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DEMAND RESPONSE FROM A PEER-TO-PEER ENERGY TRADING COMMUNITY

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ABSTRACT

In order to address the various challenges and well utilize the opportunities brought by the increasing penetration of distributed energy resources at the demand side of power systems, a new paradigm, peer-to-peer (P2P) energy trading, has emerged in recent years, where prosumers and consumers are able to directly trade energy with each other. Besides the inherent potential benefits such as facilitating local power and energy balancing, a P2P energy trading community as a whole also has the potential to provide ancillary services to power systems to create additional value. In this paper, a price-based mechanism was proposed, in which the customers of a P2P energy trading community can further respond to the price signals issued by power utilities to provide ancillary services such as demand reduction and generation curtailment. A continuous double auction with a residual balancing mechanism was proposed as the P2P energy trading mechanism. Simulation results verify that the proposed mechanisms are able to increase the social welfare of the whole P2P energy trading community without compromising any individual's interests, and at the same time incentivize customers to provide ancillary services to power utilities.

Keywords: demand response, peer-to-peer energy trading, continuous double auction, local electricity market, distributed energy resource, microgrid

1. INTRODUCTION

Conventional power systems are highly centralized and unidirectional. In terms of power flow, a vast majority of electricity is generated by centralized large generators, transmitted through transmission networks, and finally distributed to end users. In terms of money flow in deregulated electricity markets, electricity retailers buy electricity in large quantities from the wholesale market and then resell it in small quantities to customers in the retail market. As a result, capital flows from customers to electricity retailers, who further distribute the revenues among transmission system operators (TSOs), distribution network operators (DNOs) and generators.

However, with the rapidly increasing penetration of distributed energy resources (DERs) at the demand side of power systems, conventional centralized and unidirectional paradigms are no longer fit-for-purpose, and innovative technical and market paradigms are needed for addressing the emerging challenges. In this context, peer-to-peer (P2P) energy trading has been proposed and developing fast in recent years for better organizing and managing the customers with DERs.

P2P energy trading enables customers to directly trade energy with each other, and is considered to have the potential to bring a wide range of technical and economic benefits [1], [2]. In academia, an increasing number of studies have been made regarding P2P energy trading from different perspectives, including market design [3], trading platform [4], [5], communication infrastructure [6], social implications [7] and policy making [8]. In practice, a large number of projects have been conducted in many countries of the world, such as the Brooklyn microgrid project in the U.S. [9], the Power Ledger project in Australia [10], the SunContract project in Slovenia [11], etc., trailing and exercising P2P energy trading.

Besides the many inherent potential benefits for the customers who participate, a P2P energy trading

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community as a whole has the potential to provide ancillary services to power systems to create additional value. This is termed by T. Morstyn et al. as ‘federated power plant’, which is ‘a virtual power plant formed through P2P transactions between self-organizing prosumers’, and is considered to ‘address social, institutional and economic issues faced by top-down strategies for coordinating virtual power plants, while unlocking additional value for P2P energy trading’ [12].

Although with the above concept design, no detailed research has been conducted regarding how to realize the demand response (DR) from a P2P energy trading community. Therefore, in this paper, a price-based mechanism was proposed for the customers in a P2P energy trading community to respond to the price signals issued by power utilities to provide ancillary services such as demand/generation increase/reduction. A continuous double auction (CDA) with a residual balancing mechanism was proposed as the P2P energy trading mechanism. A case study in the context of UK was conducted for assessing the performance of the proposed mechanisms.

2. OVERALL FRAMEWORK

The overall framework for demand response from a P2P energy trading community is illustrated in Fig. 1, with the timeline shown in Fig. 2.

P2P energy trading and demand response are conducted for each time slot, but the agreements are made some time slots in advance (called as ‘Agreement Period’). For example, as shown in Fig. 2, for the P2P energy trading and demand response to be executed at *t* (i.e. the purple time slot), the agreements are made T_{ad} ahead, and the Agreement Period is as long as ΔT.

