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A Game Theory Based Interaction Strategy between Residential Users and an Electric Company

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Abstract – With the development of smart grid technology, it has become a hotspot to increase benefits of both residential users and electric power companies through demand response technology and interactive technology. In this paper, the game theory is introduced to the interaction between residential users and an electric company, making a mutually beneficial situation for the two. This paper solves the problem of electricity pricing and load shifting in the interactive behavior by building the game-theoretic process, proposing the interaction strategy and doing the optimization. In the simulation results, the residential users decrease their cost by 11% mainly through shifting the thermal loads and the electric company improves its benefits by 5.6% though electricity pricing. Simulation analysis verifies the validity of the proposed method and shows great revenue for the economy of both sides.

Keywords: Interaction, Game theory, Optimization, Demand response

1. Introduction

In recent years, smart grid has been globally recognized as the future direction of power systems [1-2]. Demand side management (DSM), an important kind of smart grid technologies, optimizes power consumption mode to improve the efficiency of power systems. Load shifting is one of the major measures of demand side management, especially for the cases where there is distributed generation of high penetration [3]. Load shifting can mitigate the adverse effects of intermittent distributed generation and shave the peak load, which therefore becomes a key function of the user side energy management.

The technology of interaction between the residential users and the electric company is mainly composed of three aspects: home energy management, electricity pricing and the interaction process.

In the area of home energy management, the main focus is to use optimization techniques to assist residential users to schedule their loads optimally. Reference [4] studied the usage of smart home appliances. Reference [5] and [6] involved the information and communication technology into the energy management system. Reference [7-10] studied the method to improve the energy efficiency with the assistance of demand response technology. Reference [11] achieved the optimal home energy management by establishing a model of mixed-integer linear programming. However, in these researches, the electricity price is assumed to be fixed and the electric companies are assumed not to respond to the change of residential load. Reference [12] investigated the whole system of the home energy management with electric vehicles and distributed energy. Reference [13] presents a load-management innovation to provide a limited but uninterrupted DC power supply to homes in India. In a typically power deficient situation, load shedding becomes unavoidable. From reference [4] to reference [13], we found that these studies mainly focus on the users' responding process to the electric company.

To consider the response of electric companies, the electricity pricing is necessary to be studied. Residential loads respond to electricity prices such as time-of-use (TOU) price, so electric companies can also manage the demand side by taking proper pricing policies. Numerous references researching in the field of electricity pricing have been published. Reference [14] and [15] studied the pricing strategy for electric vehicles by behavioral theory. Reference [16] focused on the process of pricing in an area in which electronic devices are involved. Reference [17] studied a novel distributed approach for optimal management of unidirectional V2G considering multiple energy suppliers. These researches focus on the process of electric pricing but ignore the process of the interaction between the users and the grids.

In the field of the interaction between the residential users and electric company, a great amount of relevant studies are published to explore this issue and lots of achievements have been done. A survey [18] showed that the interaction between the power utility and users can be well modeled by the game theory and previewed the promising development of applying the game theory in the

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interaction. Reference [19] put forward a game model of users and an electric company and got the Nash Equilibrium of the model. Under the results of Nash Equilibrium, both the users and the electric company got extra benefits. In reference [20], the interaction was modeled as a two-level game where the interaction among the electric companies was formulated as a non-cooperative game while an evolutionary game was established for the interaction among the residential users. And the proposed strategies in [20] were able to make both games converge to their own optimal equilibrium. While in reference [21], a game-theoretic energy schedule (GTES) method was proposed for both electric company and users, and the peak-to-average power ratio was reduced by optimizing the users' energy schedules in a two-step centralized game.

Among the aforementioned literatures, researchers always focus on the Nash Equilibrium in various proposed game game-theoretic model while ignore the cooperative game between the users and the electric company. Actually the results of the cooperative game may bring more benefits for the electric company and less electric payment for the users. In addition, most references go on the competition only by optimizing users' loads scheduling. That is to say, the electric company lacks the interactive behavior such as making electricity prices to improve its own revenue.

