Multi-Round Double Auction-Enabled Peer-to-Peer Energy Exchange in Active Distribution Networks

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***Abstract*—Distributed energy resources, together with information and communication technologies, have transformed the traditional electricity consumers into proactive consumers, namely prosumers. Prosumers can exchange their surplus energy with consumers through peer-to-peer (P2P) energy sharing. In this paper, the framework of P2P energy exchange in active distribution networks is developed using a multi-round double auction (MRDA) with average pricing mechanism (APM) integrated with distributional locational marginal price. The advantages of the proposed P2P framework include, 1) modeling and integration of the costs of voltage regulation, congestion, and power loss into the payments of agents for each transaction; 2) the entire distribution network clustered into multiple zones with transactions cleared at different levels, which decreases the additional costs for successful transactions, reduces the computational time, and increases the number of successful transactions; and 3) the matching algorithm encourages more prosumers and consumers to participate in P2P energy sharing and increases the efficiency and benefit from P2P market. The proposed MRDA-APM framework is validated by testing on the 33-node and 141-node distribution test systems. Simulation results demonstrate the effectiveness of the proposed mechanism for P2P energy exchange from both technical and computational viewpoints.**

***Index Terms*—Distribution market, distributional locational marginal pricing, double auction, energy exchange, peer-to-peer market.**

I. Introduction

THE LARGE-SCALE deployment of distributed energy resources (DERs) and information and communication technologies (ICT) enables the emerging of pro-active consumers known as prosumers, with the capability of both producing and consuming energy in active distribution networks [1]. During certain times of a day, prosumers can sell their surplus energy to other consumers for monetary benefits, provision of ancillary services to the grid, etc. The energy exchange among prosumers and consumers could be enabled through peer-to-peer (P2P) energy trading. However, the distribution system operator (DSO) cannot manage large number of participants in the distribution energy market, due to the inaccessibility to real-time data and the behavior of market participants (e.g., offered prices, utilities of agents, and the amount of energy to be traded). Therefore, it is motivated to explore the possibility of building a P2P energy trading market under DSO's control.

The recent development of P2P market-oriented pragmatic projects include 1) design and modeling of the P2P market, e.g., Enerchain [2], NRGcoin [3], and P2P community energy trading with multi-time, multi-scale, and multi-qualities (P2P3M) [4]; and 2) implementation of control and ICT platform for prosumers, e.g., EMPOWER, Smart Watts, and Community First Village [5]. Besides practical P2P projects, research efforts on local energy market designs can be generally divided into three categories: 1) Business layer focusing on market structures and tools; 2) Physical layer; and 3) Market settlement time of local market with various considerations, as shown in Table I.

A. Business Layer

Different research studies in this layer can be categorized into two main directions: market structures and market tools.

1) Market Structure: There are various literature works on the market structure including, centralized, decentralized, and fully distributed designs. In the centralized design, DSO solves the optimal power flow (OPF) to obtain the optimal scheduling of DERs and clears the market with distributional locational marginal pricing (DLMP), derived from the duality analysis of network energy balance constraint, using second-order cone programming (SOCP) relaxation [6]–[8]. It is assumed that detailed information regarding agent behaviors, bid price, amount of energy to be traded, etc. must be accessible to system operators to schedule the generating units and DERs. Therefore, effective market mechanisms should be designed to extract this hidden information and consider consumers as price maker entities in local market designs.

On the other hand, decentralized and distributed designs address the challenges by sharing limited private information for decision-making. For instance, in [9], a decentralized DLMP-based market is presented considering a novel method for convergence acceleration by removing redundant Lagrangian multipliers. A market framework for decentralized congestion management using mobile distributed storage is presented in [10]. Alternating direction method of multipliers (ADMM) and dual decomposition are examples of fully distributed solution algorithms to solve DERs dispatching through sharing limited information among neighboring nodes [11], [12]. Besides, addressing the privacy of agents

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TABLE I
SUMMARY OF RECENT STUDIES ON DISTRIBUTION MARKET DESIGN AND P2P ENERGY SHARING

