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A game theoretic approach for peer to peer energy trading

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Abstract

In a community Microgrid where peer to peer (P2P) energy trading is carried out, many prosumers have conflicting interests. It is difficult for individual prosumers to capture the conflicting interests in the decision-making process (e.g. control of individual batteries). It is also difficult to motivate prosumers to cooperate for achieving the goals of P2P trading. This work proposed a P2P trading mechanism and modeled the decision-making process using the game theoretic approach and Shapley value. The game theoretic approach delivered distributed energy management solutions for individuals in the trading process considering both optimality and fairness among prosumers. The trading mechanism using Shapley value was compared with previous algorithms for P2P energy trading, e.g. bill sharing (BS), mid-market rate (MMR) and supply demand ratio (SDR). Simulation results illustrated the effectiveness of the proposed method. Optimality and fairness for P2P energy trading were significantly improved.

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Keywords: Peer to peer energy trading, game theory, Shapley value, fairness

1. Introduction

The integration of distributed generators (DGs) into electrical power systems is being widely promoted by countries in the world [1]. Many energy consumers are now becoming prosumers, i.e. both producers and consumers of electricity. Peer-to-peer (P2P) energy trading is being considered as an effective method to manage the distributed energy resources (DERs) in community Microgrids, and provide regional market solutions. P2P energy trading describes energy trade between prosumers, or between prosumers and consumers, where the excess electricity from

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prosumers is shared among neighbors [2]-[5].

In a community Microgrid where P2P energy trading is carried out, there are many prosumers with conflicting interests. It is difficult for individual prosumers to capture the conflicting interests in the decision-making process (e.g. control of individual batteries). It is also difficult to motivate prosumer to cooperate for achieving the goals for P2P trading. In this context, many studies worked on designing mechanisms for P2P energy trading [6]-[14].

The P2P trading mechanisms are divided into three categories: auction model (e.g. [6], [7]), multi-agent model (e.g. [4], [8]), and analytical model (e.g. [9]-[14]). For example, an auction based local energy market was proposed in [6] to allow prosumers to trade their energy with each other in a grid-connected Microgrid. A learning mechanism based on 1-D recursive least squares was used to estimate the spot price and demand level for the energy bidding or offering in the auction platform. A multiagent-based model was used in [8]. A competitive local market was created, where the lumped load was supplied with the lowest price due to the competitive behaviour of the DER owners. An analytical model refers to pricing the electricity from DERs in a local market based on certain rules, calculation methods or game theoretic approaches. For example, a supply demand ratio (SDR) method was used to define the internal pricing in a Microgrid in [9]. This allows prosumers to carry out an internal price-based demand response. A mid-market rate (MMR) based P2P energy sharing models was proposed in [10], but the flexibility in DERs were not considered. The game theoretic approach was also adopted for P2P energy sharing in [11]-[14].

Many of these studies in [6]-[14] were either not able to ensure individual prosumers be better off, or not fair to prosumers for their contributions to the community (e.g. contribution to energy cost savings). Therefore, it is required to model the decision-making process of each participant with considerations of both optimality and fairness. In this work, the game theory and Shapley value is used to model the trading mechanism and the decision making process of prosumers. This delivered a distributed energy management solution for individuals in the P2P trading process considering both optimality and fairness among prosumers.

2. P2P energy trading

With the traditional peer-to-grid (P2G) energy trading, a photovoltaic (PV) battery system in a premises is managed from an individual prosumer's perspective, through maximizing the self-consumption of the prosumer's own generation. This is because the retail supplier normally offers a lower export tariff than the supplier charges for buying electricity. At the time when there is insufficient energy from the PV battery system, the prosumer buys energy from the supplier, and when there is excess energy, the surplus is sold to the same supplier.