In this paper, the interaction between residential users and an electric company can be regarded as a "game" and the game theory is introduced in the interaction. Firstly, this paper analyzes the interaction between residential users and an electric company which are regarded as two players. Then the game-theoretic model for both two players is established. The Nash Equilibrium is firstly calculated and the final solution will be obtained after going on the proposed cooperative game process. Finally, simulation results verify the validity of the proposed model and method. In the simulation, the users who participate in the interaction can gain extra benefit from the optimal schemes for the loads. While the electric company can also obtain higher revenue from the final optimal pricing.

The main innovation of this paper lies on the cooperative game between the users and the electric company and applying the electricity pricing into the interaction. And the contribution of this paper is establishing the game-theoretic process and proposing the interaction strategy though introducing the game theory into the interaction. And the proposed method could offer the optimal schemes for users and electric prices for the company so that the two sides both increase their revenue and reach a win-win situation.

2. Optimization Models of the Residential Users and Electric Company

The interaction between the electric company and residential users is based on the process in which they optimize their operation based on their own interests. Thus, the discussion on the optimization models of the users and the electric company is of necessity before the analysis of the interaction strategy.

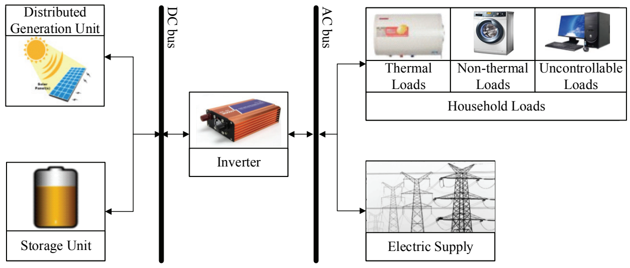

Fig. 1. The structure of a typical residential house

2.1 The optimization model for residential users

For residential users, a typical residential house is always composed of a distributed generation unit like the PV array, a storage unit like the battery, household loads and the electric supply from the bulk power grid. The structure of a typical residential house is shown in Fig. 1. Specially, the household loads are usually divided into three classes, thermal loads, non-thermal loads and uncontrollable loads.

Because the residential user's goal is to save the electricity bill and the main constraints are the upper and lower limits of the power consumption. Thus, model for the residential users can be calculated as follows:

$$\begin{aligned} &\min\ z_1 = \sum_{i}^{N} k(i)p(i)x_{tr}(i)\Delta t \\ &s.t.\ \ \frac{1}{N}\sum_{i}^{N}(x(i){+}x_e x_{th}(i)) = \bar{x} \\ &\qquad x_{\min} < x(i){+}x_e x_{th}(i) < x_{\max} \end{aligned} \tag{1}$$

In the objective function of (1), z_1 represents the total electricity cost of the residential user, the decision variable $x_{tr}(i)$ represents the power exchanged between the user and the electric company at the i^{th} time slot, $p(i)$ represents the electricity price at the i^{th} time slot, N is the total number of time steps throughout the scheduling horizon (a day), Δt represents the length of each time step, and $k(i)$ is an indicator which reflects the direction of the power flow. It equals to 0 if the house feeds power back to the grid while equals to 1 if the house imports electricity from the power grid. So $k(i)$ can be calculated as Eq. (2):

$$k(i) = \begin{cases} 1 & ,x(i) > 0 \\ 0 & ,x(i) \le 0 \end{cases} \tag{2}$$

In the constraints of (1), $x(i)$ represents the power consumption the non-thermal loads of the residential user at the i^{th} time slot. In addition, x_e and $x_{th}(i)$ represent the rated power and ON/OFF state of thermal loads respectively. $\bar{x}$, $x_{\min}$ and $x_{\max}$ represent the average, maximum and minimum of the power consumption of the user. The $x_{tr}(i)$ can be calculated by:

$$x_{tr}(i) = x(i) + x_e x_{th}(i) - x_{DG}(i) - x_{dis}(i) \tag{3}$$

where $x_{DG}(i)$ and $x_{dis}(i)$ represent the power output of the PV array and battery respectively;

