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A PEER-TO-PEER ENERGY TRADING HIERARCHY FOR MICROGRIDS IN DISTRIBUTION NETWORKS

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ABSTRACT

Microgrids and peer-to-peer (P2P) energy trading are important technical and market arrangements to deal with the challenges brought by the increasing penetration of distributed energy resources (DERs). In this paper, a P2P energy trading hierarchy was proposed for microgrids in distribution networks. Hierarchical P2P markets were established for facilitating the energy trading between prosumers and consumers. A two-stage matching method, including bilateral and pool-based matching, was proposed to match the generation and demand in the hierarchical P2P markets. An extended Mid-Market Rate (MMR) pricing method was further proposed for clearing the hierarchical P2P markets. The proposed hierarchy and matching and pricing methods were tested on a distribution network adapted from a practical network in Neath Port Talbot, Wales, UK. Simulation results demonstrate the operation of the proposed hierarchy, and indicate that the proposed hierarchy, with the proposed matching and pricing method, has the potential to bring greater social welfare compared to the conventional market paradigm.

Keywords: peer-to-peer energy trading, microgrid, distribution network, prosumer, distributed energy resource, local electricity market

1. INTRODUCTION

In the face of the energy crisis and environmental pollution, it has become the consensus and development direction of the countries in the world to develop the distribution energy resources (DERs) including wind energy, solar energy, and even demand-side interruptible services [1]. According to the prediction of the International Energy Agency (IEA), two-thirds of the world's electricity will come from distributed renewable sources by 2040, accounting for 40% of the total installed capacity of the entire power system [2]. However, the IEA also warned that the realization of the above vision should be based on a series of innovations of technology and trading mode in the existing power system, to cope with the impacts of widespread DERs [3]. As for this problem, most experts argued that the large-scale connection of DERs is bound to be accompanied by the intelligentization of the power grid and the change of relevant electricity trading mode, especially in the distribution networks [4]-[6].

[7] argued that with the participation of customers in the investment of DERs and the corresponding electricity trading, their roles will change from conventional consumers to prosumers that can both generate and consume electricity. This transform will lead to changes in the existing power supply and trading mode. Microgrid is considered as an important power supply mode in future power systems with a high penetration of prosumers [8], and peer-to-peer (P2P) energy trading is

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considered as a promising trading mode for future power systems to manage prosumers [9]. A number of studies have been made to propose various schemes for P2P energy trading within a microgrid, such as Mid-Market Rate [10] and the schemes based on reverse auction [11], supply and demand ratio [12] and evolutionary and Stackelberg game approaches [13]. There have also many studies which developed mechanisms for the energy trading between multiple microgrids, such as those in [14]-[16].

The above studies focus on the energy trading within a microgrid or between microgrids, but there is still a lack of research on establishing a hierarchical energy trading mechanism for microgrids across the multiple layers of distribution networks, with only a few studies in place [17]. In this paper, a further step was made in this direction, proposing a P2P energy trading hierarchy for microgrids in distribution networks. Furthermore, a two-stage matching method with extended Mid-Market Rate (MMR) pricing was proposed as the energy trading mechanism.

2. PEER-TO-PEER ENERGY TRADING HIERARCHY FOR MICROGRIDS

The P2P energy trading hierarchy consists of multiple layers of local P2P energy trading markets, as illustrated in Fig. 1. At the bottom layer, within each microgrid, a P2P energy trading market is adopted to organize the energy trading between the prosumers and consumers in the microgrid. However, it is highly possible that the microgrids cannot exactly balance their generation and demand, and thus they need to participate in the higher-layer P2P energy trading markets (i.e. the 'Bottom-Layer Distribution Markets' shown in Fig. 1) for inter-migrogrids balancing. Similarly, although significantly facilitating the inter-migrogrids balancing, there may still be some unbalance in the Bottom-Layer Distribution Markets, so they participate in even higher layer distribution markets for further balancing. There may be several layers of distribution markets. Finally, there is one top-layer distribution market, which interacts with conventional wholesale market or retail market for final balancing.