In a community Microgrid several customers share the connection to the main grid. The combined load is subject to random coincidence of the individual loads, which averages stochastic fluctuations [15]-[17]. This means that surplus PV power from a customer can be consumed by another customer with excess consumption. If a group of prosumers cooperate with each other, it is possible to minimize the total group energy cost. Therefore, P2P energy trading provides options for prosumers to trade energy within the neighborhood through local buying and selling, allowing local funds to remain within the local economy [18].

Fig. 1 shows the architecture of P2P energy trading. There are N prosumers in the P2P sharing community. Each prosumer has an individual PV battery system installed.

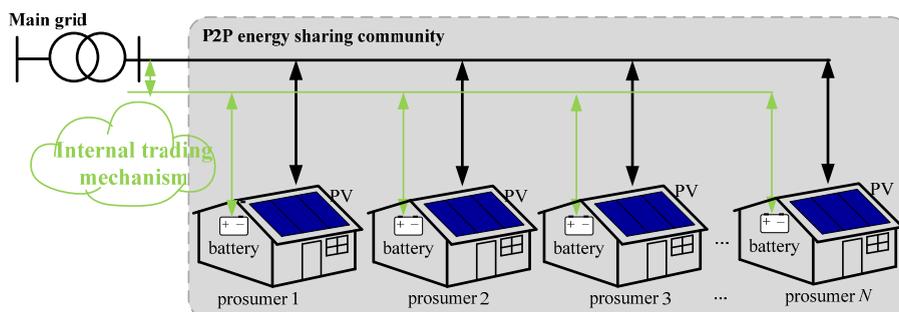


Fig. 1. P2P energy sharing structure in a community Microgrid

3. System model

The P2P energy trading in a community Microgrid is considered as a cooperative game using the game theory. Let $\mathcal{N} = \{1,2,3, \dots, N\}$ denote the set of prosumers (players) in the community, with an integer number $i \in \mathcal{N}$ and $N \triangleq |\mathcal{N}|$. Let $\mathcal{T} = \{1,2,3, \dots, T\}$ denote the operation time period to be considered, with a time slot $t \in \mathcal{T}$ and $T \triangleq |\mathcal{T}|$. The time interval between two time steps is Δt . We define the following vectors for each time slot t :

- NP_i is the net load of prosumer i without considering battery. NP_i is positive for energy consumption, and negative for generation. [kWh]
- λ_{buy} is electricity buy price (i.e. price of electricity bought from the supplier). [\pounds/kWh]
- λ_{sell} is electricity sell price (i.e. export tariff, price of electricity sold to the supplier). [\pounds/kWh]
- b_i is the electricity bill or income of prosumer i . b_i is positive for the amount of money to pay, and negative for the amount of money to be repaid (i.e. income to receive). [\pounds]
- x_i is the energy from batteries of prosumer i . x_i is positive for battery charge and negative for battery discharge. x_i is the variable to be determined in the decision-making process under P2P trading. [kWh]

The methodology is structured as follows (as seen in Fig. 2). Firstly, the value of energy coalition is calculated. This process evaluates all the financial benefits for all the possible coalitions (groups of prosumers). The net load of individual players (including the player’s batteries) and the electricity prices for trading with the supplier are the inputs for the calculation of the coalition. Then, the Shapley value is used to allocate the energy bill/income of individual prosumers. This process provides a fair distribution of the sharing benefits. In the sequence, a constrained nonlinear programming (CNLP) optimization is executed. This results in an optimal operation of individual batteries. Then, the whole process iterates until the results converge. Finally, an optimal operation of individual batteries is obtained.