For thermal loads, without loss of generality, an electric water heater is taken as an example to describe the modeling process. When the water heater is on, the thermodynamic process can be described as

$$\theta(i+1) = \theta(i) + QR - [\theta_{en} + QR - \theta(i)]\exp[-\Delta t/(RC)] \tag{4}$$

where $\theta(i)$ and θ_{en} are the water temperature and the ambient temperature. *Q*, *R* and *C* represent heater capacity, thermal resistance and thermal capacitance respectively. While the water heater is off, its thermodynamic process can be described as

$$\theta(i+1) = \theta_{en} - [\theta_{en} - \theta(i)]\exp[-\Delta t/(RC)] \tag{5}$$

If there is hot water use, the water temperature should be modified by:

$$\theta(i) = \{\theta_{cur}[M - d(i)] + \theta_{en} d(i)\}/M \tag{6}$$

where *M* represents the capacity of the tank, $d(i)$ represents the demand of hot water at the i^{th} time slot, θ_{cur} represents the temperature before the cold water injected into the tank.

Taking the uncertainty of the uncontrollable loads into consideration, there is

$$x_{tr}(i) = x(i) + x_e x_{th}(i) - x_{DG}(i) - x_{dis}(i) + l(i) \tag{7}$$

where $l(i)$ represents the uncertainty of the uncontrollable loads.

2.2 The optimization model for electric company

For the electric company, the objective is to maximize the economic benefits of itself which is composed of the line loss and revenue of power selling. The residential loads supplied by this electric company are assumed to be connected with an infinite system. The voltage and the power factor of the users are U_0 and $\cos\varphi$. The power caused by line loss at the i^{th} time slot is defined as

$$x_L(i) = \frac{x_\Sigma(i)^2}{\cos^2\varphi U_0^2} R_L \tag{8}$$

In Eq. (8), $x_\Sigma(i)$ represents the power transferred from the electric company to the user, and the resistance of the line is R_L. It is assumed that the number of residential users participating in the interaction with the electric company and residential users who do not is N_1 and N_2 respectively, then there is

$$x_\Sigma(i) = N_1 x_{tr}(i) + N_2 x_0(i) \tag{9}$$

As the interactive behavior of the residential users is determined by the electricity price made by the electric company, the optimization problem used by the electric company to maximize its economic benefits can be written as

$$\begin{aligned} \min\ z_2 &= \sum_i^N (p(i) - p_0(i)) x_\Sigma(i)\Delta t - \sum_i^N p_0(i) x_L(i)\Delta t \\ s.t.\ & \frac{1}{N}\boldsymbol{n}\cdot\boldsymbol{p} = p_0 \\ & p_{\min} < p(i) < p_{\max} \end{aligned} \tag{10}$$

where decision variable $\boldsymbol{p}$ represents the vector of the price which contain two values (the peak price and off-peak price). $\boldsymbol{n}$ is a N-dimensional vector with each entity equaling to 1. And the first constraint means that the average price should be certain. $p_{\min}$ and $p_{\max}$ are the lower limit and upper limit of the price. $p_0(i)$ represents the price of the electricity purchased from the power plant.

3. The Interaction Process between the Residential Users and Electric Company

In the models of the users and the electric company, they regard each other's decision variables as known conditions. Therefore, the interaction process can be regarded as a game. Therefore the game theory is adopted in the analysis of the interaction process.

3.1 Game process

The users optimize their load schedules based on the price, the former model (1) can be summarized as

$$\begin{aligned} \min_{\boldsymbol{x}}\ & z_1 = f_1(\boldsymbol{x}, \boldsymbol{l}_\Delta, \boldsymbol{p}) \\ s.t.\ & g_1(\boldsymbol{x}, \boldsymbol{p}) = 0 \\ & h_1(\boldsymbol{x}, \boldsymbol{p}) \le 0 \end{aligned} \tag{11}$$

where $\boldsymbol{l}_\Delta$ is the uncertainty of the loads which obey normal distribution and $\boldsymbol{x}$ is the decision variable set containing $x(i)$ and $x_{th}(i)$. For users if $\boldsymbol{p}$ is known, $\boldsymbol{x}$ can be solved from (11).

