Peer-to-Peer Trading Among Prosumers Based on Cooperative Game

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Abstract. With the massive access to renewable energy and the change in power system operation, users change from traditional energy consumers to prosumers with electricity production/consumption. In this context, we introduce the cooperative game into peer-to-peer (P2P) trading of prosumers to achieve optimal energy management and rational benefit distribution. Firstly, a P2P trading model is established based on cooperative game for prosumers. Secondly, the alternating direction multiplier method (ADMM) is adopted to realize P2P trading in a distributed manner. Finally, Shapley value method is used to allocate the profit of prosumers. The simulation analysis of three prosumers verifies the effectiveness of the P2P trading and proves that the proposed model can effectively reduce the cost of prosumers.

Keywords: Prosumer · Peer-to-peer · ADMM · Cooperative game

1 Introduction

Nowadays, in the context of a large number of distributed energy access and the development of the electricity market, more and more energy consumers are gradually transforming into prosumers that take into account both electricity production and consumption [1]. Prosumers generally consist of distributed renewable energy, heating, ventilation, air conditioning (HVAC) systems, battery energy storage (BES) and other resources aggregated, with dual attributes of electrical source and load, which are notably characterized by a high degree of integration and interaction between electricity and information [2].

At present, domestic and foreign scholars have achieved many research findings in the energy management and market-based trading of prosumers. The energy sharing mechanism is employed to optimize the scheduling of large-scale prosumer groups in References [3, 4]. Reference [5] studies the demand response of prosumers in a centralized trading model. Reference [6] evaluates the centralized power trading between prosumers through "Source-Load-Storage" cooperative scheduling. However, References [3–6] only consider a single interaction between prosumers and the external grid, and

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each prosumer only has energy interaction with main grid, which makes insufficient use of the complementary characteristics and lacks in the optimal utilization of the overall resources.

In fact, since the electricity consumption behavior and patterns of multiple prosumers have good complementary characteristics and interactive nature, the research on the trading strategy of prosumers should not be limited to between prosumers and main grid, but should also gradually move towards energy sharing among prosumers. Cooperative game is currently widely used in the coordination and optimization of prosumers, as it can accurately reflect the characteristics of the interactions between prosumers and effectively promote intelligent decision-making. Reference [7] designs a benefit allocation scheme applicable to a cooperative model with the participation of a large number of prosumers. Reference [8] proposes a leasing model for shared energy storage dynamic capacity based on the cooperative relationship between energy storage systems, where the benefits are distributed using Nash bargaining. Reference [9] coordinates the scheduling of multiple prosumers through the park platform to maximize the economic benefits of the park, and Shapley value is adopted to allocate benefits to each user. References [10, 11] investigate the energy sharing strategy of prosumers based on cooperative game and apply the Shapley value method to allocate the cooperative surplus. However, the adoption of centralized management in the above references requires full mastery of information related to electricity consumption resources of prosumers, which involves the issue of user information security.

These problems can be avoided through peer-to-peer (P2P) trading, which has attracted widespread attention in recent years. Reference [12] designs a decentralized transaction mechanism of prosumers based on P2P mode to reduce the risk of information exposure. Reference [13] proposes a supply demand ratio method for setting intra-park tariffs, which can coordinate generation or consumption users. In recent years, the alternating direction method of multipliers (ADMM) [14, 15], which transmits less information and iterates faster, has been widely used for P2P trading. References [14, 15] apply ADMM to share resources under the premise of ensuring the privacy and security of participating subjects to achieve secure and economic operation of multiple subjects.

Based on previous researches, the distributed transactions between prosumers have been studied a lot, but the profit distribution is not complete. We establish an energy sharing model for prosumers based on the cooperative game with Shapley method, and make a reasonable profit distribution among prosumers. Firstly, the P2P trading model based on cooperative game is established under the premise of energy sharing, then ADMM is used to realize the P2P trading between prosumers to protect the privacy and security of devices. Finally, the profit of prosumers is reasonably allocated according to Shapley value method. On this basis, the effectiveness of the model proposed in this paper is verified through the analysis of three prosumers.