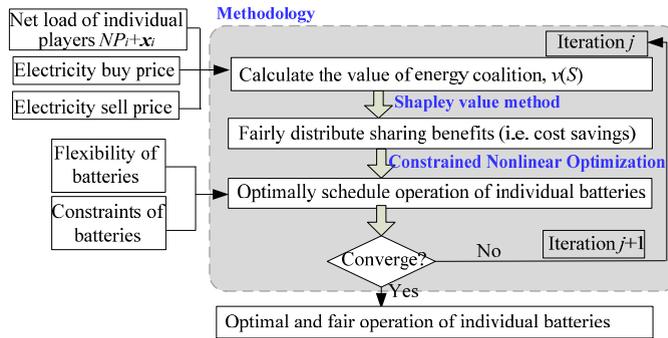


Fig. 2. Structure of the methodology

3.1. Coalition and value of energy coalition

For each coalition $\mathcal{S} \subseteq \mathcal{N}$, a value function is specified representing the value of \mathcal{S} . The value of \mathcal{S} is the energy payment or income of the coalitions \mathcal{S} when the coalition trades with the supplier. The value function of energy coalition \mathcal{S} is calculated by

$$v(\mathcal{S})^t = \lambda_{grid}^t * \sum_{i=1}^{|\mathcal{S}|} (NP_i^t + x_i^t) \tag{1}$$

where $\sum_{i=1}^{|\mathcal{S}|} (NP_i^t + x_i^t)$ is the total net load of coalition \mathcal{S} . For the first iteration (i.e. $j = 1$), it is assumed that there is no energy provided by the batteries, i.e. $x_i^t = \mathbf{0}$. $|\mathcal{S}|$ is the total number of prosumers in the coalition \mathcal{S} . λ_{grid} is the electricity price for trading with the supplier, and λ_{grid} is presented by

$$\lambda_{grid}^t = \begin{cases} \lambda_{buy}^t & \text{when } \sum_{i=1}^{|\mathcal{S}|} (NP_i^t + x_i^t) > 0 \\ \lambda_{sell}^t & \text{when } \sum_{i=1}^{|\mathcal{S}|} (NP_i^t + x_i^t) < 0 \end{cases} \tag{2}$$

3.2. Shapley value

The Shapley value is considered as a fair method to allocate resources for a cooperative game. The Shapley value is used to allocate the energy bill or income of individual customers. This allocation is conducted by considering the marginal contributions of individual prosumers. Here, the Shapley value of a cooperative game is given by

$$b_i^t = \frac{1}{N!} \sum_{S \subseteq N \setminus \{i\}} |S|! (N - |S| - 1)! [v(S \cup \{i\})^t - v(S)^t] \tag{3}$$

where b_i^t is the energy bill or income of prosumer i at time slot t . $S \subseteq N \setminus \{i\}$ is a coalition without prosumer i . $(S \cup \{i\})$ is a coalition of S and prosumer i . Equation (3) represents the marginal contribution of prosumer i , i.e. the average of the difference in the values of coalition between coalitions of S with and without prosumer i .

With the energy bill or income of each prosumer calculated by Equation (3), the average internal selling price (ϕ_{sell}^t) and buying price (ϕ_{buy}^t) between prosumers can be calculated by

$$\phi_{inter}^t = \begin{cases} \phi_{sell}^t = \frac{\sum_{i=1}^g b_i^t * |G_i^t|}{|\sum_{i=1}^g G_i^t|} & i \in \mathcal{G} \\ \phi_{buy}^t = \frac{\sum_{i=1}^l b_i^t * L_i^t}{\sum_{i=1}^l L_i^t} & i \in \mathcal{L} \end{cases} \tag{4}$$

where $\mathcal{G} = \{G_1^t, G_2^t, G_3^t, \dots, G_g^t\}$ are the set of prosumers who are energy producers at time slot t . $\mathcal{L} = \{L_1^t, L_2^t, L_3^t, \dots, L_l^t\}$ are the set of prosumers who are energy consumers at time t . g and l are integer numbers. g is the total number of producer prosumers; l is the total number of consumers, and $g + l \leq N$.