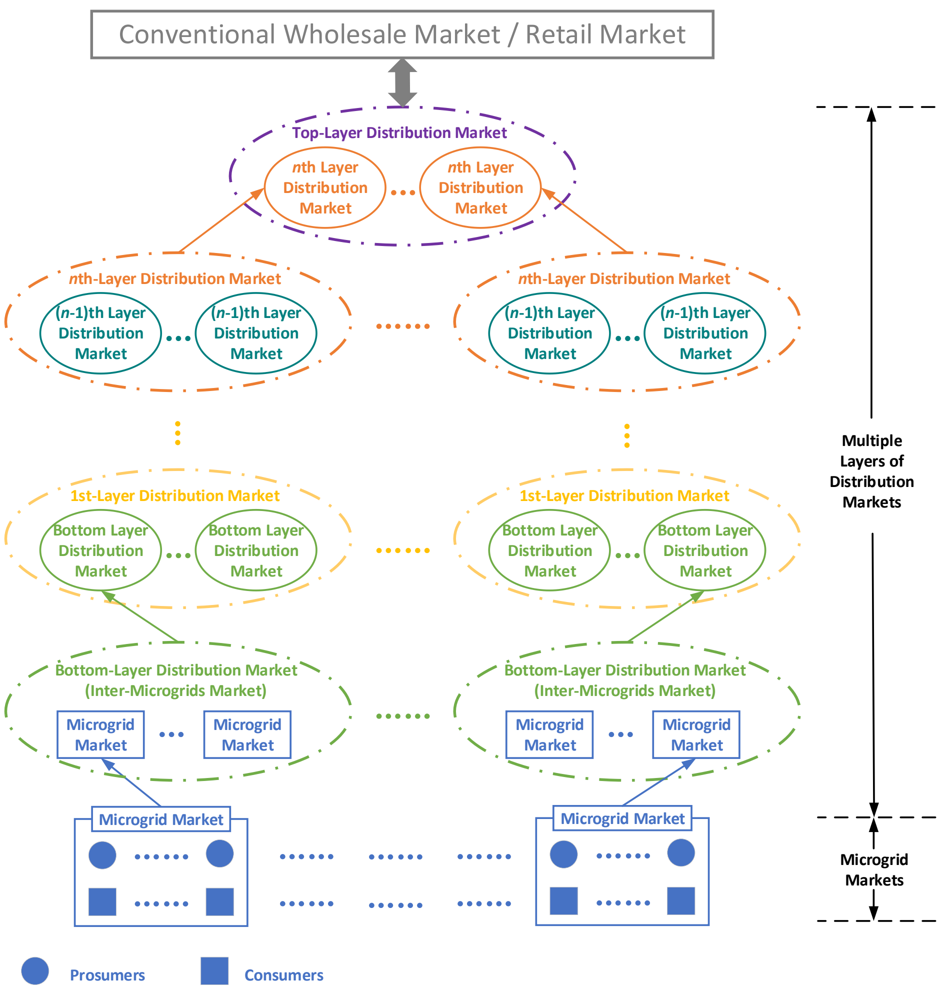

Fig. 1 The P2P energy trading hierarchy for microgrids in distribution networks

The rationality for designing such hierarchical markets rather than one large united market is that an extremely large platform with numerous participants will result in high investment and operating costs, high communication burden, high calculation burden, lower reliability (being more vulnerable to single-point failure) and lower market efficiency. The optimal number of layers depend on the specific features of customers and networks in the area, and remains to be a research topic for the future. In this paper, the hierarchy is divided according to the voltage levels of the distribution grid.

3. TWO-STAGE MATCHING WITH EXTENDED MID-MARKET RATE PRICING FOR THE HIERARCHY

For the microgrid market and all the layers of distribution markets in the hierarchy, the same P2P energy trading rules are applied. The differences between different markets just lie in the participants. For a microgrid market, the participants are the prosumers and consumers within the microgrid. For distribution markets, the participants are the lower layer markets. A two-stage matching method with extended Mid-Market Rate pricing was proposed as the P2P energy trading mechanism for the markets.

3.1 Two-stage matching

The generation and demand of participants in a market of the hierarchy are matched in a two-stage process.

At the first stage, a bilateral matching is conducted. If the generation surplus of a participant exactly equals to the demand required by another participant, they are matched as a pair, and the generation surplus is assigned to supply the demand.

For the participants that did not get matched at the first stage, a pool-based matching is conducted as the second stage. The aggregated generation surplus of all the participants are used to supply the aggregated demand of all the participants. The left generation surplus / demand unmet is to be balanced at the higher level market.

