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A Bidding System for Peer-to-Peer Energy Trading in a Grid-connected Microgrid

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Abstract

Peer-to-Peer (P2P) energy trading is a novel paradigm of power system operation, where people can generate their own energy from Renewable Energy Sources (RESs) in dwellings, offices and factories, and share it with each other locally. An architecture model was proposed to present the design and interoperability aspects of components for P2P energy trading in a microgrid. A specific Customer-to-Customer business model was introduced in a benchmark grid-connected microgrid based on the architecture model. The core component of a bidding system, called Elecbay, was also proposed and simulated using game theory. Test results show that P2P energy trading is able to balance local generation and demand, therefore, has a potential to enable a large penetration of RESs in the power grid.

Keywords: Peer-to-Peer Energy Trading, Bidding System, Game Theory, Electricity Demand Flexibility, Microgrid

1. Introduction

With the increasing integration of distributed energy resources (DERs), traditional energy consumers will become prosumers, who can both generate and consume energy [1]. Generation of DERs is unpredictable and intermittent, and prosumers who have surplus energy can either store it with energy storage devices, or supply others who are in energy deficit. This energy trading among prosumers is called Peer-to-Peer (P2P) energy trading. It not only contributes to the balance of energy [2], but also reduces congestions on transmission and distribution lines [2] [3].

Although energy trading is mainly based on large-scale transactions at present, trials of small-scale or medium-scale P2P energy trading have already been investigated across the globe, for example, Vandebron in Netherlands [4], Piclo in the UK [5], sonnenCommunity in Germany [6], and "Energy Internet" in China [7].

In this paper, P2P energy trading among prosumers in a grid-connected microgrid is studied. In Section 2, a four-layer architecture model of P2P energy trading is proposed. Section 3 discusses a business model and the design of online trading platform 'Elecbay'. In Section 4, the objectives and game theory method for the simulation of P2P energy trading within the microgrid are presented. A case study in Section 5 is presented and the benefits of using the P2P energy trading are analyzed.

2. Four-Layer Architecture Model of Peer-to-Peer Energy Trading

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A Smart Grid (SG) is an electricity network that can intelligently integrate the actions of all users connected to it (generators, consumers and those that do both) in order to efficiently deliver sustainable, economic and secure electricity supplies. It employs innovative products and services together with intelligent monitoring, control, communication and self-healing technologies[2]. P2P energy trading cannot be implemented without the SG technologies including Information and Communication Technologies (ICT), monitoring, and control functions.

It is critical and quite challenging to define a standardized architecture of P2P energy trading which consolidates complicated technologies and infrastructures. A Smart Grid Architecture Model (SGAM) Framework [8] was proposed by CEN, CENELEC, and ETSI to enable European Standardization Organizations to perform continuous standard enhancement and development in the field of Smart Grids. Based on the SGAM, a 4-layer architecture model of P2P energy trading is designed in Fig. 1.

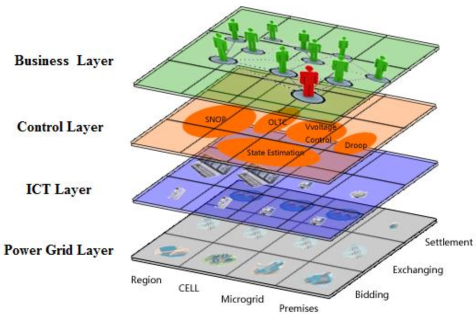


Fig. 1. Four-Layer Architecture Model of Peer-to-Peer Energy Trading

Layers	Components
Power Grid Layer	Existing power grid with DGs, flexible loads, storage, EVs, etc
ICT Layer	Communication network and devices, data storage, information flow, etc
Control Layer	Monitoring and control system owned by SO and DNOs, control functions, etc
Business Layer	Participants in local markets, market authorities, trading platforms, etc

Table 1. Components of Each Layer in the Four-Layer Architecture Model of P2P Energy

There are three dimensions in the model. The first dimension is the time-scale of P2P energy trading. Bidding is the first process of trading when energy users (generators, consumers and prosumers) signing contracts with each other prior to real-time energy exchange. Exchanging is the second process, during which energy is generated, transmitted and consumed by users. Settlement is the final process when bills and transactions are finally settled via various payment methods. The second dimension shows the size of the P2P energy trading users, i.e. single premises, microgrids, CELLs, and regions. In the third dimension, the hierarchical process of P2P energy trading is categorized into four interoperability layers for management. The components in each layer are summarized in Table 1.

This paper focuses on the interconnections between the business layer and the power grid layer during the bidding process within a grid-connected microgrid.