3.3. Energy cost minimization

The decision making process is modelled as a CNLP optimization. The control of individual batteries is considered as the decision variable. The optimization objective is to minimize the energy bill or to maximize the income of individual prosumers, and this is presented by

$$[x_i] = \arg \max_{i \in N, x_i} \left\{ - \sum_{t=1}^T |NP_i^t + x_i^t| * \phi_{inter}^t \right\} \tag{5}$$

s.t.

$$\begin{aligned} \phi_{inter}^t &= \begin{cases} \phi_{sell}^t & \text{when } (NP_i^t + x_i^t) < 0 \\ \phi_{buy}^t & \text{when } (NP_i^t + x_i^t) > 0 \end{cases} \\ -P_{i,BD,max}^t * \Delta t &\leq x_i^t \leq P_{i,BC,max}^t * \Delta t \\ SOC_{i,min} &\leq SOC_i^{t=0} + \frac{\sum_{t=1}^t (x_i^t * \eta)}{W_{i,N}} \leq SOC_{i,max} \\ \eta &= \begin{cases} 1/\eta_{BD} & \text{when } x_i^t < 0 \\ \eta_{BC} & \text{when } x_i^t > 0 \end{cases} \end{aligned} \tag{6}$$

where $P_{i,BD,max}^t$ and $P_{i,BC,max}^t$ are the maximum discharge and charge power of the converter of the battery at prosumer i . $SOC_{i,min}$ and $SOC_{i,max}$ are the minimum and maximum state of charge of the battery. η_{BD} and η_{BC} are the battery discharging and charging efficiencies. The techniques used in [19] and [3] were used there to discard the absolute value calculation in the objective function.

3.4. Fairness index

The fairness index measures the fairness of different trading mechanisms. When using the Shapley value to allocate the energy bill/income for prosumers, each user’s share of the cost is completely fair. The distance between normalized billing vector when using any trading mechanism and the normalized billing vector for the Shapley value S_i^* was considered as a fairness index, as presented in Equation (8). This method was previously adopted in reference [20].

$$\mathcal{F} = \sum_{i=1}^N \left| \frac{B_i}{\sum_{i=1}^N B_i} - \frac{S_i^*}{\sum_{i=1}^N S_i^*} \right| \tag{7}$$

where \mathcal{F} is the fairness index. S_i^* is the customer bill or income of prosumer i when using the Shapley value. B_i is the bill or income of prosumer i when using other trading mechanisms. The fairness index measures the fairness of any trading mechanism compared to the Shapley value. It is clear that a lower index \mathcal{F} indicates a fairer billing mechanism.

4. Case study

The proposed methodology was demonstrated on a residential community with PV battery systems. The community Microgrid has 10 prosumers, 5 of which have individual PV battery systems (i.e. $N = 10$). The other 5 households do not have solar PV or batteries, and they are consumers. However, for simplicity we considered they are prosumers with PV and battery capacity of zero. Therefore, the proposed model for prosumers is applicable to all the players in the community. All the solar PV systems were 4 kWp. All the batteries were 4 kWh and the maximum charging and discharging power was 4 kW. Both the charging and discharging efficiencies were 90%. One day of 24 hours with 15-minute resolution was considered. The price of the energy bought from the retail supplier was taken as 0.15 £/kWh and the price at which energy is sold to the grid was 0.05 £/kWh [21].

Fig. 3 shows the daily electricity bill/income of individual prosumers when considering different P2P trading mechanisms, including bill sharing (BS), mid-market rate (MMR), supply demand ratio (SDR), and Shapley value. These trading mechanisms are compared with the P2G trading. It was found that the Shapley value method significantly reduced all the prosumers’ energy bill or increased the prosumers’ income compared to the P2G energy trading. It was also found that, the amount of billings allocated by using Shapley value is between that of using MMR and SDR methods. This is because that the internal buying and selling prices were found between these two methods, as shown in Fig. 4.

The fairness indexes and the energy costs of the community were presented in Fig. 5. The Shapley value method not only provided a fair billing allocation, but also enabled an optimal control of individual control of batteries. Therefore, the total community energy cost when using Shapley value was relative low.