Similarly, the electric company maximizes the revenue by making the prices when the loads of residential users are certain. Therefore, the model (10) where the decision variable vector is $\boldsymbol{p}$ can also be summarized as

$$\begin{aligned}&\min_{\boldsymbol{p}} z_2 = f_2(\boldsymbol{x}, \boldsymbol{l}_\Delta, \boldsymbol{p})\\ &s.t. \quad g_2(\boldsymbol{x}, \boldsymbol{p}) = 0\\ &\qquad h_2(\boldsymbol{x}, \boldsymbol{p}) \le 0\end{aligned} \tag{12}$$

Afterwards the game process can be described as follows: the electric company makes the price; then the users optimize their load schedules; then the electric company updates the price based on the users' load schedules and so forth. Finally, after a large number of cycles, a stable solution is reached.

The interaction process described above can be written as follows：

$$\Gamma(N, X, P, z_1, z_2) \tag{13}$$

where $N = \{1,2\}$ is the set of the players, in which 1 represents the user and 2 represents the electric company. X is the set of the player1's strategy and P is the set of the player2's strategy. As the tactic of player2 is known by player1 and player2 knows nothing about player1's tactic, the player2 uses hybrid strategy. It is assumed that $\mu(\cdot)$ is a probability measure of P and the σ algebra of $\overline{P}$ satisfies：

$$\mu(P) = 1 \tag{14}$$

The payment function of player2 is,

$$K(x,\mu) = \int_P z_2(p) d\mu \quad , \mu \in \overline{P} \tag{15}$$

$$d\mu = f(p)dp \tag{16}$$

where $f(\cdot)$ is the density function of $\mu(\cdot)$.

3.2 Nash equilibrium

Nash Equilibrium is a strategy combination, such that each player's strategy is a best response to the other participants. Players in the game who unilaterally deviate from the Nash Equilibrium will not increase their income.

For player1, its Nash Equilibrium can be calculated by：

$$\min_x \max_\mu f_a(\boldsymbol{x}, \mu) \tag{17}$$

For player2, its Nash Equilibrium can be calculated by：

$$\min_\mu \max_x K(\boldsymbol{x}, \mu) \tag{18}$$

Nash Equilibrium $(\boldsymbol{x}^*, \mu^*)$ ought to satisfy：

$$K(\boldsymbol{x}^*, \mu^*) \le K(\boldsymbol{x}^*, \mu) \tag{19}$$

$$z_1(\boldsymbol{x}^*, \mu^*) \le z_1(\boldsymbol{x}, \mu^*) \tag{20}$$

In this study, player1's strategy is a mixed strategy, so x^* ought to be the function of player1' strategy

$$\boldsymbol{x}^* = f(p^*) \tag{21}$$

3.3 Nash equilibrium approximate calculation

In this paper, Nash Equilibrium approximate calculation method presented in [14] is improved to solve the Nash Equilibrium. In this model, as player1's strategy is a mixed strategy, its decision variables are all the decision variables of player1's. Assuming that S is the policy space of the two players and L_Δ is the set of $\boldsymbol{l}_\Delta$, there is

$$S = X \times P \tag{22}$$

$$y_r = \mu(\Delta P_r) \tag{23}$$

Assume $\boldsymbol{y} = (y_1, y_2 \cdots, y_k, \cdots y_n)$ and $\boldsymbol{y}$ approximate substitutes μ. $\boldsymbol{y}^*$ represents the player2' strategy under Nash Equilibrium. Then there is

$$E(\boldsymbol{y}^*) \le E(\boldsymbol{y}^* \| y_r) \tag{24}$$

Player2's Nash Equilibrium can be calculated by

$$\begin{aligned}&\min_{\boldsymbol{x}} \; Z = \sum_{r=1}^{n} y_r \delta_r\\ &s.t. \quad 0 \le y_r \le 1\\ &\qquad \sum_{r=1}^{n} y_r = 1\end{aligned} \tag{25}$$

