electricity consumption expected by the user in the period. In actual use of electricity, users will compare their actual electricity consumption with the electricity dissatisfaction threshold during the period, resulting in psychological fluctuations affecting their own utility. Specifically expressed as: when $q_i^t \prec m_i^t$, the user is not satisfied with the power consumption process; When $q_i^t \succ m_i^t$, the user is satisfied with the power consumption process; When $q_i^t = m_i^t$, the cost of customer dissatisfaction is zero. Therefore, the unsatisfactory cost of electricity consumption of user i can be expressed as [26,33]:

$$\begin{aligned}\varphi_i(q_i^t) = \lambda_i(q_i^t - q_i^{t,\max})^2 - \\ \lambda_i(m_i^t - q_i^{t,\max})^2, \lambda_i \succ 0, t \in H, i \in N\end{aligned} \quad (2)$$

Where: λ_i is a positive parameter, $q_i^{t,\max}$ is the upper limit of power consumption of user i in the t period, then the cost function of user i including power dissatisfaction in the t period can be expressed as:

$$\vartheta_i(q_i^t) = C_i^t + \mu_i \varphi_i(q_i^t), t \in H, i \in N \quad (3)$$

Where: μ_i is the dissatisfaction parameter of user i, with $\mu_i \succ 0$. Based on references [26] and [33], equation (2) is used in this paper to measure the customer's dissatisfaction with electricity consumption, which is influenced by the customer's actual electricity consumption q_i^t and the threshold of dissatisfaction with electricity consumption m_i^t, and is positively correlated with the dissatisfaction parameter λ_i. The μ_i in equation (3) can be understood as a weight factor, which represents the importance of users' dissatisfaction with electricity consumption in the t period. Users can have different μ_i values in different periods according to their own power consumption preferences, that is, users with larger μ_i values are more interested in power consumption dissatisfaction (equivalent to increasing the cost of power dissatisfaction).

3.1.3 User envy and guilt cost

Since the user will compare the power consumption of other users in the process of electricity consumption, the actual utility generated by their own electricity consumption will be compared with the utility of other users, which will further affect their own utility. Therefore, for user i, if the utility of user $j(j \in N)$ is lower than that of user i by means of communication, he will feel guilty because of his high utility. On the other hand, if user j's utility is higher than his own, jealousy will occur. The essential difference between the cost function of envy and guilt and the cost function of user dissatisfaction in the previous section is that the former is the user's first comparison with his expected electricity consumption, and the latter is the comparison with other users after the former occurs. Therefore, the cost of jealousy and guilt caused by the effect of user i's utility on the utility of other users can be expressed as [24,25,27,34]:

$$u_i(q_i^t) = -\frac{\alpha_i}{n-1}\sum_{j\neq i}\max(\varphi_j - \varphi_i, 0) - \frac{\beta_i}{n-1}\sum_{j\neq i}\max(\varphi_j - \varphi_i, 0), t \in H; i, j \in N \tag{4}$$

Where: $u_i(q_i^t)$ is the jealousy and guilt cost of user i in the t period, φ_i, φ_j are the cost functions of the i and j users including electricity dissatisfaction, αi and βi are the jealousy and guilt coefficients of user i, $0 \le \alpha_i \le 1$, $0 \le \beta_i \le 1$, respectively. n indicates the total number of users.

3.1.4 Total user utility

To sum up, according to whether demand response is taken during peak period and whether there is electricity transfer during off-peak period, the total utility function of users is divided into the following three cases respectively.

Case 1: When $t \in H_{peak}^{ado}$ is in the peak period and adopts the peak-balancing mechanism, the actual electricity consumption of user i at the t period is q_i^t, and the compensation electricity of user i given by the e-commerce supplier is s_i^t, then the total utility function of user i at the t period is as follows:

$$U_i^t(q_i^t, s_i^t) = [rs_i^t - \frac{c}{2}(s_i^t)^2]^+ - \varphi_i(q_i^t) + u_i(q_i^t), t \in H_{peak}^{ado}, i \in N \tag{5}$$

Where: $U_i^t(q_i^t, s_i^t)$ is the total utility function of user i in the t-th period.