2 A Cooperative Game-Based P2P Trading Model for Prosumers

2.1 Model

In this paper, the P2P trading framework is shown in Fig. 1. Prosumers are connected to the main grid to purchase and sell electricity. The P2P platform is responsible for the P2P transactions between prosumers and the profit distribution. These prosumers contain renewable energy sources, HVAC systems, BESs and basic loads.

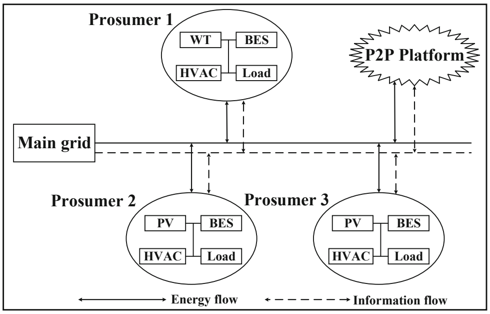

Fig. 1. The framework of P2P trading among prosumers.

When prosumers cooperate with each other, a fair and reasonable benefit distribution scheme is an important factor influencing prosumers to join cooperative alliances. The cooperative game emphasizes collective rationality, and the core problem of the study is how the participating subjects carry out cooperation and distribute the benefits obtained from cooperation. In this paper, the objective function of prosumers is to minimize the total cost, which is described as follows:

$$\min \sum_{n \in N} C_n^{grid} + C_n^{HVAC} + C_n^{bes} \tag{1}$$

In the formula: C_n^{grid}, C_n^{HVAC} and C_n^{bes} are the cost of purchasing power from the grid, the discomfort cost according to HVAC systems and BES degradation cost of prosumer n.

$$\begin{cases} C_n^{grid} = \sum_{t \in T} \lambda_{n,t}^{grid,buy} P_{n,t}^{buy} - \lambda_{n,t}^{grid,sell} P_{n,t}^{sell} \\ C_n^{HVAC} = \sum_{t \in T} \alpha_n (T_{n,t}^{in} - T_n^{ref})^2 \\ C_n^{bes} = \sum_{t \in T} \lambda_n^{bes} (P_{n,t}^{ch} + P_{n,t}^{dis}) \end{cases} \tag{2}$$

In the formula: $\lambda_{n,t}^{grid,buy}$ and $\lambda_{n,t}^{grid,sell}$ are the purchasing price and selling price from the main grid; α_n is the coefficient for the discomfort cost; λ_n^{bes} is the given coefficient for the degradation cost of charging and discharging of BES; $P_{n,t}^{buy}$ and $P_{n,t}^{sell}$ are the purchased power and selling power from the main grid of prosumer n at time t. $T_{n,t}^{in}$ and T_n^{ref} represent the indoor temperature and the comfortable temperature respectively; $P_{n,t}^{ch}$ and $P_{n,t}^{dis}$ are the BES charge and discharge power of prosumer n at time t.

Prosumers also need to satisfy the following operational constraints:

$$0 \leq P_{n,t}^{ch} \leq P_n^{ch,\max} \tag{3}$$

$$0 \leq P_{n,t}^{dis} \leq P_n^{dis,\max} \tag{4}$$

$$S_{n,t}^{bes} = S_{n,t-1}^{bes} + \eta_n^{ch}(P_{n,t}^{ch}) - (P_{n,t}^{dis})/\eta_n^{dis} \tag{5}$$

$$S_n^{bes,\min} \leq S_{n,t}^{bes} \leq S_n^{bes,\max} \tag{6}$$

$$S_{n,T}^{bes} \geq S_{n,0}^{bes} \tag{7}$$

$$T_{n,t}^{in} = (1 - \frac{1}{G_n R_n})T_{n,t-1}^{in} + \frac{1}{G_n R_n}T_{n,t}^{out} - \frac{\eta_n^{HVAC}}{G_n}P_{n,t}^{HVAC} \tag{8}$$

$$T_{n,t}^{in,\min} \leq T_{n,t}^{in} \leq T_{n,t}^{in,\max} \tag{9}$$

$$P_{n,t}^{res} + P_{n,t}^{dis} + P_{n,t}^{buy} = P_{n,t}^{sell} + P_{n,t}^{load} + P_{n,t}^{HVAC} + P_{n,t}^{ch} + \sum_{m \in N \backslash n} P_{n,m,t} \tag{10}$$