Category	Feature	Model Characteristic	References
Market Structure	Centralized	System Operator access to all required information in advance to solve the optimization	[6]–[8], [11], [13] [17]–[19], [31], [24]–[26] [32] [33]
	Decentralized	System operator only access to aggregated version of information (Not agent by agent information)	[9], [15], [16], [29]
	Distributed	Agents share limited information directly with each other without supervision of a central entity	[1], [12], [21], [28] [30], [34]
Market Tool	Auction Theory	Single and double-sided auction models	[15], [16]
	Game Theory	Stackelberg game, Cooperative and non-cooperative games, Generalized nash game, etc.	[20], [17], [18], [19]
	Blockchain	Smart contracts, Hyperledger, Ethereum, Consortium blockchain, etc.	[14], [15], [31], [23], [24]
Physical Grid Layer	Network Constraint Considerations	Voltage, Power loss, Capacity constraints, etc.	[6], [7], [9], [11], [12] [13], [16], [31], [25], [28] [32], [33]
	Extra Network Cost Allocation	Voltage regulation cost, Power loss cost, Congestion cost, et.	[1], [25]
Market Settlement Time	Day-ahead	Operation a day before without having time limitation	[1], [6]–[8], [11], [13] [17]–[19], [21], [25], [26] [28], [29], [32], [33]
	Real-time	Operating during the day with time limitation	[12], [15], [16], [31] [24], [30]

regarding the data sharing, the major concern of distributed techniques in local market designs is the convergence issue, which results in high computational time due to the potentially large number of market participants in the distribution network [13].

2) Market Tool: Recently, there has been preeminent attention on local energy markets based on P2P energy exchanges, which provides a platform for direct negotiations between prosumers and consumers. To this end, proper market mechanisms and structures are needed to enable this platform for agents. Research studies on P2P energy trading can be categorized into three different directions: a) Auction-based P2P markets; b) Game theory-based P2P markets; and c) Blockchain-based P2P markets; as well as the Hybrid methods combining both market structures and market tools, such as blockchain-based distributed P2P energy trading [14]. Each category is discussed below in details.

a) Auction-based P2P Market: An iterative double auction for enabling localized P2P electricity trading is proposed in [15] considering consortium blockchain technology. The major focus of this paper is the balance between local generation units and local demand. However, not considering the network constraints may significantly affect the matching results between prosumers and consumers due to the physical limits of power system operation. To address this limitation, a decentralized P2P energy trading based on continuous double auction is proposed in [16], by considering the network's physical constraints. However, the proposed model fails to address the additional network charges which significantly affect matching results, such as the cost-saving of consumers and the profit of prosumers. Additionally, some agents may participate in the market with better prices, but due to communication delays, they may miss the opportunity to trade with more consumers/prosumers (e.g., the first-come-first-serve rule). Moreover, trading with neighboring agents as well as motivating agents to participate in the P2P market has not been addressed in the auction-based market designs and need proper mechanism to address the limitation of auction-based P2P designs.

b) Game theory-based P2P Market: Game theory is another market tool that affects/depends on the agents' decisions based on the action of other agents in P2P markets. The general form of this approach is known as the multi-leader multi-follower game. Considering the cooperative game theory approaches, a Stackelberg game is proposed for P2P energy trading in [17], [18], in which a unique and stable equilibrium can be achieved. Another Stackelberg game-theoretic approach for P2P energy trading in virtual microgrids is proposed in [19], considering load demand uncertainty and modeling the communication layer. Since game theory approaches depend on agents' behavior (leader-follower rule), a psychology-based motivational game-theoretic approach for P2P energy trading is investigated in [20] considering human behaviors. Apart from cooperative designs, a novel P2P energy sharing model as a non-cooperative game is proposed in [21] for energy sharing among buildings equipped with heating, ventilation, and air conditioning (HVAC) units and renewable energy units. The major deficiencies of the aforementioned research efforts are not considering the physical network constraints and additional costs associated with transactions, which significantly affect the P2P market outcomes. Additionally, game theory-based models heavily depend on iterative mechanisms to find the solution and render the model to converge in a longer time period for a system with large number of prosumers and consumers.

c) Blockchain-based P2P Market: Blockchain technology is another appropriate tool for P2P-based energy sharing mechanisms, with the characteristics of distributed data sharing among agents, privacy, and no need for a central entity. A comprehensive and systematic classification on P2P topics including different trading mechanisms, physical and communication layers, technical approaches, future blockchain-based P2P trading fundamentals, etc. is provided in [22]. P2P transactive energy exchange in local energy markets is studied in [14] based on blockchain-based technologies. Consortium Blockchain-based energy trading to reduce cost and balance between load and generation for electric vehicles are presented in [15], [23], [24]. The aforementioned studies are mainly focused on the balance between generation and load without fully considering the network constraints and additional costs for each transaction. Although the transparency, privacy, and security of transactions increase by using blockchain technologies, trading mechanisms, grid constraints, and the role of prosumers and consumers on defining the matching price as well as additional costs must be addressed in blockchain-based P2P-based markets.

d) Hybrid Method-based P2P Market: The hybrid methods for P2P energy sharing are the combination of market tools and market structures. For instance, an iterative mechanism is introduced in [25] for peer and system-centric trading, with a strong assumption that DSO has the access to all required information about prosumers and consumers to clear the market. Additionally, consumers are considered as price taker entities in this method which neglects the role of consumers in P2P markets. Considering the flexibility of loads, authors of [26] propose a P2P local market for the joint trading of energy and uncertainty associated with local generation. This P2P model is proposed to trade forecasted PV power and uncertain power due to forecast error without considering grid constraints. Besides, different designs such as bilateral and auction-based P2P energy trading are reviewed in [27]. Bilateral contract-based designs are investigated in [28]–[30]. However, the hybrid methods presented in this section mainly follow the iterative process which significantly increases the computational time in distribution systems with a large number of market participants. Another factor that may increase the time of P2P matchings is the price adjusting factors, in which smaller values will increase the computational time.