Case 2: When $t \in H_{offpeak}^{ado}$ is in the off-peak period and there is electricity transferred from the peak period, that is, the total electricity consumption at this time is the sum of electricity consumed in the off-peak period q_i^t and electricity transferred from the peak period s_i^t. If s_i^{t*} is the optimal compensation power of a given user i of the e-commerce vendor at the t period, then the total utility function of user i at the t period is:

$$U_i^t(q_i^t) = -C_i^t(q_i^t + s_i^{t*}) - \mu_i\varphi_i(q_i^t + s_i^{t*}) + u_i(q_i^t + s_i^{t*}), t \in H_{offpeak}^{ado}, i \in N \tag{6}$$

Case 3: When $t \in H_{peak}^{unado} \cup H_{offpeak}^{unado}$ is at the peak period without adopting the peak adjustment mechanism or is at the off-peak period and there is no transfer electricity at the peak period, the actual electricity consumption of user i is q_i^t, then the total utility function of user i at the t period is as follows:

$$U_i^t(q_i^t) = -C_i^t - \mu_i \varphi_i(q_i^t) + u_i(q_i^t),$$
$$t \in H_{peak}^{unado} \cup H_{offpeak}^{unado}, i \in N \quad (7)$$

3.2 Profit from Selling E-Commerce

In the t period, the e-commerce seller purchases the traditional thermal power D_{Tr}^t from the power plant, and all the power generation of the power plant is purchased by the e-commerce seller, that is, in the market clearing state, then $D_{Tr}^t(p_{Tr}^t) = a_{Tr}^t - b_{Tr}^t p_{Tr}^t, a_{Tr}^t, b_{Tr}^t \succ 0$ is a constant [23]. p_{Tr}^t is the unit cost of electricity purchased by an e-commerce vendor. The electricity supplier buys electricity and sells it to n users. The unit electricity price of the e-commerce seller is p^t, q_i^{t*} is the optimal electricity consumption of user i in the t period when the e-commerce seller does not adopt the peaking mechanism, and the probability of adopting the peaking mechanism in the peak period is $\rho(0 \le \rho \le 1)$, then the expected profit function of the e-commerce seller in the peak period is as follows:

$$U_R(p^t) = -C_i^t - \mu_i \varphi_i(q_i^t) + u_i(q_i^t),$$
$$t \in H_{peak}^{unado} \cup H_{offpeak}^{unado}, i \in N \quad (8)$$

Where: $\Delta c = c^{H_{peak}^{ado}} - c^{H_{offpeak}^{ado}}$ When implementing a peaking mechanism for an e-commerce vendor, the user's power demand changes from H_{peak}^{ado}'s unit power purchase cost ($c^{H_{peak}^{ado}}$) during peak to $H_{offpeak}^{ado}$'s unit power purchase cost ($c^{H_{offpeak}^{ado}}$) during off-peak periods The difference of $c^{H_{peak}^{ado}} = p_{T_r}^{H_{peak}^{ado}}, c^{H_{offpeak}^{ado}} = p_{T_r}^{H_{offpeak}^{ado}}$. $p_{T_r}^t D_{T_r}^t$ is the electricity purchase cost of the e-commerce supplier.

When the e-commerce supplier adopts the peak load mechanism, two situations will occur during the off-peak period: first, the period contains the optimal compensation electricity s_i^{t*} transferred from the peak period, then the total optimal electricity consumption is $q_i^{t*} + s_i^{t*}$; The second is that the peak period does not include the electricity consumption, that is, only the optimal electricity consumption q_i^{t*}. Therefore, the expected profit function of off-peak e-commerce is as follows:

$$U_R(p^t) = \sum_{i=1}^{n} \left\{ \rho[p^t(q_i^{t*} + s_i^{t*}] + (1-\rho)(p^t q_i^{t*}) \right\}$$
$$-p_{T_t}^t D_{T_t}^t, t \in H_{offpeak}^{ado} \cup H_{offpeak}^{unado} \quad (9)$$

Where: $\rho[p^t(q_i^{t*} + s_i^{t*}]$ represents the profit brought by the electricity consumption of user i in off-peak period (including the optimal transfer of electricity when the peak load mechanism is adopted) to the e-commerce seller; $(1-\rho)(p^t q_i^{t*})$ represents the profit brought by the electricity consumption of off-peak user i when the peak load mechanism is not adopted.