$$P_{n,m,t} + P_{m,n,t} = 0 \tag{11}$$

In the formula: $P_n^{ch,\max}$ and $P_n^{dis,\max}$ are the maximum charge and discharge power of BES; $S_{n,t}^{bes}$, $S_n^{bes,\min}$ and $S_n^{bes,\max}$ are the storage capacity, minimum storage capacity and maximum storage capacity; η_n^{ch} and η_n^{dis} are the efficiency of charge power and discharge power; G_n and R_n are the thermal capacity and resistance of HVAC systems; η_n^{HVAC} is the energy conversion efficiency of HVAC systems; $P_{n,t}^{HVAC}$ is the energy consumption of HVAC systems; $T_{n,t}^{in,\min}$ and $T_{n,t}^{in,\max}$ are the minimum and maximum indoor temperature of prosumer n; $P_{n,t}^{res}$ is the renewable energy output of prosumer n at time t; $P_{n,t}^{load}$ is the basic load of prosumer n at time t; $P_{n,m,t}$ is the exchanged power between prosumer n and prosumer m at time t.

2.2 Shapley Value-Based Benefit Allocation Strategy

Shapley value method is an equitable revenue allocation method in cooperative game [16]. In this paper, Shapley value is used to allocate the profit of each prosumer. This method can fully consider the marginal contribution of each prosumer, and the P2P trading gain of prosumer n can be expressed as:

$$x_n = \sum_{\substack{n \in S \\ S \subset N}} \frac{(|S| - 1)!(n - |S|)!}{N!} \cdot M_n \tag{12}$$

$$M_n = v(S) - V(S \backslash \{n\}) \quad n \in S, S \subset N \tag{13}$$

In the formula: M_n indicates the marginal contribution of prosumer n to the alliance S; $|S|$ is the number of prosumers in S; and $|N|$ represents the total number of prosumers in the game. x_n is the profit distributed by prosumer n.

3 ADMM-Based Distribution Scheduling for Prosumers

When multiple subjects collaborate to optimize, important information within each subject cannot be fully shared. A centralized scheduling not only makes it difficult to describe the energy interaction process among subjects, but also poses the risk of privacy leakage. In this paper, we adopt ADMM to decouple the coupling between prosumers and obtain the optimal energy interaction value through iterative interaction.

To address the coupling constraint Eq. (11), we reformulate it in the following standard ADMM form by introducing an auxiliary variable $\hat{P}_{n,m,t}$.

$$P_{n,m,t} = \hat{P}_{n,m,t} \tag{14}$$

$$\hat{P}_{n,m,t} + \hat{P}_{m,n,t} = 0 \tag{15}$$

Then we establish the augmented Lagrangian for the problem as follows:

$$F = \sum_n \left\{ C_n^{grid} + C_n^{HVAC} + C_n^{bes} + \sum_{m \neq n} \sum_t \begin{bmatrix} \lambda_{n,m,t}(P_{n,m,t} - \hat{P}_{n,m,t}) \\ +\frac{\tau}{2}(P_{n,m,t} - \hat{P}_{n,m,t})^2 \end{bmatrix} \right\} \tag{16}$$

In the formula: $\lambda_{n,m,t}$ is the dual variable and τ is the penalty parameter.

The ADMM solution contains three steps. The first step is prosumer n updating its own scheduling policy in the $k + 1$ iteration:

$$\begin{aligned} &\min \left\{ C_n^{grid} + C_n^{HVAC} + C_n^{bes} + \sum_{m \neq n} \sum_t \begin{bmatrix} \lambda_{n,m,t}^k(P_{n,m,t} - \hat{P}_{n,m,t}^k) \\ +\frac{\tau}{2}(P_{n,m,t} - \hat{P}_{n,m,t}^k)^2 \end{bmatrix} \right\} \\ &s.t. \ (3) - (10) \end{aligned} \tag{17}$$

The second step is P2P platform updating the auxiliary variable in the $k+1$iteration:

$$\min \sum_{n\in N}\sum_{m\neq n}\sum_{t}\left[\lambda_{n,m,t}^{k}(P_{n,m,t}^{k+1}-\hat{P}_{n,m,t})+\frac{\tau}{2}(P_{n,m,t}^{k+1}-\hat{P}_{n,m,t})^{2}\right] \tag{18}$$