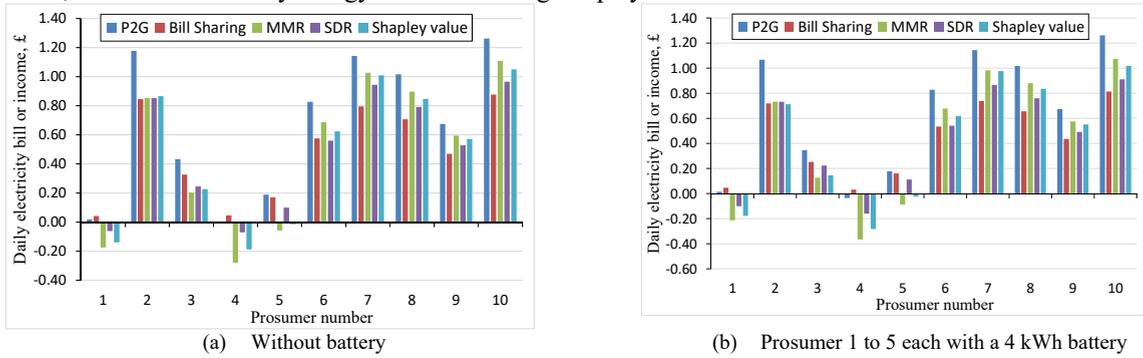


Fig. 3. Daily energy bill or income of individual prosumers (prosumer 1 to 5 each with a 4 kWp solar PV, positive value means electricity bill, and negative value means income)

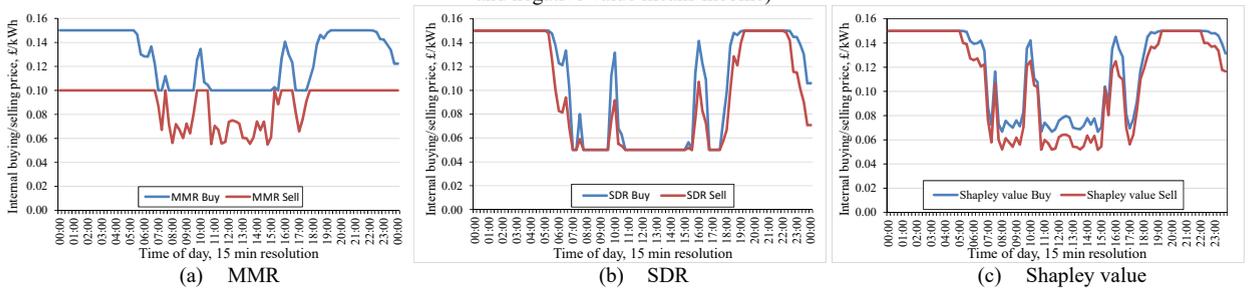


Fig. 4. Internal buying and selling price for every 15 minutes in a day, £/kWh

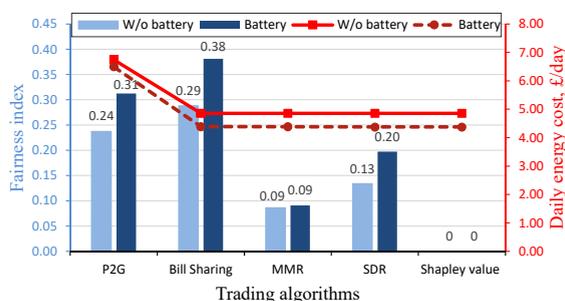


Fig. 5. Fairness indexes (the smaller value, the fairer) and total daily energy cost of the community

4. Conclusions

To capture the conflicting interests between prosumers, and encourage prosumers to cooperate for P2P energy trading in a community Microgrid, this work proposed a P2P trading mechanism and modelled the decision-making process using the game theoretic approach and Shapley value. The optimization model for the control of individual batteries considered control actions of every other individuals. Therefore, the method provided both optimality and fairness for P2P energy trading.

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