3. Peer-to-Peer Business Model

For P2P energy trading in a microgrid, a business model for local markets is required. In recent years, different business models for local supply have been proposed and tested [9], e.g. local white label model, local aggregator model, local pool model, etc. These business models were all designed based on existing business models in large-scale electricity wholesale markets. Therefore, a new business model for local P2P energy trading was proposed based on the eBay-style C2C e-commerce business model and the GB electricity wholesale market [10] [11]. The platform, called “Elecbay”, allows energy users to sign contracts and to make payment with each other. The operational structure of Elecbay is illustrated by Fig. 2. The processing of each order in Elecbay is demonstrated in Fig. 3 [10].

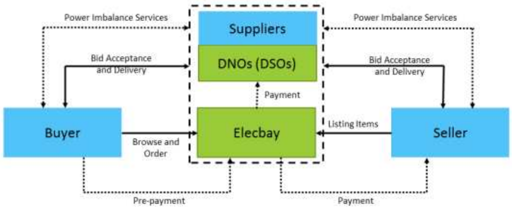


Fig. 2. Operational Structure of Elecbay

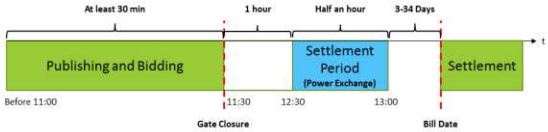


Fig. 3. Processing of Each Order in Elecbay

4. Simulation of Bidding in Elecbay

The objectives of simulating the bidding process amongst users in Elecbay are:

1. To clarify how users in a local market carry out P2P energy trading with each other;
2. To obtain new load profiles of users after the P2P energy trading;
3. To provide a platform for power system analysis of microgrid under P2P energy trading scenarios.

The Elecbay simulation model mimicked the bidding process before gate closure. . All the input data is based on historical and forecast information. Beside, following assumptions were made when developing the model:

1. Uncertainties of generators or demand were not considered;
2. The P2P market is highly competitive, so that the unit price labelled by each user should be very close to each other's. Transaction fee which should be collected by Elecbay is also ignored;
3. Traditional energy suppliers act as passive users in the P2P market, and provide energy with less attractive unit prices. Therefore, they will mainly contribute to maintaining the energy balance.

Since the generation of RESs is uncontrollable, P2P energy trading among prosumers relies on the schedule and control of flexible demand and energy storage. In this paper, only the flexible demand is considered as a first trial.

4.1. Simulation of a single time period using Game Theory

Game theory methodology has been widely used in the study of electricity market. It is a functional tool for modeling the competitions in electricity markets [12] [13] and assessing the performance of network constrained electricity markets [14].

There are two basic types of games in game theory: cooperative game and non-cooperative game. A non-cooperative game is a game in which players make decisions independently [15] and is therefore formulated for the simulation of bidding in Elecbay based on the rules of the market.

To find the most possible biding result of all energy users within the local P2P-based energy market, the Nash equilibrium is a used to solve the non-cooperative game involving two or more players, in which each player is assumed to know the equilibrium strategies of the other players, and no player has anything to gain by changing only their own strategy If each player has chosen a strategy and no player can benefit by changing strategies while the other players keep theirs unchanged, then the current set of strategy and the corresponding payoffs constitutes a Nash equilibrium[15]. A mathematical method for finding Nash equilibrium of a non-cooperative game in MATLAB [16] was used as illustrated below.

Players of the game: Energy users in the market with flexible demand, denoted by $1, 2, \ldots, i, \ldots, n$.

Strategies of the players: the ON/OFF status of the flexible demand owned by each user, denoted by $s_1^i, s_2^i, \ldots, s_j^i, \ldots, s_{mi}^i$.

Strategy combinations: (s_1^{1}, s_1^{2}, ..., s_1^{n}), …, (s_{m1}^{1}, s_{m2}^{2}, ..., s_{mn}^{n}). The total number of strategy combinations is

$$M = \prod_{i=1}^{n} m_i \tag{1}$$

Payoff function:

$$u_k^i = \frac{E_{out-i}}{\left|E_{mgout-k}\right| \times C_k^i} \tag{2}$$

where $k \in [1, M]$; E_{out-i} is the energy output of user i in strategy combination k; $E_{mgout-k}$ is the energy output of the whole microgrid in strategy combination k; C_k^{i} is the cost index of user i in strategy combination k.

For users who own generators that burn fuels, the cost index is in proportion to the cost of fuel that has been burnt. However, for users who trade energy by scheduling the flexible demand, the cost index is related to the user's comfort level. The probability of the flexible demand ON ($p_{Flex-ON}$) is used to represent the value as shown in Fig 4(d)[17]. Then the cost index is defined as:

$$C_k^i = \begin{cases} \dfrac{1}{1 - 2p_{Flex-ON}}, & when\ flexible\ demand\ OFF \\ 1, & when\ flexible\ demand\ ON \end{cases} \tag{3}$$

Therefore, the payoff of a single user in a certain strategy combination is determined by the unit price of electricity supply and the comfort level of the user with flexible demand. The unit price of electricity supply is inversely proportional to the overall energy output of the microgrid. The comfort level of the user depends on the probability of using the flexible demand during the energy exchanging time period.