This two-stage matching process is summarized in Fig. 2, where n and m are the index for the participants in the market; $\boldsymbol{N}$ is the set of all the customers in the market; ND represents net demand, with negative values indicating generation surplus and positive values indicating electricity deficit. t is the index for a time slot; $\boldsymbol{M}_t^{\text{bilateral}}$ is the set of participants that are matched in the bilateral way; G_t and D_t are the aggregated generation surplus and electricity deficit

Two-Stage Matching Process

1st Stage: Bilateral Matching

For $n \in \boldsymbol{N}$
  For $m \in \boldsymbol{N} - \{n\}$
    If $ND_{n,t} = -ND_{m,t}$ and $ND_{n,t} \neq 0$
      Add n, m to the set $\boldsymbol{M}_t^{\text{bilateral}}$;
      Break;
    End if
  End for
End for

2nd Stage: Pool-Based Matching

Set $G_t = (-1) \cdot summation(ND_{n,t})$
  for all $n \in \boldsymbol{N} - \boldsymbol{M}_t^{\text{bilateral}}$ and $ND_{n,t} < 0$
Set $D_t = summation(ND_{n,t})$
  for all $n \in \boldsymbol{N} - \boldsymbol{M}_t^{\text{bilateral}}$ and $ND_{n,t} > 0$
Set $\boldsymbol{M}_t^{\text{pool}} = \boldsymbol{N} - \boldsymbol{M}_t^{\text{bilateral}}$;
Set $ND_t^{\text{Market}} = D_t - G_t$

Fig. 2 The two-stage matching in a market of the hierarchy

of the participants that are matched in a pool-based way; $summation(\cdot)$ is the summation function; $\boldsymbol{M}_t^{\text{pool}}$ is the set of participants that are matched in the pool-based way; ND_t^{Market} is the net demand of the whole market, which is to be balanced at the higher layer market.

3.2 Extended Mid-Market Rate pricing

For the participants matched by the proposed two-stage method, electricity prices need to be decided so that the participants know how much to pay/receive.

MMR pricing is an established pricing mechanism for P2P energy trading [10], which has been used by researchers from different institutions for P2P energy trading studies [18], [19]. The basic principle of MMR pricing is that the prices for P2P energy trading are made in the middle of the grid retail price and the feed-in tariff rate, so that both the producers and consumers benefit. If the generation and demand cannot be balanced locally, the P2P trading prices need to be modified considering the electricity imported from / exported to the external market.

The current version of MMR can only be applied to one single P2P energy trading market, but cannot be applied to hierarchical markets with inter-markets power exchange directly. Therefore, an extended MMR pricing method is proposed in this paper to make it function as the pricing mechanism for the hierarchical markets proposed in this paper.

Specifically, in any market of the proposed hierarchy, for the participants that are matched in the bilateral way, the internal buying and selling prices, p_t^{buy} and p_t^{sell} are calculated as

$$p_t^{\text{buy}} = p_t^{\text{sell}} = c_t^{\text{mid}}, \tag{1}$$

where

$$c_t^{\text{mid}} = \frac{p_t^{\text{retail}} + p_t^{\text{FIT}}}{2}. \tag{2}$$

In (2), p_t^{retail} and p_t^{FIT} are the grid retail price and feed-in tariff rate, respectively.

For the participants that are matched in the pool-based way, the internal buying and selling prices are decided by

$$p_t^{\text{buy}} = \begin{cases} c_t^{\text{mid}} & if\ ND_t^{\text{Market}} \le 0 \\ \dfrac{c_t^{\text{mid}} \cdot G_t + ND_t^{\text{Market}} \cdot p_t^{\text{buy-higher}}}{D_t} & if\ ND_t^{\text{Market}} > 0 \end{cases}, \tag{3}$$

$$p_t^{\text{sell}} = \begin{cases} \dfrac{c_t^{\text{mid}} \cdot D_t + ND_t^{\text{Market}} \cdot p_t^{\text{sell-higher}}}{G_t} & if\ ND_t^{\text{Market}} \le 0 \\ c_t^{\text{mid}} & if\ ND_t^{\text{Market}} > 0 \end{cases}, \tag{4}$$

where $p_t^{\text{buy-higher}}$ and $p_t^{\text{sell-higher}}$ are the internal buying and selling prices of the higher layer market. If the market considered is the Top-Layer Distribution Market (shown in Fig. 1), $p_t^{\text{buy-higher}} = p_t^{\text{retail}}$ and $p_t^{\text{sell-higher}} = p_t^{\text{FIT}}$.

From (3) and (4), it is seen that for the participants that are matched in the pool-based way, the internal prices depend on the net demand of the whole market, thus affected by the internal prices of the higher layer market which balances the net demand for this market. As a result, the internal prices of the markets in the hierarchy should be calculated from the Top-Layer Distribution Market to the Microgrid Markets at the bottom (as shown in Fig. 1).