4. Model Building and Analysis

4.1 Model Building

From formula (5) to (7), we can see that the optimization problem of user i is $\max U_i^t(q_i^t, s_i^t)$ and from formula (8) and (9), we can see that the optimization problem of e-commerce is $\max U_R(p^t)$. Therefore, in the two-layer programming model, the upper-layer problem is:

$$\max U_R(p^t) \quad (10)$$

$$\text{s.t.} \sum_{i=1}^{n} q_i^t \le D_{Tr}^t \quad (11)$$

The lower level questions are:

$$\max\sum_{i=1}^{n}U_i^t(q_i^t,s_i^t) \quad (12)$$

Where: $U_R(p^t)$ represents the profit of the e-commerce seller in the t period, $\sum_{i=1}^{n}q_i^t \le D_{Tr}^t$ indicates that in the period of $\forall t\in H$, the traditional thermal power generation D_{Tr}^t purchased by the e-commerce seller from the power plant can completely supply the electricity demand of all users at this time $\sum_{i=1}^{n}q_i^t, U_i^t(q_i^t,s_i^t)$ represents the total utility of user i in the t period, $\sum_{i=1}^{n}U_i^t(q_i^t,s_i^t)$ is the total utility of n users in the t priod.

4.2 Model Solving and Analysis

4.2.1 Model Solving

To facilitate calculation and analysis of the optimization problem of user i, assume that among the other $n-1$ users other than user i, the number of users j conforming to $\varphi_j-\varphi_i\succ 0$ is n_1, and the number of users j conforming to $\varphi_j-\varphi_i\prec 0$ is n_2. The number of users conforming to $\varphi_j-\varphi_i=0$ is $n-1-n_1-n_2$, and the following statement is obtained:

Proposition 1: When $t\in H_{peak}^{ado}$ is in the peak period and the peak-balancing mechanism is adopted, the optimal compensation electricity $s_i^{t*}=r/c$ provided by the e-commerce supplier to the user i.

Proposition 2: When $t\in H_{peak}^{ado}$ is in the peak period and the peak balancing mechanism is adopted, the optimal power consumption of user i is $q_i^{t*}=q_i^{t,\max}-p^t/2\mu_i\lambda_i$; When $t\in H_{offpeak}^{ado}$ is in the off-peak period and there is transfer of electricity in the peak period, the optimal electricity consumption i of user $q_i^{t*}=q_i^{t,\max}-p^t/2\mu_i\lambda_i-r/c$; When $t\in H_{peak}^{unado}\cup H_{offpeak}^{unado}$ is at the peak period and the peak load mechanism is not adopted or the peak period is off and there is no electricity demand transferred from the peak period, the optimal electricity consumption of user i is $q_i^{t*}=q_i^{t,\max}-p^t/2\mu_i\lambda_i$.

Proposition 3: When $t\in H_{peak}^{ado}\cup H_{peak}^{unado}$ is in the peak period, the optimal electricity price $p^{t*}=\mu_i\lambda_i[q_i^{t,\max}+\rho(b-r/c)/(1-\rho)]$ of the e-commerce supplier; When $t\in H_{offpeak}^{ado}\cup H_{offpeak}^{unado}$ is in the off-peak period, the optimal electricity price p of e-commerce suppliers $p^{t*}=\mu_i\lambda_i q_i^{t,\max}$.

4.2.2 Optimal Solution Analysis

Based on the solution results of the above model, the following propositions can be obtained.

Proposition 4: When $t\in H_{peak}^{ado}$ peak period adopts the peak balancing mechanism, the optimal compensation electricity s_i^{t*} given to user i by e-commerce sellers is positively correlated with the subsidy rate r.

Proving proposition 4 is similar to proving proposition 1.

Proposition 4 gives the effect of subsidy rate on the optimal compensation electricity quantity. According to the expression $s_i^{t*}=r/c$, the optimal compensated electricity is determined by the unit subsidy rate given to users by e-commerce sellers and the transfer cost constant generated when users decide to transfer electricity consumption. It can be seen that the sales of electricity can increase the compensation electricity by increasing the subsidy rate for users, thereby saving procurement costs. The increase in the subsidy rate will make the user tend to transfer more electricity consumption and thus be compensated, that is, the actual electricity consumption is reduced. Overall, proposition 4 highlights the importance of subsidy rates on the impact of compensated power.