Assume $Z = Z(\boldsymbol{y})$, and divide L_Δ into m areas. Let $\Delta L_{\Delta j}$ represent the j^{th} areas and $\boldsymbol{l}_{\Delta j}$ approximate substitute each point in $\Delta L_{\Delta j}$. Then there is

$$\delta_i = \sum_{j=1}^{m} f_2(\boldsymbol{\alpha}_i, \boldsymbol{l}_{\Delta j}, \boldsymbol{\beta}_i) k_j \tag{26}$$

where k_j is the probability of $\boldsymbol{l}_\Delta \in \Delta L_{\Delta j}$. Assume that $i_{\max}$ and $\boldsymbol{y_0}$ satisfy the follow equations:

$$\delta_{i_{\max}} = \max_{i=1,2\ldots\ldots n} \delta_i \tag{27}$$

$$y_{0i} = \begin{cases} 1 & i = i_{\max} \\ 0 & i \ne i_{\max} \end{cases} \tag{28}$$

and $\boldsymbol{y}$ satisfies:

$$\begin{aligned} Z(\boldsymbol{y}) - Z(\boldsymbol{y_0}) &= \sum_{i=1}^{n} y_i \delta_i - \sum_{i=1}^{n} y_{0i} \delta_i \\ &= \sum_{\substack{1 \le i \le n \\ i \ne i_{\max}}} y_i \delta_i - \sum_{\substack{1 \le i \le n \\ i \ne i_{\max}}} y_i \delta_{\max} \\ &= \sum_{\substack{1 \le i \le n \\ i \ne i_{\max}}} y_i (\delta_i - \delta_{\max}) \le 0 \end{aligned} \tag{29}$$

Only when $\boldsymbol{y}=\boldsymbol{y_0}$, $Z(\boldsymbol{y})-Z(\boldsymbol{y_0})=0$. Then we have

$$\boldsymbol{y}^*=\boldsymbol{y_0} \tag{30}$$

$\mu(\cdot)$ obeys Gaussian distribution, that is,

$$\mu(\boldsymbol{p})=\frac{1}{(\sqrt{2\pi\sigma})^N}\exp[-\frac{(\boldsymbol{p}-\boldsymbol{p}^*)^2}{2\sigma^2}] \tag{31}$$

where $\boldsymbol{p}^*$ represents the price of $\Delta P_{i_{\max}}$, and $d_{\min}$ represents the minimum distance from $\boldsymbol{p}^*$ to the areas which is neighbor to $\Delta P_{i_{\max}}$.

$$d_{\min}=3\sigma \tag{32}$$

3.4 Determine the evaluation rules

The pure strategy of player1 can be calculated by random number table method based on its Nash Equilibrium and the strategy of player2 can be calculated by such strategy.

Under Nash Equilibrium, the profits of the players are not the optimal solution. To get the optimal solution, corporative game is necessary. It is assumed that the objective function of player1 is u^* and the payment functions of player2 is K^*.

Therefore, the objective functions are changed into the following equations:

$$z_{1,T}=f_1(z_1,z_2) \tag{33}$$

$$z_{2,T}=f_2(z_1,z_2) \tag{34}$$

After conversion, the objective functions ought to obey

$$\frac{\partial f_1}{z_1}>0,\frac{\partial f_1}{z_2}<0,\frac{\partial f_2}{z_1}>0,\frac{\partial f_2}{z_2}<0 \tag{35}$$

According to the barging, the new objective function can be described as

$$z_{1,T}=-(z_1-u^*)(-z_2+K^*) \tag{36}$$

$$z_{2,T}=-(z_1-u^*)(-z_2+K^*) \tag{37}$$

If $z_1<u^*$, $z_2>K^*$, the new equations obey Eq. (35).

According to Eqs. (36) and (37), the final solutions will be gotten by the same method as Nash Equilibrium. In this paper, optimization is involved in the process of game. As for non-thermal loads, considering the good performance in continuous optimization and global optimization, the PSO (Particle Swarm Optimization) algorithm is used in the solution process. Compared with other intelligent optimization techniques, the PSO algorithm has the simple structure and few parameters and doesn't need any gradient information of constraints, so the PSO algorithm can achieve suitable solutions. As for thermal loads, due to the discrete 0-1 variables, the thermal loads optimization has more constraints than the non-thermal loads. While the pruning algorithm proposed in [8] can easily solve the optimization problem with optimality, robustness, speed and flexibility. Therefore method mentioned in paper [8] is utilized to optimize the thermal loads.

