Applied Energy Symposium 2021: Low carbon cities and urban energy systems
September 4-8, 2021, Matsue, Japan
Paper ID: 104

Power Transaction Strategies Based on Stackelberg Game Model and Smart Contract Between PV Users and Electric Power Aggregator

GE Xiangdi[1], HOU Hui[1], WANG Yifan[1]

1 School of Automation, Wuhan University of Technology, Wuhan 430070, China

ABSTRACT

In order to accelerate the realization of the global “double-carbon” goal, we introduced game theory into the electricity market to formulate a reasonable strategy to transaction. A strategy of purchasing and selling power is proposed in this paper. Firstly, we devised a transaction strategy based on Stackelberg game. Then, we designed an incentive mechanism for this game. This mechanism takes the reputation value of users as an index and adopts the smart contract technology in blockchain, which can reduce the transaction risk. The proposed strategy can encourage users to use electricity reasonably and sale surplus electricity to the grid. In addition, it can increase the benefits of electric power aggregator and users effectively.

Keywords: transaction strategies, game theory, Nash equilibrium, incentive mechanism, smart contract

1. INTRODUCTION

With the environment issues becoming more severe, the researchers have paid more attention to low carbon technologies around the word. As the primary source of carbon emissions in the electricity market, the task of energy conservation and emission reduction is challenging [1]. PV users who adopt the strategy of "the power generation to self-use, the surplus power sell to the grid" can reduce waste of resources and carbon emissions effectively. In order to promote PV users to sell surplus power to the grid to maximize the interests of both parties, it is particularly important to formulate reasonable transaction strategies and incentive mechanisms.

At present, a variety of trading mechanisms have been designed at home and abroad. ZARE K et al. [2] designed a bilateral contract based on the spot market which considered the interests of power companies. JIA Chen et al. [3] made a further study of bilateral contract. a dynamic power purchase and sale strategy is proposed based on the uncertain factors such as the market electricity price. In order to maximize the profit of the load aggregator, a bilevel model of power supplier-load aggregator is established in [4]. However, most of the above researches just consider the profit of the power companies, few considered the demand of users.

Therefore, some studies introduce game theory into the electricity market to formulate transaction strategies based on the users’ demand response to maximize the benefits of market participants [5]. In [6], a decision model of the electricity retailer in day-ahead market was established based on potential game, which can reduce the power sales cost of power companies and users' power consumption costs. A dynamic game-theoretic model was developed to analyze the impacts of market reforming in [7]. A Stackelberg game strategy was adopted to study the real-time electricity price strategy of microgrid in [8]. However, although the above-mentioned reference can meet the needs and benefits of trading participants, there still need some incentive mechanism to promote users to sell surplus energy to electric power aggregator (EPA).

Introducing some incentive into the game appropriately could encourage users to participate in electricity trading and increase the profits of both parties. PING Jian et al. [9] designed a Vickrey-Clarke-Groves auction mechanism to promote users to make rational bids. However, this auction process is too complex and not suitable for ordinary users. ALSKAIF T et al. [10] designed a scheduling algorithm based on reputation value, which provides ideas for the design of incentive mechanism in this paper.

To encourage users to sell surplus power to EPA and

Selection and peer-review under responsibility of the scientific committee of CUE2021

maximize the benefits of market participants, a strategy of purchasing and selling power is proposed in this paper. Our major contributions are summarized as follows:

1) A Stackelberg game model between PV users and EPA is proposed considering the development of PV users in the future.

2) An incentive mechanism is designed for this game based on smart contract in blockchain considering the reputation value of PV users. The smart contract in blockchain can execute the mechanism automatically. Meanwhile, users with high reputation value will be rewarded, and users with low reputation value will be punished.