$s.t.(16)$

The third step is P2P platform updating the dual variable in the $k+1$iteration:

$$\lambda_{n,m,t}^{k+1}=\lambda_{n,m,t}^{k}+\tau(P_{n,m,t}^{k+1}-\hat{P}_{n,m,t}^{k+1}) \tag{19}$$

The convergence criteria of the model are that the primal residuals and dual residuals are less than the thresholds.

$$r_{n,m,t}^{k+1}=\left\|P_{n,m,t}^{k+1}-\hat{P}_{n,m,t}^{k+1}\right\|\leq\varepsilon_{r} \tag{20}$$

$$s_{n,m,t}^{k+1}=\left\|P_{n,m,t}^{k+1}-P_{n,m,t}^{k}\right\|\leq\varepsilon_{s} \tag{21}$$

The specific flow of the proposed solution is shown in Algorithm 1.

Algorithm 1
1: Initialize $k=1$, $\tau=0.01$, $\lambda_{n,m,t}=0$;
2: **repeat**
3: Each prosumer updates its schedule by (18);
4: Update axillary variables by (19);
5: Update dual variables by (20);
6: $k=k+1$;
7: **until** $\boldsymbol{r}(k+1)<\varepsilon_{r}$ and $\boldsymbol{s}(k+1)<\varepsilon_{s}$
8: Distribute profits of prosumers according to (12);
9: Output results: scheduling strategies

4 Example Analysis

4.1 Model Parameters

In this paper, simulation tests are performed on the three prosumers shown in Fig. 1. These prosumers contain renewable energy sources, HVAC systems, BESs and basic loads. Prosumer 1 is equipped with wind turbine, and Prosumers 2 and 3 are equipped with PV. The HVAC system parameters are given as follows: $G_n=1.5$kWh/°C, $R_n=1.33$°C/ kWh and $\eta_n=0.15$. The indoor comfort temperature is set at 20–25 °C for all prosumers. The maximum charge and discharge power of BES is 20 kW and the storage level is limited to [20, 120] kWh. The ADMM penalty parameters is set as 0.001 and the criterion for convergence of primal and dual residuals is set as 0.01 (Fig. 2).

4.2 Result Analysis

Figures 3 and 4 illustrate the energy trading profiles of prosumers with the main grid without P2P trading and with P2P trading. Note that a positive power indicates that prosumers purchase electricity from the main grid; otherwise, they sell electricity. Without P2P trading, prosumers purchase energy directly from the main grid for energy shortages and sell energy to the main grid for energy surpluses, and prosumers interact relatively frequently with the main grid. It can be seen from Fig. 4 that with P2P trading, prosumers significantly reduce the amount of electricity exchanged with the main grid. The comparison results show that the proposed approach can lessen the energy dependency of prosumers on the main grid.

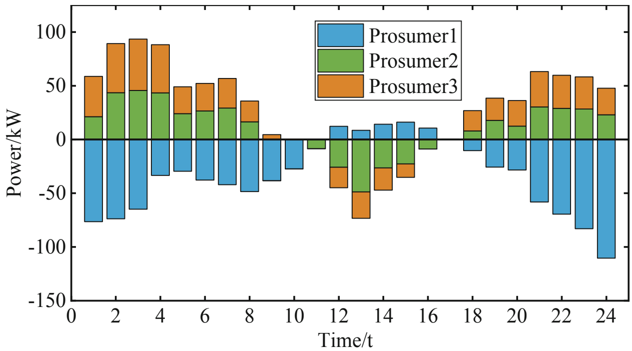

Fig. 2. Profiles of energy trading with the main grid without P2P trading.

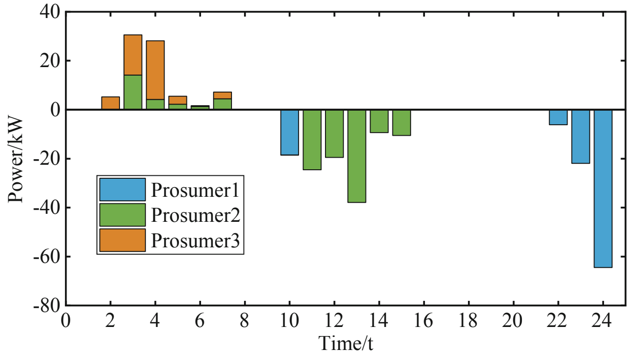

Fig. 3. Profiles of energy trading with the main grid with P2P trading.