4. *CASE STUDY*

The energy trading within a hierarchical distribution network was studied to demonstrate and verify the proposed trading framework and the pricing mechanism. The distribution network was generated based on the parameters of a practical network in the 'LSOA W01000897' area of Neath Port Talbot, Wales, UK [20], [21]. The parameters used are listed in Table 1.

Based on the parameters listed in Table 1, the distribution network studied in this paper was generated. The number of the 132/33 kV, 33/11 kV and 11/0.4 kV substations was assumed as N_{132}, N_{33} and N_{11}. The number of 11/0.4 kV substations below each 33/11 kV substation was assumed to be (N_{11}/N_{33}). All

Table 1 The parameters regarding the network used [20], [21]

Parameter	Description	Value
N_{132}	Number of the 132/33 kV substation	1
N_{33}	Number of the 33/11 kV substations	2
N_{11}	Number of the 11/0.4 kV substations	20
N_{dom}	Total number of the domestic customers	632
N_{nondom}	Total number of the non-domestic customers	41
$\bar{P}_{dom}$	Average active power consumption of domestic customers in this area	0.33 kW
PAR_{dom}	Typical peak-average ratio for the power consumption of domestic customers	1.49
VAR_{dom}	Typical valley-average ratio for the power consumption of domestic customers	0.51
$\bar{P}_{nondom}$	Average active power consumption of non-domestic customers in this area	1.58 kW
PAR_{nondom}	Typical peak-average ratio for the power consumption of non-domestic customers	1.30
VAR_{nondom}	Typical valley-average ratio for the power consumption of non-domestic customers	0.74

the customers were assumed to be connected at the 0.4 kV networks. The number of domestic and non-domestic customers below each 11/0.4 kV substation were evenly sampled from $[0.9N_{dom}, 1.1N_{dom}]$ and $[0.9N_{nondom}, 1.1N_{nondom}]$.

The generated distribution network is shown in Fig. 3, where it is seen that the top 132/33 kV substation has two 33/11 kV substations; each 33/11 kV substation has ten 11/0.4 kV substations; and each 11/0.4 kV substation has different numbers of customers (from 31 to 37). It is assumed that the layers of P2P energy trading markets are consistent with the voltage levels of the distribution network. That is, the customers below each 11/0.4 kV substation form a Microgrid Market. The 11/0.4 kV substations below the same 33/11 kV substation form a Bottom-Layer Distribution Market. The two 33/11 kV substations below the 132/33 kV substation form the Top-Layer Distribution Market.

The energy trading for an 1-hour period in the future was considered. During the 1-hour period, the generation and demand were assumed constant. The demand of domestic and non-domestic customers were evenly sampled from $[VAR_{dom}P_{dom}, PAR_{dom}P_{dom}]$ and $[VAR_{nondom}P_{nondom}, PAR_{nondom}P_{nondom}]$, where P_{dom} was sampled from the normal distribution $N(\bar{P}_{dom}, 0.2\bar{P}_{dom})$ and $P_{nondom} \sim N(\bar{P}_{nondom}, 0.2\bar{P}_{nondom})$. For the area below each 11/0.4 kV substation, it was assumed $\lambda\%$ of the domestic and non-domestic customers were installed with onsite PV systems, where $\lambda \sim U(9,27)$. The installed capacity of the domestic and non-domestic PV systems were evenly sampled from $(0,5]$ kW and $(5,10]$ kW. At the time period considered, it was assumed that the generation of all the PV systems reached 60% of their installed capacity.

With the generation and demand of each customer as assumed above, the proposed two-stage matching method with the extended MMR pricing was used to organize the energy trading between customers. The results are also shown in Fig. 3. Fig. 3 shows that how the participants at different layers are matched with each other. It is seen that in the Microgrid Markets at the bottom, most customers (90%) were matched in the pool-based way, and all the participants at the higher layer markets were matched in the pool-based way. In Fig. 3, the numbers in the blocks show the net demand of the participants at different layers, from which it can be seen how the net demand of each customer / each layer of P2P energy trading markets is balanced.

The social welfare of all the customers with the proposed matching and pricing methods was calculated as the total income of the customers who sold electricity minus the total payment of the customers who bought electricity. The social welfare of the conventional market paradigm was calculated for comparison as well, in which each customer directly traded with the utility company at the grid retail price and feed-in tariff rate. The results are presented in Table 2. It is seen that the proposed P2P energy trading hierarchy with the two-stage matching and extended MMR pricing methods is potentially able to bring much greater benefits compared to the conventional market paradigm.