2. BENEFIT MODEL OF PURCHASING AND SELLING

In this paper, the transaction model between photovoltaic (PV) users with generation system and an EPA with distributed energy and energy storage devices is considered. In a certain period of time, PV users could predict how much power they will generate and/or use. Then, they can choose to sell their surplus power or buy enough power for themselves increase their benefits. At the same time, EPA can buy power from PV users or power grid, and then sell power to other users who need to buy power. The transaction relationship between PV users and EPA is shown in Fig. 1.

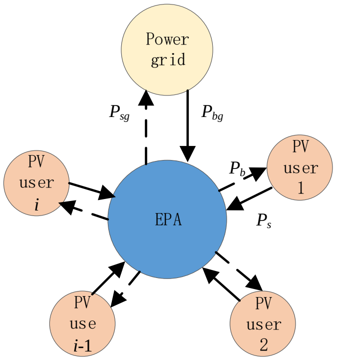

Fig 1 Transaction relationship between PV users and EPA.

2.1 *Benefit model of PV users*

In this paper, we suppose there are *i* PV users, each user has PV power generation capability. In a certain period of time, we defined the power consumption and the power generation of user *i* is x_i^T and E_i^T. Thus, when $E_i^T > x_i^T$ or $E_i^T < x_i^T$, PV user *i* could sale surplus power to EPA with price p_s or purchase power from them with price p_b. However, when $E_i^T = x_i^T$, they will no longer participate in the transaction, so we don't consider this case. Then, we defined *I* as the set of PV users, *B* as the set of power-purchasing users and *S* as the set of power-selling users. For each $i \in I$, if the price p_s changed, PV users could maximize their benefits by adjusting their power consumption.

Logarithmic utility function can describe users' benefits of power consumption effectively, and it divide users' overall benefits into power consumption benefits and power sales benefits [11], [12]. The utility function of PV users is:

$$\max A_i = \begin{cases} k_i \ln\left(1+x_i^T\right) + p_s\left(E_i^T - x_i^T\right) & E_i^T - x_i^T > 0 \quad (1) \\ k_i \ln\left(1+x_i^T\right) + p_b\left(E_i^T - x_i^T\right) & E_i^T - x_i^T < 0 \quad (2) \end{cases}$$

Where A_i is the overall benefit of user *i* and k_i is the preference parameter. Different users will consider different values at different times based on users' demand response. The price p_b cannot be higher than the power sales price p_{bg} of power grids (i.e., the power sales price that EPA sales to power grid), otherwise users will be more willing to buy electricity from power grids. The price p_b cannot be lower than the price p_s, otherwise EPA will sell electricity at a loss. At the same time, the price p_s cannot be lower than the power-purchase price p_{sg} of power grids (i.e., the power purchase price that EPA buy from power grid), otherwise users will be more willing to sell surplus energy to power grids, and it cannot be higher than the power sales price p_{bg} of power grids. Therefore, we can get that $p_s \le p_b \le p_{bg}$ and $p_{sg} \le p_s \le p_{bg}$, i.e., $p_{sg} \le p_s \le p_b \le p_{bg}$.

2.2 *Benefit model of EPA*

It is assumed that the EPA has distributed energy stations, but cannot generate power and does not have the right to operate distribution network. EPA needs to buy power from PV users or power grids, and then sell power to users to get profit and increase their benefits. In this transaction model, PV users can be divided into power-selling users and power-purchase users. The total power sold by all power-selling users and the total power purchased by all power-purchase users are:

$$E_s = \sum_{i \in S}\left(E_i^T - x_i^T\right) \tag{3}$$

$$E_b = \sum_{i \in B}\left(x_i^T - E_i^T\right) \tag{4}$$

As the leader of this transaction, EPA can set the price p_s and the price p_b when users want to sell or buy power. When $E_s > E_b$, the power purchase from PV users is surplus, so EPA could sell the surplus power to power grids at price p_{sg}. When $E_s < E_b$, the power purchase from PV users is not enough to be sold to other users, and so EPA could buy power from power grids at price p_{bg}. However, when $E_s = E_b$, the transaction reached a balance of supply and demand, they will no longer participate in the transaction, so we don't consider this case. In order to maximize the benefits of EPA, we assumed that all the surplus power cannot be stored and will be sold to power grids. The utility function of EPA is:

$$\max A_{buy} = \begin{cases} p_b E_b + p_{sg}\left(E_s - E_b\right) - p_s E_s & E_s > E_b \quad (5) \\ p_b E_b + p_{bg}\left(E_s - E_b\right) - p_s E_s & E_s < E_b \quad (6) \end{cases}$$