Proposition 5: $\forall t\in H$, the optimal electricity consumption q_i^{t*} of user i is independent of the jealousy coefficient α_i and guilt coefficient β_i of the user.

Proving proposition 5 is similar to proving proposition 2.

Proposition 5 shows that the optimal power consumption of a user is based on the maximization of total utility, so theoretically the optimal power consumption should be determined by each component of the utility function, but in fact it is only related to the maximum power consumption limit of the user, the power price determined by the electricity seller and the parameters in the dissatisfaction function. This is because the user's satisfaction increases with the increase of power consumption in the process of electricity consumption, but each user has its own maximum power consumption limit for constraint, so it is related to it; At the same time, from the relationship between price and quantity in microeconomics, it can be seen that the electricity purchased by users is inevitably related to the price of electricity, and the higher the price, the lower the electricity purchased, and vice versa. In particular, the optimal electricity consumption is affected by the dissatisfaction cost function, but is independent of the guilt and jealousy cost function in the behavioral factors. This is because when users purchase and use electricity, they will first compare the actual electricity consumption with their psychologically expected electricity consumption threshold, thus generating the dissatisfaction cost and affecting the total utility. At this time, the user has expressed satisfaction or dissatisfaction with his actual power consumption, that is, the psychological comparison of power consumption has been produced and obtained results, and then compared with the power consumption of other users, will only further affect the total utility, but will not change the value of the optimal power consumption in the period. In other words, the user first compares with himself and then compares with others, the former occurs first and preferentially affects the user's optimal power consumption, and the power consumption decision has been completed, and the latter occurs later and does not change the user's power consumption decision.

Proposition 6: $\forall t \in H$, the optimal electricity consumption q_i^{t*} of user i is positively correlated with the product of dissatisfaction coefficient $\mu_i \lambda_i$.

Proving proposition 6 is similar to proving proposition 2.

It can be seen from proposition 6 that the user's optimal electricity consumption increases with the increase of the product of the dissatisfaction coefficient, that is, when the price of electricity is given and the upper limit of electricity consumption, the optimal electricity consumption increases with the increase of the product of the dissatisfaction coefficient, which indicates that the comparison between the user and his expected electricity consumption threshold will greatly affect the user's electricity consumption experience. And it directly affects the optimal electricity consumption variable. Optimal electricity consumption by $t \in H_{peak}^{ado}$, $q_i^{t*} = q_i^{t,\max} - p^t / 2\mu_i \lambda_i, t \in H_{offpeak}^{ado}$. The optimal electricity consumption at $q_i^{t*} = q_i^{t,\max} - p^t / 2\mu_i \lambda_i - r / c$ and $q_i^{t*} = q_i^{t,\max} - p^t / 2\mu_i \lambda_i$ shows that the optimal electricity consumption of the user is related to the product of the coefficient of dissatisfaction, the price of electricity, and the upper limit of electricity consumption. Therefore, in order to study the influence of the above three factors on the optimal electricity consumption of users, the upper limit of electricity consumption and the electricity price were set as [15, 2], [20, 2] and [15, 3] respectively. Fig. 1 intuitively shows the variation of the optimal electricity consumption of users with the product of the dissatisfaction coefficient. As can be seen from Figure 1, when the dissatisfaction coefficient is unchanged, the given electricity price (p t = 2 for example), with the increase of the upper limit of the user's power consumption, the optimal power consumption also increases; Similarly, a given power consumption limit (When $q_i^{t,\max} = 15$), the higher the electricity price determined by the e-commerce seller, the lower the optimal electricity consumption of the user, which indicates that the user is very sensitive to the electricity price given by the e-commerce seller. If the e-commerce seller increases the electricity price, the electricity consumption of the user will decrease accordingly. That is, the optimal electricity consumption increases with the increase of the product of the upper limit of electricity consumption and the dissatisfaction coefficient, and decreases with the increase of the electricity price.