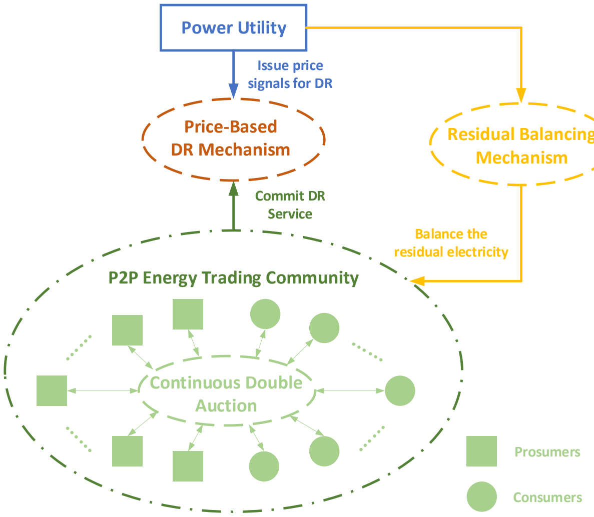

Fig. 1 The overall framework for demand response from a P2P energy trading community

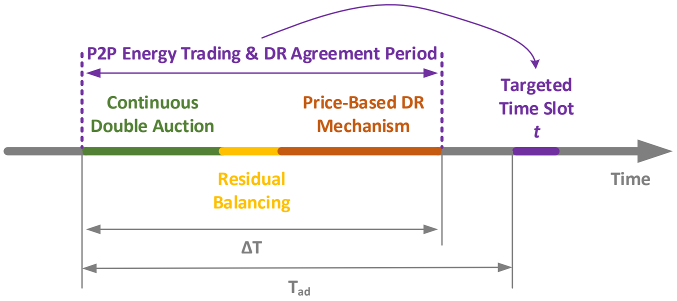

Fig. 2 The timeline of the P2P energy trading and demand response

During the Agreement Period, first of all, the customers (including prosumers and consumers) in the P2P energy trading community participate in the continuous double auction to directly trade surplus electricity with each other. After the time window of continuous double auction ends, the un-traded electricity demand/generation are supplied/purchased by the power utility through the residual balancing mechanism. After the time window of residual balancing ends, the time window for demand response starts, during which the power utility issues the price signals for incentivizing demand response, and the customers in the P2P energy trading community respond correspondingly.

3. CONTINUOUS DOUBLE AUCTION WITH A RESIDUAL BALANCING MECHANISM

A continuous double auction with a residual balancing mechanism was proposed as the mechanism for P2P energy trading between customers.

3.1 Continuous double auction

Continuous double auctions match buyers and sellers who are interested in trading, and are deemed as highly efficient mechanisms. They are widely used in the trading of various types of commodities, such as stocks as well as electricity. The continuous double auction described in [13] was adopted in this paper as a part of the P2P energy trading mechanism.

As presented in Section 2, the continuous double auction is run to decide the energy trading between customers for each time slot in advance. For any targeted time slot *t*, in the corresponding time window in advance, customers submit bids or asks according to their roles being ‘buyers’ (who have electricity deficit at *t*) or ‘sellers’ (who have electricity surplus at *t*). A bid, which is submitted by a buyer, is represented by $o_b(b, \pi_b, \sigma_b, \tau_b)$, which means that the buyer *b* would like to by the σ_b (kWh) amount of energy at the price π_b (£/kWh), and the bid arrives at the ‘exchange’ at the time τ_b. Note that the exchange is a centralized or decentralized platform set for P2P energy trading within the community. Similarly, an ask, which is submitted by a seller is represented by $o_s(s, \pi_s, \sigma_s, \tau_s)$.

Within the time window of the continuous double auction, bids and asks will arrive at the exchange asynchronously. After they arrive, the bids and asks are allocated in an 'order book', where the bids are sorted in the descending order of the bid prices π_b and the asks are sorted in the ascending order of the ask prices π_s. For both bids and asks, if several ones have the same prices, they are sorted based on the arrival time - the later a bid/ask arrives, the lower it ranks.

Every time a bid/ask arrives, it will be allocated in the order book based on the above-described principles, and then the exchange will try to match the bids and asks in the order book. If the following relationship is satisfied for a bid o_b and an ask o_s:

$$\pi_b \geq \pi_s, \tag{1}$$

then the following amount of electricity will be matched:

$$\sigma_{matched} = \min(\sigma_b, \sigma_s). \tag{2}$$

The trading price for the matched amount of electricity will be decided as

$$\pi_t = \frac{\pi_b + \pi_s}{2}. \tag{3}$$

The bid/ask that is fully matched will be removed from the order book, and the bid/ask that is not fully matched will be updated by

$$o'_b = (b, \pi_b, \sigma'_b, \tau_b) \quad if\ \sigma_b - \sigma_s > 0\ , \tag{4}$$

$$o'_s = (s, \pi_s, \sigma'_s, \tau_s) \quad if\ \sigma_b - \sigma_s < 0\ , \tag{5}$$

where

$$\sigma'_b = \sigma_b - \sigma_s\ , \tag{6}$$

$$\sigma'_s = \sigma_s - \sigma_b\ . \tag{7}$$

The matching process will go from the top to the bottom of the order book, and will end once no matching can be made. The matching process will be triggered every time a new bid/ask arrives. When an amount of demand and generation, σ_{matched} (kWh), is matched at the price π_t (£/kWh), a P2P energy trading agreement, <σ_{matched}, π_t>, is established between the corresponding buyer and seller, specifying the quantity and price to be traded.