Where A_{buy} is the overall benefit of EPA, the price p_{sg} and p_{bg}'s pricing standards are formulated by power grids or regulatory agencies.

3. STACKELBERG GAME

3.1 Stackelberg game

Game theory is a common theory in market transactions and market competition. Introducing game theory into electricity market to formulate trading strategies can maximize the benefits of market participants. Staceklberg game is a special non-cooperative dynamic game, in which there exists a hierarchy among the participants. When a participant changed their own decisions, others' decision will also be affected. In a meanwhile, each participant in this game is rational and independent, and their goal is to maximize their own benefits by choosing different schemes [13].

In our model, the EPA is the leader in this game, and the PV users are the followers. Leader can choose their own strategies first, and then followers can decide their strategies. Thus, followers can adjust their best countermeasures accordingly after observing the leaders' strategies. Leaders can also adjust their strategies based on followers' best strategies to maximize their own benefit. Their optimal strategy group is called Nash equilibrium. The Nash equilibrium of this game can be expressed as:

$$G = \left\{\left(I \cup J\right), X_{\mathrm{i}}^{T}, P_s, P_b, A_i, A_{buy}\right\} \quad (7)$$

Where X_i^T is an adjustable power consumption strategy group of user *i*. Strategy $\left(p_s^*, p_b^*, x^*\right)$ is the Nash equilibrium point of this game, and it needs to satisfy the following inequalities:

$$A_i\left(p_s^*, p_b^*, x^*\right) \geq A_i\left(p_s^*, p_b^*, x_i, x_{-i}^*\right) \quad \forall i \in I, \forall x_i \in X_i \quad (8)$$

$$A_{buy}\left(p_s^*, p_b^*, x^*\right) \geq A_{buy}\left(p_s, p_b, x^*\right) \quad \forall p_s \in P_s, \forall p_b \in P_b \quad (9)$$

Where $x^* = \left[x_1^*, x_2^*, \cdots, x_n^*\right]$, $x_{-i}^* = \left[x_1^*, x_2^*, \cdots, x_{i-1}^*, x_{i+1}^*, \cdots, x_n^*\right]$.

In summary, PV users and EPA's goal are $\max A_i$ and $\max A_{buy}$. EPA can formulate the optimal price p_s and the price p_b, PV users could choose the optimal power consumption plan according to their pricing, and the Nash equilibrium's solution of this game is the optimal solution of this objective function. When Nash equilibrium is reached, PV users and EPA cannot improve their benefits by changing their own strategies alone.

3.2 Backward induction

The Nash equilibrium of Stackelberg game can be solved by backward induction. Backward induction is a recursive induction method, which pushes forward from the back, and it is suitable for solving Nash equilibrium of dynamic game [14]. By using this method, after the later participants choose their strategy, the optimal strategy of the previous participants can also be determined. Through step-by-step backward push, the optimal strategy choice of all participants is obtained, which is the Nash equilibrium solution of this game. The solution process of backward induction is shown in Fig. 2.