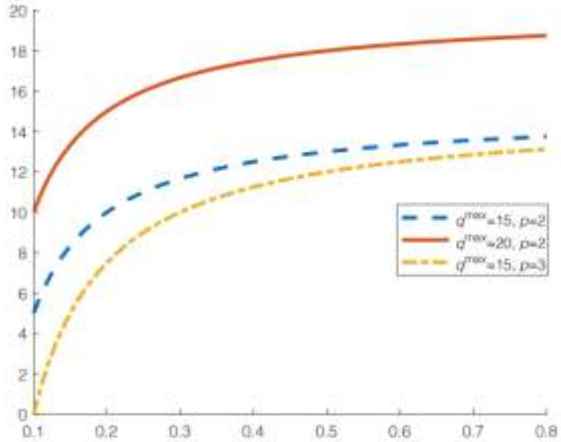

Fig. 1 Influence of product of dissatisfaction coefficients on optimal power consumption

Proposition 7: For $\forall t \in H$, the total utility U_i^t of user i is minimum if and only if the threshold of electricity dissatisfaction is $m_i^t = q_i^{t,\max}$.

Proposition 7 shows that the total utility of the user is minimum if and only if the dissatisfaction threshold m_i^t of the user i is equal to its maximum power consumption in the t period. Therefore, in order to prevent the total utility of users from being affected by the dissatisfaction threshold and the maximum power consumption in the process of electricity consumption, the upper limit of power consumption is set to 10, 15 and 30 respectively. The relationship between the electricity dissatisfaction threshold, the maximum electricity consumption and the total utility of the user is studied through Figure 2, which shows the changes of the total utility U_i^t of the user with the dissatisfaction threshold m_i^t under different power consumption ceilings. The intercept of Fig 2 shows that the total utility increases with the increase of the maximum power consumption of the user without considering the dissatisfaction function. The lowest point of the curve is the user's total utility corresponding to the optimal dissatisfaction threshold, which indicates that when the user sets his electricity consumption dissatisfaction threshold to the maximum of the current available electricity consumption, the user's total utility will become the minimum. If users want to improve their total utility, they can raise or lower their dissatisfaction threshold. When the maximum power consumption of the user in this period is too large, such as $q_i^{t,\max} = 30$ in Fig 2, considering the user's dissatisfaction may make the total utility zero or even lower, that is, for users with large power consumption, it is more important to select an appropriate dissatisfaction threshold.

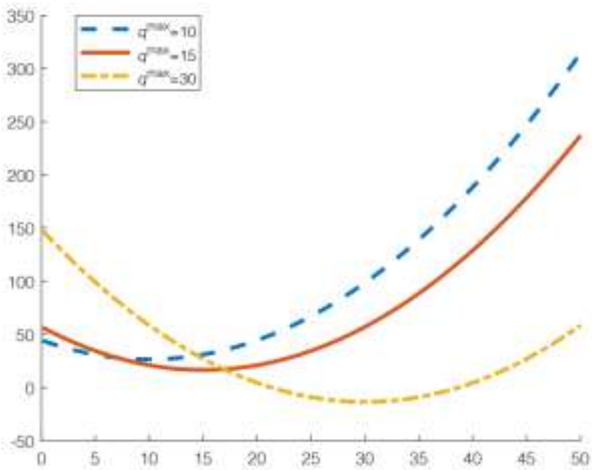

Fig. 2 Influence of electricity consumption dissatisfaction threshold on the total utility of users

If the e-commerce supplier adopts the peak regulation mechanism during peak hours, users will decide whether to accept the peak regulation mechanism according to whether the peak regulation mechanism can improve their total utility. Therefore, in order to study the changes brought by the peak regulating mechanism to the total utility of users, Fig 3 shows the changes of the total utility of users with the power consumption before and after the peak regulating mechanism is adopted.

Consider the daily electricity supply by an e-commerce supplier to 3 users in a region, and the value summary of each variable involved is shown in Table 1 [23]. As shown in Fig 3, when the e-commerce supplier adopts the peaking mechanism and user i accepts the scheme, the total utility of the user is significantly higher than that without the scheme. As can be seen from formula (5), when users accept the peaking mechanism, inconvenience costs will be incurred due to the transfer of part of electricity consumption, and at the same time, the e-commerce supplier will provide corresponding subsidies to users, thus bringing corresponding utility, that is, the total utility of the corresponding compensation obtained by users after accepting the peaking mechanism is higher than the total utility without adopting the scheme.