After calculating the Nash equilibrium in MATLAB, a strategy combination is chosen to be the most possible bidding result of users in the market for a certain energy exchanging time period.

4.2. Simulation of multiple time periods considering the flexibility of demand

When multiple energy exchanging time periods are considered, the strategy chosen by a user for one period has significant influence on the strategies to be chosen for the following periods. That is because the input $p_{Flex-ON}$ changes in each exchanging time period. Two more parameters are used to indicate the different input $p_{Flex-ON}$ for different time periods:

$\Delta p_{Flex-ON-i}$: the change of $p_{Flex-ON}$ after flexible demand of user i was determined to be ON.

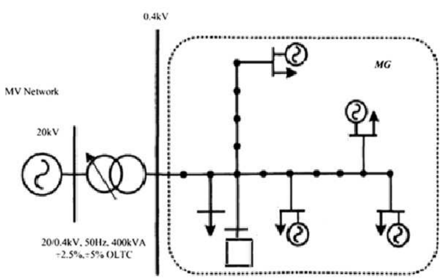
$\Delta p_{Flex-OFF-i}$: the change of $p_{Flex-OFF}$ after flexible demand of user i was determined to be OFF

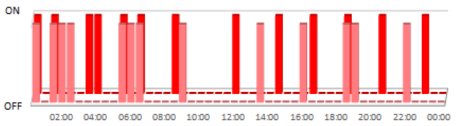
Those two parameters vary based on the type of the flexible demand [17]. For example, electric water heaters depend on the temperature of water while air conditioners depend on the room temperature.

5. Case Study

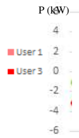
To test the proposed simulation model in Section 4, the European Union Benchmark LV Microgrid Network [2][18] was used, as presented in Fig. 4.

There are totally 10 energy users with electric water heaters. Others are not considered as players in the game. Each home owns PV generators only. The PV generation profiles, load profiles of non-flexible demand, and the probability of turning ON electric water heaters are given in Fig. 4. Other information of energy users' is shown in Table 2.





(a)

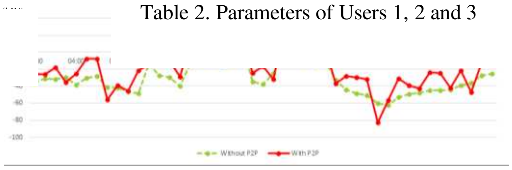


Parameters	User 1	User 2	User 3
P of maximum PV generation	5kW	5kW	5kW
P of maximum flexible demand	3kW	3kW	3kW
P of maximum non-flexible demand	4kW	4kW	4kW

Table 2. Parameters of Users 1, 2 and 3

Fig. 4. European Union Benchmark LV Microgrid Network

(c)



(d)

Fig. 5. (a) ON/OFF Status of Flexible Demand owned by Users; (b) Power Output Comparison of User 1; (c) Power Output of Users with P2P Trading; (d) Overall Power Output of the Microgrid with and without P2P trading

Simulation results are presented in Fig. 5. Fig. 5(a) and Fig. 5(c) show that with P2P energy trading in the microgrid, the flexible demand of energy users with different load profiles, or probability of using the flexibility demand, are scheduled to be ON during different time periods of the day. The flexible demand are less likely to be turned ON or OFF simultaneously.

In Fig 5(b) and Fig 5(d), it can be seen that users try to inject more energy to the microgrid when PVs are generating power. As a result, the overall energy consumption of most users and of the whole microgrid decrease if implementing the P2P energy trading within the microgrid, although there are still the time periods that the peak energy consumption is higher than that without P2P energy trading. This is caused by some energy prosumers that choose the same strategy because of their own benefits. The overall reduction of energy consumption of the whole microgrid illustrates that the P2P energy trading is able to balance the local generation and demands.

6. Conclusion

P2P energy trading is one of the promising paradigms of smart grid in the near future. A four-layer architecture model was proposed to standardise the interactions amongst different technologies for P2P energy trading. An online platform "Elecbay" was designed based on the business model of a local P2P energy trading market within a grid-connected microgrid. To investigate the behaviour of energy prosumers in the new market, and to achieve new load profiles considering P2P energy trading scenarios, a simulation model of the bidding in Elecbay was developed in MATLAB based on the game theory method. Case study shows that P2P energy trading is able to balance local generation and demand, and therefore, has a potential to facilitate a large penetration of RESs in the power grid.

In the future research, power system analysis will be carried out using the load profiles of prosumers obtained in the P2P energy trading market in order to investigate the possible control methods.

Acknowledgements

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