3.2 Residual balancing mechanism

After the time window of the continuous double auction ends, it is highly possible that there are still several bids and/or asks in the order book, which are not matched. In [13], the corresponding amount of demand and/or generation will be curtailed. This design raises the risks of demand/generation curtailment for customers, and thus may hinder some of them from participating in the P2P energy trading.

Therefore, in this paper, an alternative residual balancing mechanism is proposed, in which the electricity demand in the un-matched bids is set to be fully supplied by the power utility at the retail price p_{retail} (£/kWh), and the generation in the un-matched asks is set to be fully purchased by the power utility at the Feed-in Tariff (FiT) rate p_{FiT} (£/kWh).

4. PRICE-BASED DEMAND RESPONSE MECHANISM

After the time windows of continuous double auction and residual balancing end, the agreement results of P2P energy trading have been fixed, and these results will be sent to the power utility as the basis for it to assess its operational schedules and decisions.

Then the power utility may foresee some operational problems such as over voltage or congestions in the power networks. Also, the power utility may identify some possible actions that may improve the operational economy and security of the power systems, such as peak shaving. In these situations, the power utility may want to issue price signals during the time window for demand response to incentivize the customers to change their electricity consumption /generation pattern which was decided in the continuous double action.

Specifically, in the designed price-based demand response mechanism, the power utility can issue the amount of demand reduction or generation curtailment, ΔP_{total} (kWh), needed for the time slot t with a remuneration price p_{DR} (£/kWh). Then the customers can decide whether or not and with how much amount to participate, and submit their decisions to the power utility. If a customer j decides to provide ΔP_j (kWh) of demand reduction or generation curtailment, the remuneration it will get from the power utility, $R_{\text{DR},j}$ (£), equals to

$$R_{DR,j} = \Delta P_j \cdot p_{DR}\ . \tag{8}$$

However, if the customer provides demand reduction / generation curtailment, it may breach the P2P energy trading agreements with other customers, which were made in the continuous double auction. In this case, other customers may have to turn to trading with the power utility, possibly resulting in higher electricity bill or lower revenues.

As a result, a customer is required to compensate other customers, if it breaches the P2P energy trading agreement due to the commitment of demand response. Assume that the P2P energy trading agreement breached is <$\sigma_{\text{matched},i}$, $\pi_{t,i}$> and the amount of demand reduction or generation curtailment with regard to this agreement is ΔP_i (kWh). If the demand response committed is demand reduction, the compensation needs to be paid is

$$C_{DR,i} = \Delta P_i \cdot (\pi_{t,i} - p_{FiT}). \tag{9}$$

If the demand response committed is generation curtailment, the compensation needs to be paid is

$$C_{DR,i} = \Delta P_i \cdot (p_{retail} - \pi_{t,i}). \tag{10}$$

Note that in (9) and (10), there are always

$$\pi_{t,i} - p_{FiT} \geq 0, \tag{11}$$

$$p_{retail} - \pi_{t,i} \geq 0, \tag{12}$$

because otherwise the P2P energy trading agreement cannot be reached at the very beginning (i.e. otherwise the customer will trade with the power utility rather than other customers).

Also note that if the demand reduced or generation curtailed is from/to the power utility, no compensation needs to be made to the power utility, because this somehow help reduce the burden of the power utility in terms of residual balancing.

Finally, it is specified that, if the total amount of demand response exceeds the need of the power utility, ΔP_{total}, the power utility just accepts the ones which are submitted earlier.

5. OPTIMAL BIDDING STRATEGY OF CUSTOMERS

With the P2P energy trading and price-based demand response mechanisms established in Sections 3 and 4, the optimal bidding strategy of the customers under the mechanisms need to be studied, so that the performance and implications of the established mechanisms can be assessed. A reasonable strategy, i.e. the 'profit margin adjustment with zero intelligence plus (ZIP) traders', has been proposed in [13] for the customers to bid in the continuous double auction. Therefore, this paper focuses on the optimal bidding strategy of the customers in the proposed price-based demand response mechanism.