Table 1 Values of variables and parameters

Variables/parameters	Value	Variables/parameters	Value
n	3	ρ	0.1
b	11	r	1.25
c	1	m_i^t	2
λ_i	0.3	μ_i	0.6
$c^{H_{peak}^{ado}}$	30	$c^{H_{offpeak}^{ado}}$	10
α_i	1	β_i	1
n_1	1	n_2	1
p_{Tr}^t	0.5	D_{Tr}^t	40

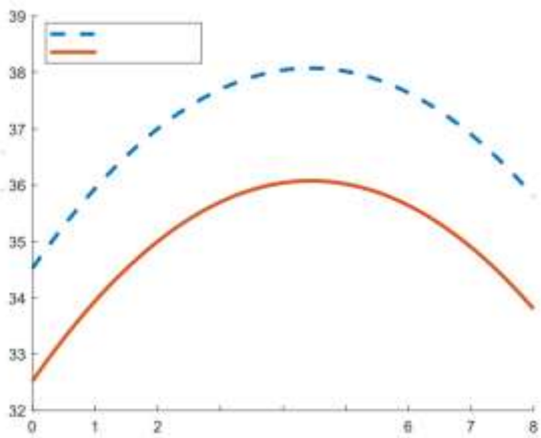

Fig 3 Comparison of users' total utility before and after adopting the peak balancing mechanism

Proposition 8: When $t \in H_{peak}^{ado} \cup H_{peak}^{unado}$, that is, during the peak period, the optimal electricity price p^{t*} of e-commerce sellers is positively correlated with the probability ρ of adopting the peak balancing mechanism during the peak period.

Proposition 8 indicates that although the peak-regulating mechanism can transfer part of the electricity consumption and relieve the pressure of electricity consumption at peak times, with the increase of the probability of adopting the peak-regulating mechanism at peak times, the optimal electricity price of the e-commerce seller will increase, resulting in problems such as the user utility and the profit of the e-commerce seller due to overpricing. In addition, according to the formula

$p^{t*} = \mu_i \lambda_i [q_i^{t,\max} + \rho(b - r/c)/(1-\rho)], t \in H_{peak}^{ado} \cup H_{peak}^{unado}$, it can be seen that the optimal electricity price of e-commerce suppliers is related to the product of the coefficient of dissatisfaction and the upper limit of electricity consumption. The optimal price of electricity is also related to the probability of adopting the peak regulating mechanism. Therefore, in order to study the influence of the probability ρ of adopting the peaking mechanism at peak times on the optimal electricity price p^{t*} of e-commerce sellers, Fig 4 shows the change of the probability of adopting the peaking mechanism of e-commerce sellers with the change of the optimal electricity price at peak times. It can be seen from Fig 4 that the optimal electricity price of e-commerce sellers is positively correlated with the probability of adopting the peaking mechanism during peak periods, indicating that the greater the probability of using a large number of refrigeration and heating functional appliances in bad weather such as high temperature and cold during this period, that is, the greater the probability of adopting the peaking mechanism during peak periods, the greater the optimal electricity price of e-commerce sellers to maximize their profits.

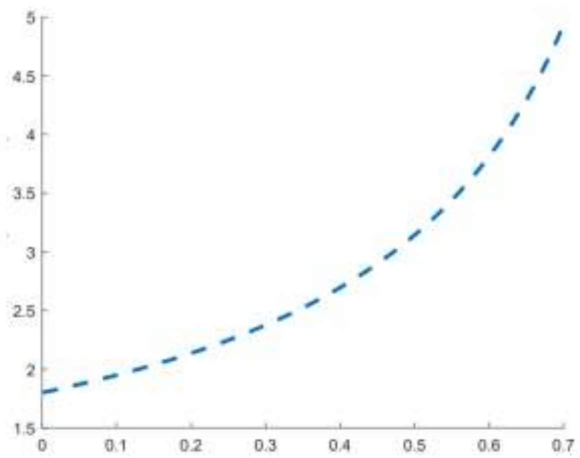

Fig. 4 Influence of the probability of adopting the peak regulating mechanism on the optimal electricity price of e-commerce sellers during peak periods

Proposition 9: When $t \in H_{peak}^{ado}$ period adopts peak regulation mechanism, e-commerce profit U_R is positively correlated with reference value b; When the base value b is constant, the optimal compensation rate r^* which makes the profit U_R of the e-commerce vendor reach the maximum value $r^* = (\Delta c - p^t)/2$ has and only has a unique value $r^* = (\Delta c - p^t)/2$.