3.5 The interaction strategy

The model and the solution method has been proposed in the sections above. The concrete implementation procedure is composed of the overall strategy of the interaction and the strategy of the battery, the final implementation procedure is shown in the following parts.

The interaction can be regarded as a game, in which the electric company makes the price by the final solution and the users optimize their loads based on the price. Thus, the interaction strategy can be described as following.

(a) Divide the set of the values of the electric company's decision variable into several areas and select one of them as the initial price.
(b) Optimize the users' loads based on the price
(c) Calculate the line loss of the electric company based on the results of optimization
(d) Repeat step (b) and (c) until all the areas are selected.
(e) Calculate the Nash Equilibrium by the method in Section 3.3.
(f) Select an area of the set of the price as the initial

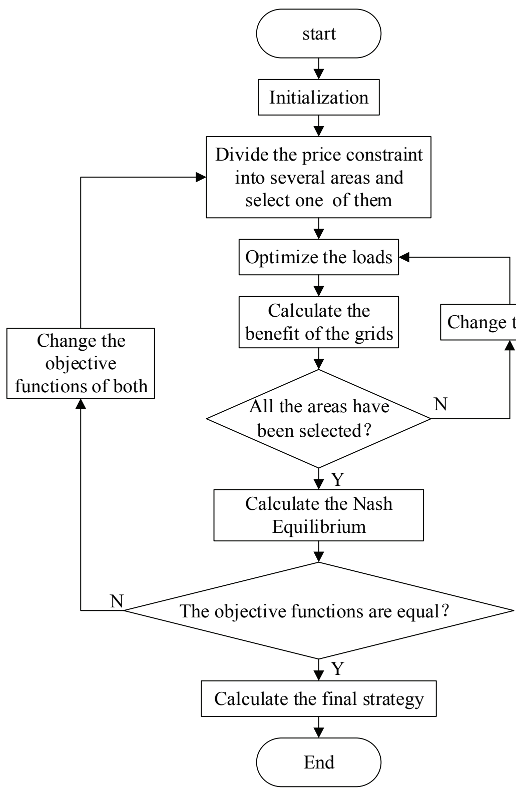

Fig. 2. Process of the overall strategy

price.

(g) Optimize the users' loads based on the price.

(h) Calculate $z_{2,T}$ in Eq. (37) based on the optimization.

(i) Change the area and repeat step (g) and (h) until all the areas are selected.

(j) Calculate the final solution by the method in Section 3.3.

(k) According to random number table method, change the mixed strategy into pure strategy.

(l) According to the price, calculate the users' strategy.

The process is shown in Fig. 2.

Moreover, in the process of the interaction, the optimization of the battery is of necessity. Therefore the strategy of the battery is shown in the following part.

The battery plays an important role in the interaction between the electric company and the users. It is assumed that the battery carries three states. 1 represents charging, -1 represents discharging and 0 represents no action. Then, the strategy can be described as following.

(a) Compare the power of PV and the users' consumption. If the former is larger than the latter, go to step (b) Otherwise, go to step (c).

(b) If the battery reaches maximum state of charge, the state is 0, otherwise, the state is 1.

(c) If the battery reaches minimum state of charge, the state is 0, otherwise, go to step (e).

(d) If the price is the peak price, the state is 1, otherwise, the state is -1.

(e) If it is the last time step, end the process, otherwise, move on to the next time step, read the data of the PV, loads and price and go to step (b).

4. Simulation Results

4.1 Simulation design

Take a residential area for example. It is assumed that there are 200 residential users and 100 of them participate in the interaction. From 6:00 to 22:00, according to the TOU price in some cities in China, the peak price is 0.6 yuan/kWh and the valley price during the period (22:00 to 24:00) is between 0.25 yuan/kW*h and 0.35 yuan/kWh. In this section, the valley price takes the value of 0.3 yuan/kWh. According to distribution technical manual, the power factor is 0.9, and the resistance is 10Ω. Simulation step is 5 minutes. The loads of the users in this study obey the uniform distribution. The mean value is equal to the value before optimization and the standard deviation is equal to 0.1 of the mean value.