A customer j makes the decision on whether and with how much amount of electricity to participate in demand response by comparing the associated income and cost. The income due to the provision of demand response can be calculated by (8), while the associated cost is calculated by

$$COST_{DR,j} = \sum_{i \in \boldsymbol{I}_{DR,j}} C_{DR,i} + L_{DR,j}, \tag{13}$$

where $\boldsymbol{I}_{DR,j}$ represents the set of P2P energy trading agreements that will be breached if the demand response is committed; $C_{DR,i}$ (£) is the compensation that needs to be made due to the breaches, which is calculated by (9); and $L_{DR,j}$ (£) is equivalent economic loss if the demand response is provided. If the demand response to be provided is generation curtailment, the equivalent economic loss equals to the income from selling electricity otherwise:

$$L_{DR,j} = \sum_{i \in \boldsymbol{I}_{DR,j}} \pi_{t,i} \cdot \Delta P_i + p_{FiT} \cdot \left(\Delta P_j - \sum_{i \in \boldsymbol{I}_{DR,j}} \Delta P_i\right). \tag{14}$$

Recall that ΔP_i is the amount of generation curtailment with regard to the P2P energy trading agreement breached i, and ΔP_j is the total amount of generation that is decided to be curtailed from the customer j.

If the demand response to be provided is demand reduction, the equivalent economic loss depends on the type of demands. For industrial and commercial demands, the loss mainly comes from the interruption of normal operation of devices or businesses, while for residential customers, the loss mainly comes from the dissatisfaction of human beings. The abstract form of the loss can be described as

$$L_{DR,j} = f(\Delta P_j), \tag{15}$$

where ΔP_i is the total amount of demand that is committed to be reduced from the customer j. The specific form of $f(\cdot)$ needs to be chosen based on the specific type of the demand.

Based on the above analysis, a customer j make decisions by solving the following optimization problem:

$$\underset{\Delta P_j}{\text{Max}} \left(R_{DR,j} - COST_{DR,j}\right), \tag{16}$$

where $R_{DR,j}$ and $COST_{DR,j}$ are calculated by (8) and (13) respectively. Note that the following constraints need to be satisfied:

$$0 \leq \Delta P_j \leq \sigma_j. \tag{17}$$

Recall that σ_j is the amount of electricity to be bought/sold in the bid/ask in the continuous double auction.

If the solution of the optimization ΔP_j^* equals to 0, it means that the customer will not provide any demand response. If the solution ΔP_j^* is a value between (0, σ_j], the customer will commit the demand response with the amount of ΔP_j^*.

6. CASE STUDY

A residential community with 100 customers was studied. The P2P energy trading and demand response for one future time slot were considered. The length of the time slot was assumed as 1 hour.

The demands of the customers for the time slot was generated based on practical statistics in the 'LSOA W01000897' area of Neath Port Talbot, Wales, UK [14], [15], which are listed in Table 1. Specifically, the demands of the customers were evenly sampled from [$VAR \cdot P_{ave}$, $PAR \cdot P_{ave}$], where P_{ave} was sampled from the normal distribution $N(\overline{P}_{ave}, 0.2\overline{P}_{ave})$.

Table 1 Demand statistics regarding the customers [14], [15]

Parameter	Description	Value
$\overline{P}_{ave}$	Average active power consumption of the customers in the area	0.33 kW
PAR	Typical peak-average ratio for the power consumption of the customers	1.49
VAR	Typical valley-average ratio for the power consumption of the customers	0.51

It was further assumed that 18% of the customers were installed with onsite PV systems. The capacity of each PV system was evenly sampled from (0, 5] kW. For the time slot considered, it was assumed that the generation of each PV system reached 60% of its installed capacity.

In the case study, it was assumed that each customer was able to accurately forecast its demand and generation at the time slot considered, and they bid in the proposed P2P energy trading and price-based demand response mechanisms with its net demand/generation, similar to that in [16].

Three scenarios are considered. Scenario 1 (S1) acted as the reference scenario, where all the customers directly buy/sell electricity from/to the power utility at the retail price / FiT rate, thus named as 'Power-to-Grid (P2G)' scenario. The FiT rate and typical retail price in the UK were used, being 0.0538 £/kWh and 0.1695 £/kWh respectively [17]. In Scenario 2 (S2), the customers participated in the proposed continuous double auction with the residual balancing mechanism for P2P energy trading. In Scenario 3 (S3), besides participating in the P2P energy trading mechanism, the customers participated in the proposed price-based demand response mechanism as well. It was assumed that the power utility would like to purchase 15 kW demand reduction service at the price 0.075 £/kWh [18]. The equivalent economic loss per kWh for demand reduction for each customer was evenly sampled from [0, p_{retail}]

The simulation results are shown in Figs. 3-5.