It can be seen from proposition 9 that if an e-commerce seller wants to increase its profit, during the period when the peak load mechanism is adopted, it can not only attract users to save the power purchase cost by increasing the base value by transferring electricity consumption, but also appropriately change the compensation rate to users to maximize profits. According to formula (8) and (9), when e-commerce sellers are in peak and off-peak periods, their profits are related to factors such as the probability of adopting the peaking mechanism during peak periods, the price of electricity and the transfer of electricity by users. As can be seen from formula (8), peak e-commerce profit is also related to the compensation standard (that is, the base value b and the compensation rate r). Therefore, in order to help e-commerce sellers reasonably formulate compensation standards and improve profits, the base values set by e-commerce sellers are set as 8, 9, and 10 respectively. Fig 5 shows the changes of e-commerce profits with compensation rates under different base values. As shown in Fig 5 (taking $b=8$ as an example), when the compensation rate is fixed, the higher the benchmark value set by the e-commerce seller, the higher the profit it will get. This is because when the actual electricity consumption of the user is lower than the baseline value, the seller will determine the compensation to the user by the difference between the baseline value and the actual electricity consumption. If the seller increases the baseline value, the user is more likely to transfer the electricity consumption to make the actual electricity consumption in the current period lower than the baseline value set by the seller, so as to obtain more compensation. At the same time, due to the increase in the transfer of electricity by users during the peak period, the electricity sellers reduce the high-priced electricity purchased from the power plants, thus saving part of the cost, and thus improving the profits of the electricity sellers; On the contrary, if the seller reduces the base value, the user needs to transfer more electricity consumption, so that the actual electricity consumption within the period is lower than the base value in order to obtain the compensation of the seller. In addition, when the baseline value is fixed, with the increase of the compensation rate, the profit of the e-commerce seller first increases and then decreases, and there is only a unique maximum value. This is because with the improvement of the compensation rate, users are more inclined to transfer more electricity consumption to obtain compensation, but as the compensation rate is getting higher and higher, the compensation given to users by the seller exceeds the partial cost saved by the seller due to the peak adjustment mechanism, resulting in lower and lower profits of the seller.

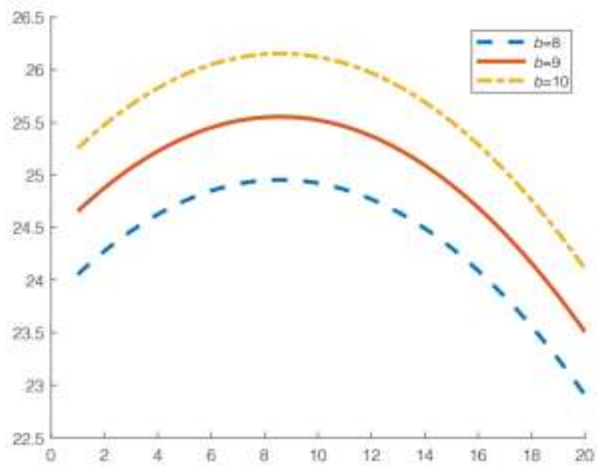

Fig 5 Influence of compensation rate on profit of e-commerce sellers

Proposition 10: When the difference between peak and off-peak unit power purchase cost Δc and the compensation rate r of the seller meet $\Delta c \succ r$, the profit of the seller after adopting the peaking mechanism is higher than the profit without adopting the peaking mechanism.

It is proved that proposition 10 shows that if and only if the difference between peak and off-peak unit power purchase cost Δc and the compensation rate r of e-commerce sellers meet $\Delta c \succ r$, the profit of e-commerce sellers after adopting peaking mechanism is higher than that without adopting peaking mechanism. Therefore, in order to visually display the profit comparison before and after retailers adopt the peaking mechanism when the difference of unit power purchase cost between peak period and off-peak period is greater than the compensation rate of e-commerce sellers, set the difference of unit power purchase cost $\Delta c = 20$ and the compensation rate $r = 1.25$ (as shown in Table 1). Figure 6 shows the changes of retailers' profits with electricity prices before and after adopting the peak regulating mechanism. As shown in Fig 6, the profit of e-commerce sellers after adopting the peak-regulating mechanism is significantly higher than that without adopting the peak-regulating mechanism. This is because the electricity purchase cost of e-commerce sellers at peak times is much higher than that at off-peak times when the peak-regulating mechanism is not adopted. The profit per unit of electricity sold to users will be lower; If the electricity supplier adopts the peak adjustment mechanism and the user transfers part of the electricity demand during the peak period to the off-peak period, the electricity supplier can still meet the electricity demand during the whole period. As the electricity demand decreases during the peak period, the compensation given to the user by the electricity supplier is lower than the electricity purchase cost saved by the peak adjustment mechanism, thus improving the profit of the electricity supplier.