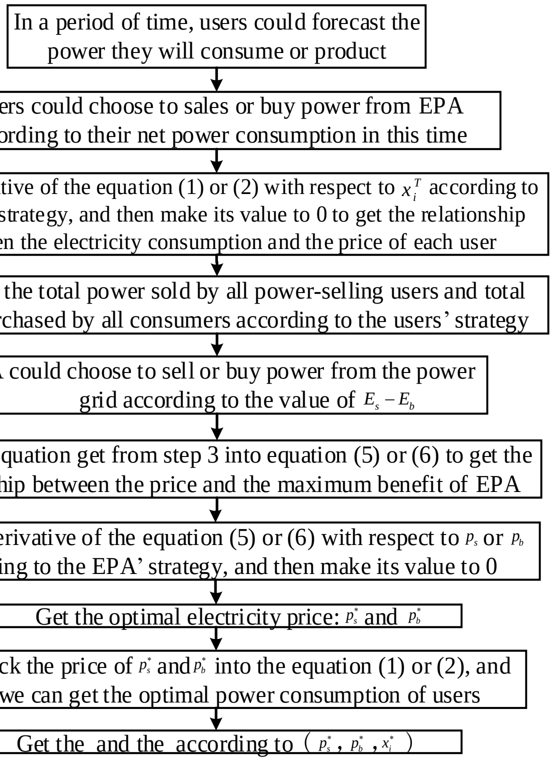

Fig 2 The solution process of backward induction.

4. REPUTATION VALUE INCENTIVE MECHANISM BASED ON SMART CONTRACT

4.1 Incentive mechanism of reputation value

It is not enough to make the electricity price only considering the game theory. Usually, it is necessary to design some incentive mechanisms to adjust the electricity price. Under the incentive of the mechanism, PV users will be more willing to adjust their electricity consumption, sell surplus power. In this paper, we designed a reputation incentive mechanism based on smart contract in blockchain. Designing mechanism based on smart contract can not only achieve decentralization and improve transaction reliability, but also encourage users to use electricity reasonably and reduce carbon emissions. Users can improve their reputation value by joining in electricity trading. The reputation value of each user will be updated once a day, and their value will gradually tend to be stable.

This incentive mainly includes two indicators: transaction quality evaluation and self-consumption evaluation. As the users' forecast of power consumption and power generation may be a discrepancy, the transaction quality evaluation is considered, that is:

$$Q_i^T = 1 - \frac{\left|E_p - E_r\right|}{E_p} \tag{10}$$

Where E_p is the planned trading power, E_r is the real trading power. The Q_i^T 's value is distributed in the range of 0.5~1. The second index is self-consumption evaluation, which considers the user consumption rate φ to measure the user consumption situation, that is:

$$\varphi_i^T = \gamma \cdot \frac{E_i^T}{\sum_{i\in I} E_i^T} \tag{11}$$

In which:

$$\gamma = \frac{\sum_{i\in I} x_i^T - \sum_{i\in I} E_i^T}{\sum_{i\in I} x_i^T} \tag{12}$$

The reputation value of each user is:

$$R_i = \frac{\sum_{i=1}^{n}\left(\alpha Q_i^T + \beta \varphi_i^T\right)}{n} \tag{13}$$

Where n is the number of transactions between PV users and EPA in one day. α and β are weight factors, which are used to reflect the importance of the two indicators. In this paper, both α and β take a value of 1, so that the user's reputation value is maintained between 0 and 2. After introducing this incentive mechanism, the utility function of PV user *i* is changed to the following equation:

$$\max A_i = \begin{cases} k_i \ln\left(1 + x_i^T\right) + p_s\left(1 - \mu_i\right)\left(E_i^T - x_i^T\right) & E_i^T > x_i^T \quad (14) \\ k_i \ln\left(1 + x_i^T\right) + p_b\left(1 - \mu_i\right)\left(E_i^T - x_i^T\right) & E_i^T < x_i^T \quad (15) \end{cases}$$

Where μ_i is the excitation coefficient, when $1<R_i$, μ_i=-0.2. when $0.8<R_i\leqslant 1$, μ_i =0. when $0.6<R_i\leqslant 0.8$, μ_i =0.1. when$R_i\leqslant 0.6$, μ_i =0.2. It can be known from equation (14) and (15) that when users have higher reputation value, they can sell power at higher price and buy power at lower price. When users have low reputation value, they need to buy power at higher price and sell power at lower price. Therefore, the user's benefit can be influenced by the reputation value.