Based on the real data of a typical house in Tianjin Province, we set the parameters of the devices in this system as follows. The power curve of the PV array is shown as Fig. 3.

And the active power of the non-thermal loads before optimization is shown in Fig. 4. Before optimization, the power of non-thermal loads is assumed to be distributed uniformly between 0.8 and 1.2 times as much as the power shown in Fig. 4. In addition, the demand of hot water for each house is shown in Fig. 5.

According to reference [22], the power of the water heater is 1kW. For other parameters of the water heater, $Q = 400$, $R = 0.7623$, $C = 431.7012$ and $M = 189.25$.

As the targets of the players are not the same, the Nash Equilibrium is not the optimal solution. To get the optimal solution, cooperative game is a necessity. Change the players' objective functions to make them get agreements as Eqs. (36) and (37) and get the optimal solution.

4.2 Simulation results

The final solution contains the power of the non-thermal

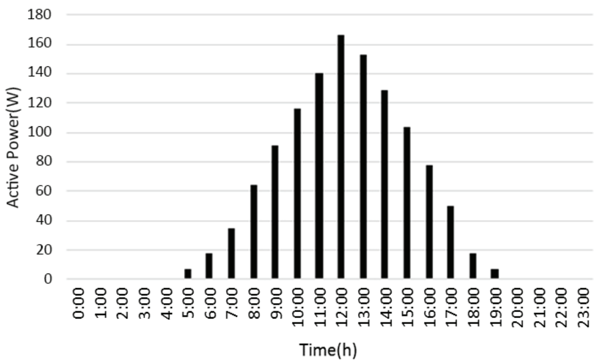

Fig. 3. Power of the photovoltaic array

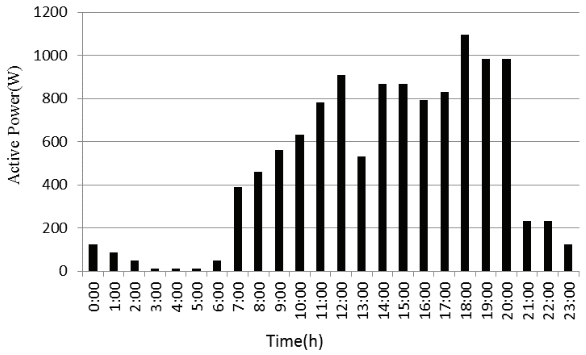

Fig. 4. Active power of non-thermal loads

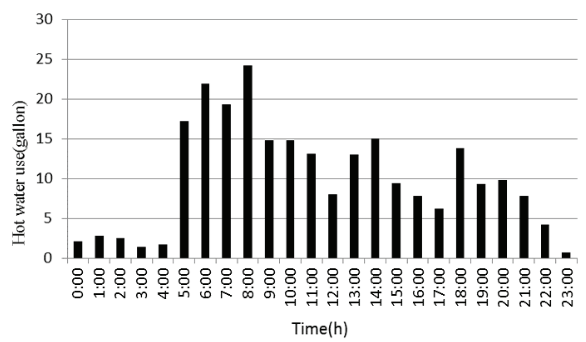

Fig. 5. Demand of hot water

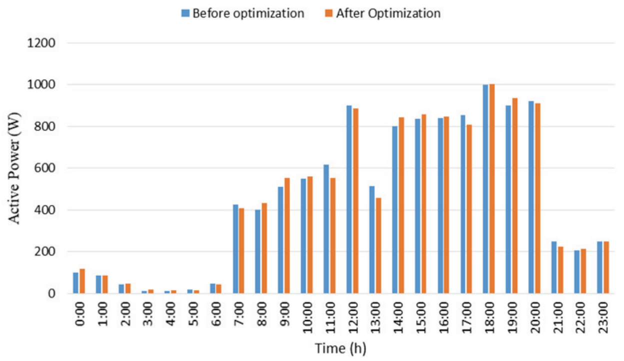

Fig. 6. Active power of non-thermal loads before and after optimization

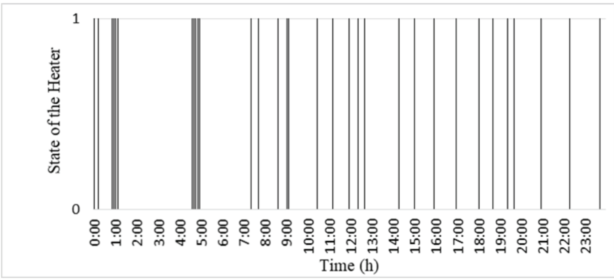

Fig. 7. The state of the thermal loads before optimization

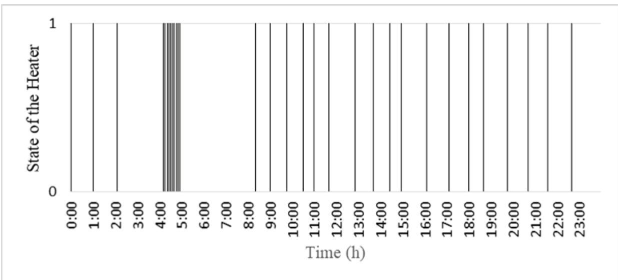

Fig. 8. The state of the thermal loads after optimization

loads, the switch state of thermal loads and the electricity price. The values of the users and electric company's objective functions can be calculated based on the results.

The power of non-thermal loads before and after optimization is shown in Fig. 6.

From Fig. 6, there is no significant law in the power consumption result before and after optimization. That means the non-thermal loads do not play a key role in the interaction. The state of the thermal loads before optimization is drawn in Fig. 7. And the state of the thermal loads after optimization is drawn in Fig. 8.

Compared with Fig. 7, the thermal loads are transferred to the time slots during which the electricity price is low. So this optimal schedule is positive for the saving the users' electric bill.

The users and electric company's objective functions values before and after optimization are shown in Table 1.

Compared with the results before optimization shown in

Table 1. The users' and electric company's objective functions values before and after optimization

	After optimization	Before optimization
Valley price (Yuan/kW*h)	0.28	0.30
Peak price(Yuan/kW*h)	0.62	0.61
The average value of the cost of Users participating in the interaction(Yuan)	8.36	9.39