Figure 4 shows the energy flow profile of P2P trading between prosumers. Combined with Fig. 3, when there is a shortage or surplus of energy, prosumers prefer to trade energy with neighboring prosumers to meet energy balance. Prosumer 1, which is equipped with wind turbine, generates high levels of wind power in the early morning and evening, and transmits energy to Prosumers 2 and 3 after meeting its own demand for electricity.

During daytime hours, Prosumer 1 chooses to purchase electricity from Prosumers 2 and 3 to make up the energy deficit.

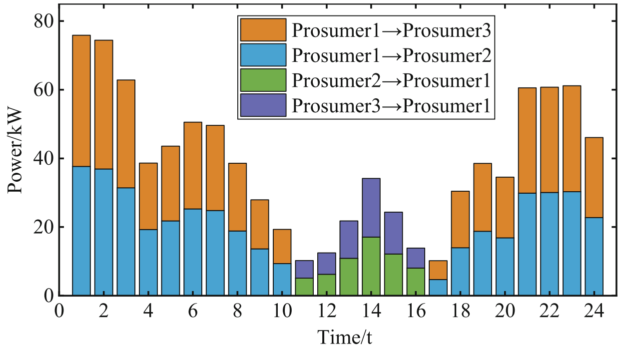

Fig. 4. Energy flow profile of P2P trading.

In this paper, Prosumers 1, 2 and 3 are taken as participants in the cooperative game and are numbered from 1 to 3 respectively. There are 7 sub-alliances in the game, which is shown in Table 1.

In order to verify the economic benefits of P2P trading, Table 2 shows the cost comparison between prosumers participating in P2P trading and those not participating in P2P trading. It can be found that P2P energy sharing reduces the operating costs of participating prosumers, where Prosumer 1 makes the highest profit for its contributing the most renewable energy to the P2P trading.

Table 1. Prosumer portfolio income.

Serial number	S	Portfolio income/$	Serial number	S	Portfolio income/$
1	{1}	95.3	5	{1, 3}	−24.8
2	{2}	−156.4	6	{2, 3}	−368.0
3	{3}	−212.8	7	{1, 2, 3}	−130.4
4	{1, 2}	24.6			

Table 2. Cost comparison with and without P2P.

	Prosumer1	Prosumer2	Prosumer3
Cost without P2P energy sharing/$	−95.3	156.4	212.8
Cost with P2P energy sharing/$	−172.5	124.9	178.0
Cost reduction/$	77.2	31.5	34.8

A schematic diagram of the convergence of primal and dual residuals of the model is given in Fig. 5. We observe from Fig. 5 that the ADMM algorithm takes 37 iterations to converge and the running time is in 50 s. So the model is verified to have good convergence.

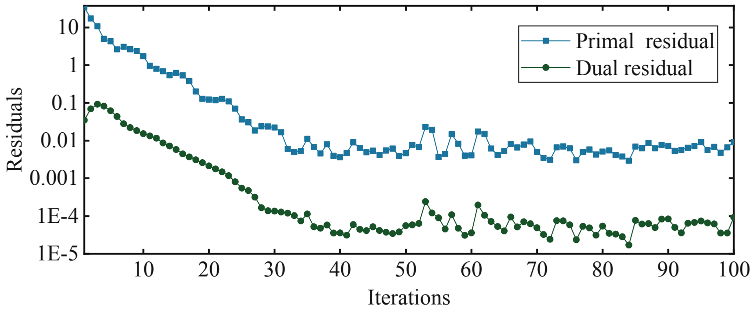

Fig. 5. Convergence of primal and dual residuals.

5 Conclusion

In this paper, a P2P trading model based on cooperative game for prosumers is established. The model is solved in a distributed manner based on the ADMM algorithm, and the profit is allocated to the prosumers according to Shapley value method. The simulation test shows that the P2P trading between prosumers can reduce the cost of electricity, and the distribution of the cooperative surplus based on Shapley value method is reasonable, which is conducive to stable cooperation. The proposed model, which is solved in a distributed solution, protects the internal equipment privacy of each prosumer in the P2P transaction, and the model converges well.

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