4.2 Trading process

The smart contract in the blockchain can automatically execute the pre-established incentive mechanism based on reliable and unchangeable data. Therefore, we designed the transaction process for this incentive mechanism. The process of this incentive mechanism is shown in Fig. 3.

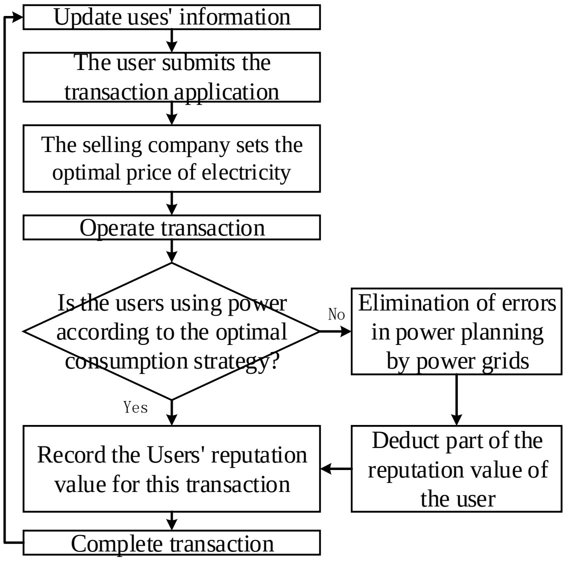

Fig 3 The flow chart of the mechanism based on reputation value.

5. SIMULATION AND ANALYSIS

In this section, we choose five PV users to join this Stackelberg game, and each PV user is equipped with a PV power generation system. This system can only generate electricity when there is plenty of sunshine. Therefore, we only discuss the transaction model of users from 7:00 am to 19:00 pm in this paper. The power consumption and the power generation of each user in this period are shown in Fig. 4 and Fig. 5. Then, we can get the net power consumption, total power purchase, total power sales and total net power consumption of users in different time periods.

Considering the actual situation in most parts of the country, we think the price $p_{sg} = 0.4$ Yuan/kWh and the price $p_{bg}=1$ Yuan/kWh. In order to simplify the calculation, the power-selling users take $k_{is}=50$, and the power-purchase users take $k_{ib}=80$. Take the power consumption and power generation at time *t* as the power consumption and power generation within one hour from time *t*. Therefore, the number of transactions on the same day is 12 (i.e. *n*=12).

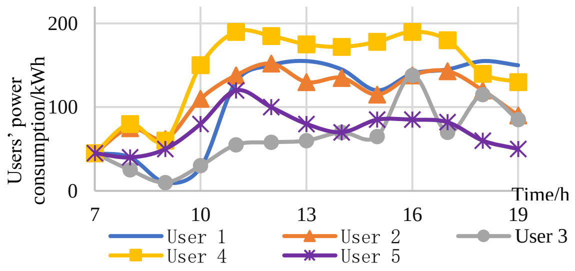

Fig 4 Users' power consumption in different time.

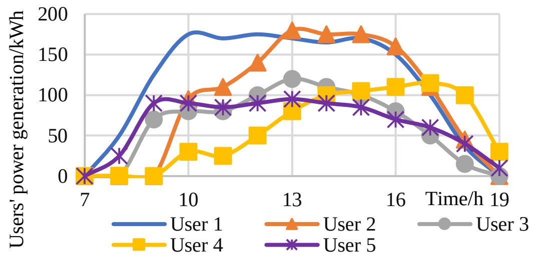

Fig 5 Users' power generation in different time.

5.1 Case studies of Stackelberg game

According to the different generation and consumption of PV users in different time periods, different optimal power prices can be determined, and then the time-of-use power price can be formulated. In this paper, the backward induction method designed in section 3 is used to make the pricing strategy of EPA. Then, the optimal quotation for each time period can be obtained as shown in Fig. 6.