In addition, when the peak adjustment mechanism is adopted, the profit curve of the e-commerce seller increases first and then decreases with the electricity price. This is because when the e-commerce seller increases the electricity price, its power purchase cost remains unchanged, and its profit increases. As electricity prices continue to rise, consumers are price sensitive and demand for electricity is reduced.

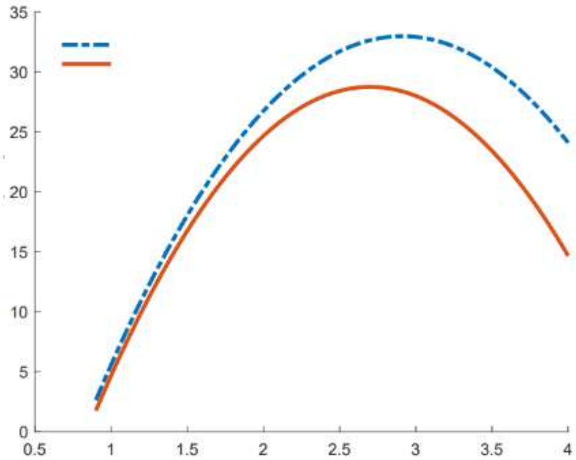

Fig. 6 Comparison of total utility before and after e-commerce sellers adopt peak regulation mechanism

5. Conclusion

In this paper, a new peak-regulating mechanism of power market is proposed, and the influence of user behavior factors on the total utility of users and the optimal compensation strategy and optimal pricing are analyzed by establishing a two-layer programming model. The main conclusions are as follows:

1) The optimal compensation electricity of a given user during the peak period is positively correlated with the subsidy rate. The increase in the subsidy rate will make users tend to transfer more electricity consumption to get compensation, thereby improving user utility and e-commerce profits.

2) When the subsidy rate is fixed during the peak period, the profit of the seller is positively correlated with the established base value; on the contrary, if the seller reduces the base value, the user needs to transfer more electricity consumption, so that the actual electricity consumption within the period is lower than the base value in order to obtain the compensation of the seller.

3) The optimal power consumption of users is related to the product of dissatisfaction coefficient, but not to jealousy coefficient and guilt coefficient. Given the price of electricity and the upper limit of electricity consumption, the optimal electricity consumption increases with the increase of the product of the dissatisfaction coefficient.

4) The profit of e-commerce sellers after adopting the peak regulating mechanism is greater than that before adopting the peak regulating mechanism, and the optimal electricity price of e-commerce sellers during peak periods is positively correlated with the probability of adopting the peak regulating mechanism, and the optimal electricity price of e-commerce sellers increases with the increase of the probability of adopting the peak regulating mechanism; In addition, the total utility of users after accepting the peak balancing mechanism is better than that before accepting the peak balancing mechanism.

The peaking mechanism adopted in this paper transfers part of the users' electricity consumption during the peak period to the off-peak period to reduce the electricity purchase cost of the e-commerce supplier. Meanwhile, the e-commerce supplier sets the benchmark value and uses the difference between the benchmark value and the actual electricity consumption of the user as the compensation power to make up for the inconvenience cost caused by the user's electricity transfer. In addition, in the process of electricity consumption, users will not only compare their electricity consumption with their own expected electricity consumption threshold, but also compare their own electricity consumption utility with other users' electricity consumption utility, thus affecting the total utility of users.

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Author Contributions: Chen Xiaodong conceived the ideas and designed the study; Mou Chunfeng collected the data; Jia Xudong analyzed the data; Deng Shubin wrote and revised the draft; Xue Yanjun revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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