Fig. 3 illustrates the revenues of customers in the three scenarios, where the negative revenues mean that the customers need to make payment to the power utility or other customers. From Fig. 3, it is seen that many customers could obtain higher revenues through participating in the proposed P2P energy trading mechanism, compared to those of the conventional P2G mechanism. By participating in the proposed demand response mechanism, many customers could obtain even higher revenues. It is worth noting that strictly no customer would be worse off by participating in the proposed P2P energy trading and demand response mechanisms, indicating that the benefits improvement brought by the P2P energy trading and demand response is 'Pareto improvement'.

Fig. 4 demonstrates how much demand reduction was committed by each customer for the power utility, so that more revenues were obtained by the corresponding customers.

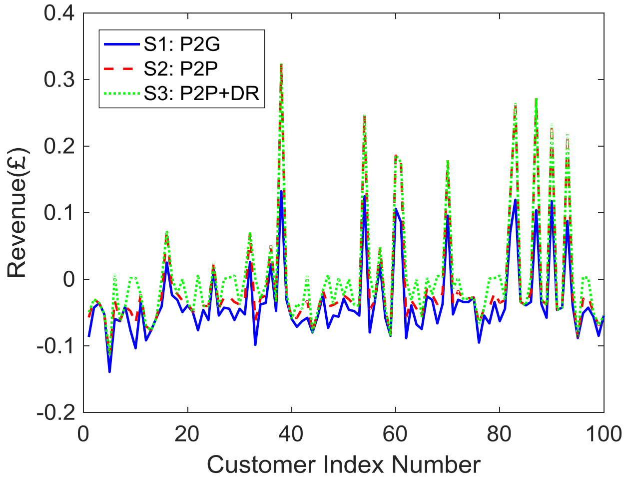

Fig. 3 The revenues of customers in the three scenarios

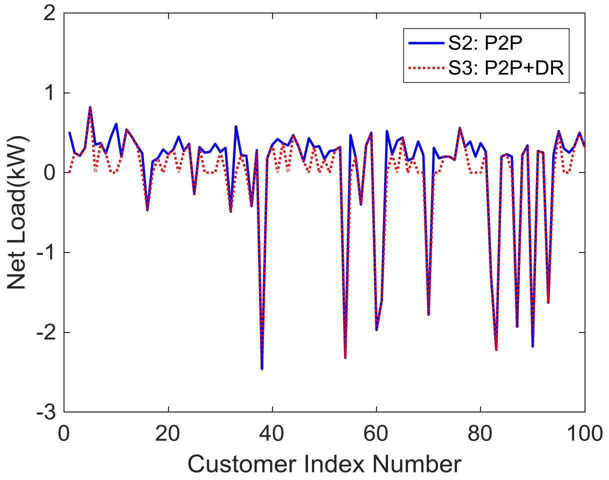

Fig. 4 The net loads of customers in S2 and S3

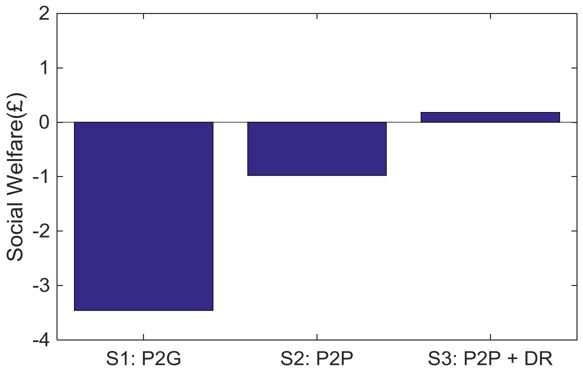

Fig. 5 The social welfare of the three scenarios

Finally, Fig. 5 shows the social welfare (i.e. the total revenues of all the customers minus any associated costs if the demand response is committed) of the three scenarios. It is seen that the proposed P2P energy trading mechanism was able to improve the social welfare by 71.7%, compared to that of the conventional P2G mechanism. With the proposed price-based demand response mechanism, the social welfare could be further improved by 118.6%, compared to the scenario with only the P2P energy trading executed.

7. CONCLUSION

In this paper, a price-based mechanism was proposed to incentivize the customers of a P2P energy trading community to provide demand response service to the power utility. The continuous double auction with a residual balancing mechanism was proposed as the mechanism for P2P energy trading. Simulation results in the case study show that the proposed P2P energy trading and price-based demand response mechanisms resulted in Pareto improvement for the revenues of all the customers. The results also show that the proposed P2P energy trading mechanism could improve the social welfare of the community by 71.7%, compared to that of the conventional P2G mechanism, and the proposed price-based demand response mechanism could further improve the social welfare by 118.6%, compared to the scenario with only the P2P energy trading executed.

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