The average value of the cost of the other users(Yuan)	9.48	9.53
Electric company's benefit(Yuan)	456.23	432.25

the results, the loads after optimization has been transferred to the valley time slots and the users' cost of the participating group and the other group have decreased by 11% and 0.5%. The electric company's benefit has increased by 5.6%. Unlike thermal loads, the non-thermal loads have transferred less. That is to say, the thermal loads plays a key role in the interaction.

It can be found that the drop of the users' and electric company objective functions lie in two main reasons. Firstly, the objective functions of the players are related. Secondly, the corporative game leads to a solution which is better than the Nash Equilibrium.

According to Table I, the gap between the peak price and the value price after optimization is larger than that before optimization and the electric company gets a better objective function value. The load shifting and the utilization of PV may lead to such phenomenon. The rise of the gap may lead the user be more willing to participating in the interaction. According to Fig. 5 and Fig. 6, the users' loads are mainly transferred to the valley time slots.

5. Conclusion

This paper illustrates a strategy to solve the interaction between residential users and an electric company to decrease the users' cost and increase the electric company's benefits. In this paper, the model based on game theory is built and solved by optimization algorithms. The model and algorithm proposed in this paper are characterized by the following features:

(a) The algorithm in this paper is composed of two optimization algorithms, PSO and pruning. The PSO is utilized to deal the non-thermal loads and the pruning method is used to solve the thermal loads schedule.
(b) Game theory is introduced into this model and the electric company and residents are regarded as players in the game. Corporative game is utilized in this model to get the win-win situation.
(c) The non-thermal loads seem inferior potential in the interaction, while the thermal loads are more easily shifted into the time slots with low electricity price. Thus compared with non-thermal loads, the thermal

loads are more powerful in the areas of interaction with the electric company.

(d) Before optimization, the loads of the residents are out of order with poor schedule, and electricity prices go against improving the revenue for the electric company. After optimization, the loads turn into a condition with lower costs for the residents (decreased by 11%) and higher income for the electric company (raised by 5.6%). That is to say, the model is able to increase both the electric company and the residents' benefits.

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