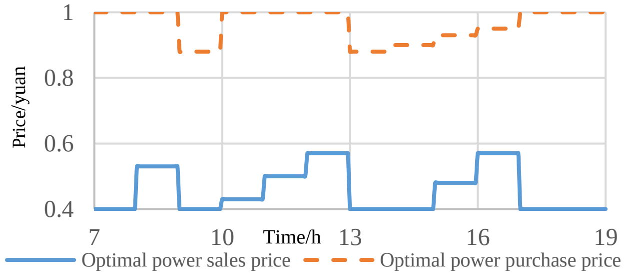

Fig 6 The optimalbe quotations of EPA in each time.

In the period of 9-10, only user 1 has more surplus power, if the price p_s is increased, other users can't sell more power. Therefore, the EPA will sell power at the lowest electricity price. In the time period 10-12 and 16-17, PV users have enough power to sell. Therefore, increasing the price p_s can promote users to sell more power to EPA. During the 13-15 time period, the power generation of users is more sufficient and users rarely need to buy power. Therefore, EPA will reduce their price p_b to promote users to increase their power consumption. During the 15-16 time period, their power consumption is approximately balanced with supply and demand, EPA should reduce the price p_b and raise the price p_s to promote users to join this transaction. The benefit of EPA based on optimal price or the grid standard price (i.e. p_{sg} and p_{bg}) is shown in Fig. 7.

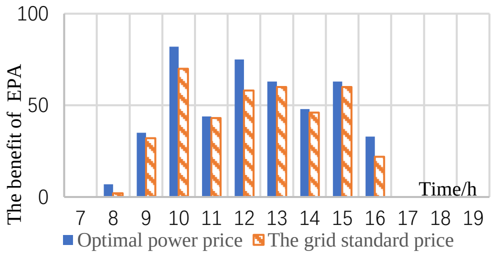

Fig 7 Benefit comparison of EPA under different prices.

From the Fig. 7, it can be seen that the benefit of EPA in 7-8 time periods and 17-19 time periods is zero. In other time periods, the benefits of EPA can be improved based on the optimal price. During the 8、10~12 and 16 time period, lots of users need to sell power. By adjusting the optimal electricity price, the demand of users can be satisfied effectively. During the 13 and 14 time period, the power consumption of PV users can be increased effectively, the power loss by PV users when selling electricity to EPA or power grids can be reduced. The benefits of users and companies will be improved.

5.2 Case studies of incentive mechanism

Assuming that the initial reputation value of all users is 1, the reputation value recorded by each user in each transaction can be obtained by equation (13). Then, the settlement reputation value of each user on the same day can be obtained as shown in Fig. 8.

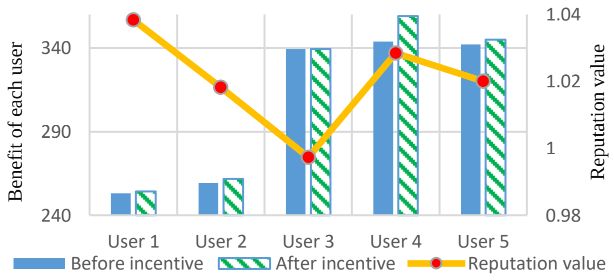

Fig 8 Reputation value of each user's settlement on the same day and the benefit comparison of each user before and after incentive in the time t=16.

It can be seen from Fig. 8 that most of users can complete the transaction well under ideal conditions. The reputation value of user 3 has declined, but it is still within a reasonable range. The reputation value of other users has increased and they will get certain preferential treatment when they need to transaction. Meanwhile, EPA will firstly trade with user 1 who have the highest reputation value. In the following studies, we take the transaction at time *t*=16 for an example. Fig. 8 also shows the benefit comparison of each user before and after adopting incentive mechanism.