Table 2 The social welfare with the proposed hierarchy compared with that of the conventional market paradigm

Framework	Total Income (£)	Total Payment (£)	Social Welfare (£)
Proposed	18.89	28.28	-9.39
Conventional	9.10	38.07	-28.97

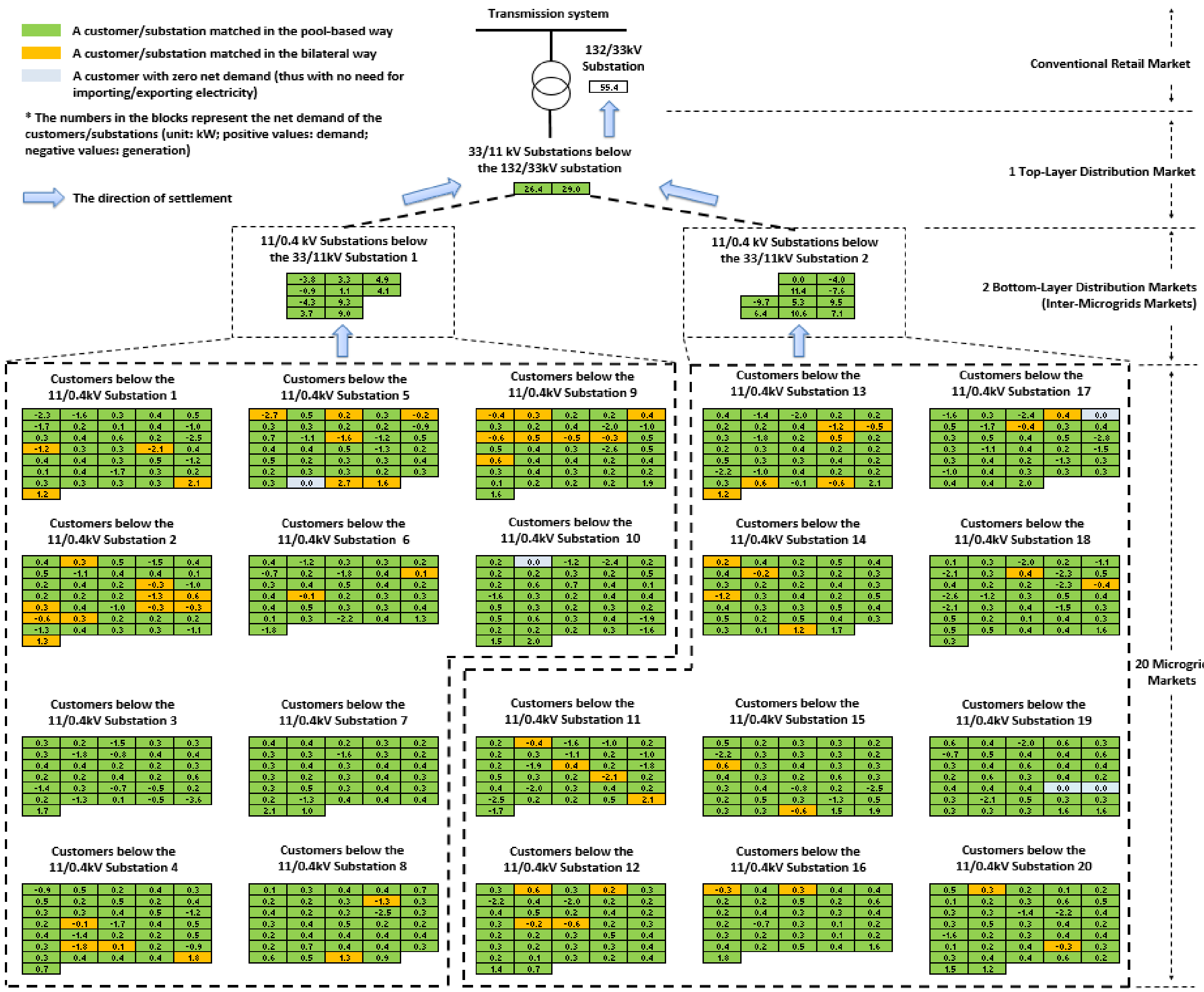

Fig. 3 The bilateral and pool-based matching results across the multiple layers of the distribution network

CONCLUSION

In this paper, a P2P energy trading hierarchy was proposed for microgrids in distribution networks. A two-stage matching method with an extend MMR pricing method was proposed for the hierarchical P2P markets. Simulation results demonstrate the operation of the proposed hierarchy, and indicate that it has the potential to bring greater social welfare compared to conventional market paradigm.

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