According to the above analysis, we can get the following results: user 1 and user 2 are power-selling users in this time. Though their reputation value is high, their trading power is less relatively, that is why their increased benefit is not high. Users 3, 4, and 5 are consumers of power in this time. As the reputation value of user 3 has declined but it is still within a reasonable range. Therefore, user 3 has neither enjoyed preferential treatment nor been punished. His benefits remain unchanged. User 4 and user 5 have higher reputation values, but the transaction volume of user 4 is larger than that of user 5, so the increased benefit of user 4 is higher than that of user 5. In general, this incentive can promote PV users to adjust their own power consumption and increase their benefit effectively.

6. CONCLUSION

In this paper, a transaction strategy is designed based on the Stackelberg game. The backward induction method is used to solve the optimal power consumption of PV users and to set the optimal price for EPA. Then, an incentive mechanism is designed for this game. With the reputation value of users as an index, the smart contract technology in the blockchain is adopted to automatically implement the incentive mechanism formulated in advance. Simulation results of several cases show that the transaction strategy based on Stackelberg game theory can make every market participant get the maximum benefit. Introducing incentives into this game can promote PV users to adjust their power consumption or sell surplus power to the EPA or power grid to improve their benefit.

REFERENCE

[1] LIU Zhenya. The fundamental way to achieve carbon peak and carbon neutrality[J]. Power Equipment Management, 2021(03): 20-23.

[2] ZARE K, MOG M P, ESLAMI M. Electricity procurement for large consumers based on information gap decision theory[J]. Energy Policy, 2010, 38(1): 234-242.

[3] JIA Chen, DU Xinhui, YAO Hongmin. Multi-objective optimization research on dynamic procurement strategy for electricity retailers considering uncertainty factors[J]. Power System Protection and Control, 2019, 47(21): 134-143.

[4] ZHANG Chunyu, WANG Qi, WANG Jiahui, et al. Real-time procurement strategies of a proactive distribution company with aggregator-based demand response[J]. IEEE Transactions on Smart Grid, 2018, 9(2): 766-776.

[5] RYO, HASE, NORIHIKO, et al. An evolutionary game for analyzing switching behavior of consumers in electricity retail markets[J]. IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, 2020, E103.A(2): 407-416.

[6] TU Jing, ZHOU Ming, LI Gengyin. A potential game based distributed optimization strategy for the electricity retailer considering residential demand response[J]. Proceedings of the CSEE, 2020, 40(02): 400-411.

[7] TIAN Ruijie, ZHANG Qi, WANG Ge, et al. Study on the promotion of natural gas-fired electricity with energy market reform in China using a dynamic game-theoretic model[J]. Applied Energy, 2017, 185: 1832-1839.

[8] BU S, YU F R. A game-theoretical scheme in the smart grid with demand-side management: towards a smart Cyber-Physical power infrastructure[J]. IEEE Transactions on Emerging Topics in Computing, 2013, 1(1): 22-32.

[9] PING Jian, CHEN Sijie, ZHANG Ning, et al. Decentralized transactive mechanism in distribution network based on smart contract[J]. Proceedings of the CSEE, 2017, 37 (13): 3682-3690.

[10] ALSKAIF T, LUNA A C, ZAOATA M G, et al. Reputation-based joint scheduling of households appliances and storage in a microgrid with a shared battery[J]. Energy & Buildings, 2017, 138: 228-239.

[11] TUSHAR W, CHAI B, YUEN C, et al. Three-party energy management with distributed energy resources in smart grid[J]. IEEE Transactions on Industrial Electronics, 2014, 62(4): 2487-2498.

[12] LEE J, GUO J, CHOI J K, et al. Distributed energy trading in microgrids: a game-theoretic model and its equilibrium analysis[J]. IEEE Transactions on Industrial Electronics, 2015, 62(6): 3524-3533.

[13] WU Lilan, JING Zhaoxia, WU Qinghua, et al. Equilibrium strategies for integrated energy systems based on Stackelberg game model[J]. Automation of Electric Power Systems, 2018, 42(04): 142-150+207.

[14] FUDENBERG D, TIROLE J. Game theory[M]. Cambridge, Mass: MIT Press, 1992.