B. Physical Grid Layer and Market Settlement Time

Besides price matching among peers, physical constraints of power systems like the voltage, power flows, etc. need to be considered for energy trading. There are plenty of research efforts on modeling the physical constraints in P2P energy sharing, as shown in Table I. The deficiencies of the iterative-based approaches have been explained in the previous sections. For auction-based P2P energy sharing, which is the more appropriate modeling since both prosumers and consumers can be considered as price maker entities, only [16] addresses network constraints. However, this study fails to address the additional costs associated with every transaction and consequently the revenue/payment of prosumers and consumers. Moreover, with the proposed method in [16], many P2P matchings satisfying the physical constraints may be subjected to rejection due to uneconomical reasons, e.g., the extra costs. On the other hand, many transactions could be finally rejected because of both uneconomical matchings and network constraint violations. Therefore, proper mechanisms are required for addressing these issues in auction-based P2P energy tradings, which have not been fully investigated yet.

Besides technical layer designs, the market settlement time of the aforementioned research efforts is another preeminent factor in designing P2P markets. As shown in Table I, the majority of papers are focused on the day-ahead operation of distribution network. However, P2P energy sharing depends on agents' participation, whose behaviors can change during the day. Besides, the uncertainty of loads and DERs must be modeled with high accuracy to ensure the reliable operation of the network. Considering the real-time aspect of P2P energy trading, iterative-based studies cannot be applicable due to the large number of agents' participation and price adjusting factors, which significantly increases the computational burden or the convergence time.

C. Major Gaps and Innovations

The major limitation of the market structure category is the computational time and hidden information accessibility. Since the studies in this category consider iterative-based approaches, computational time will be a major concern due to the large number of DERs in real distribution networks. This limitation can also be seen in game-theory-based models, since every action of an agent significantly depends on other agents' actions, and the feasible solution is achieved after exploring all possible matching scenarios. Therefore, the most appropriate design for the real-time P2P market is auction-based designs. However, considering the physical constraints of power networks as well as allocating extra costs like power loss, congestion, voltage regulation are the limitations of previous studies. Furthermore, due to the violations of network constraints, many transactions are rejected because of voltage issues or high loss costs among peers. Therefore, forming zones based on the DLMP signals in the distribution network (with at least one prosumer and one consumer per zone) can improve the success rate of transaction approval and reduce the extra costs of each transaction for both prosumers and consumers. Moreover, how to encourage and motivate small-scale prosumers to participate in the P2P market and make the design more reliable are another limitations that need to be addressed.

To address the aforementioned challenges, a multi-round double auction with an average price mechanism (MRDA-APM) integrated with DLMP components is proposed for P2P energy sharing in active distribution networks. The major contributions of the proposed P2P framework are:

- The proposed multi-round double auction provides the flexibility of matchings in bottom-up order (nodal, zonal, and distribution network layer), and encourages prosumers to first negotiate with consumers in nodal, zonal levels, and then seek for possible matchings in the distribution-level auction. The proposed hierarchical auction increases the benefit of agents by reducing additional costs through three rounds of auction. Additionally, the computational time is less compared to the existing iterative-based P2P designs.
- The proposed MRDA-APM algorithm is strongly budget balanced. Therefore, the auctioneer (DSO) never benefit directly from running the auction. Additionally, the proposed MRDA preserves the rights of agents and increases the motivation of P2P market participants, especially small-scale prosumers, to benefit from P2P market which improves the market efficiency.
- Unlike previous auction-based P2P energy trading mechanisms, the proposed auction-based framework integrates the DLMP to model the additional costs, using components of power loss and voltage regulation associated with each transaction; and also integrates these costs into the payments of both prosumers and consumers with equal cost splitting, which enables both prosumers and consumers to share the costs equally for energy trading.

The rest of the paper is organized as follows. The proposed P2P framework is introduced in Section II. Sections III and IV present the problem formulation and solution algorithm, respectively. Section V presents simulation results and analysis, and Section VI concludes the paper.

II. Proposed P2P Framework

The proposed P2P energy trading framework is shown in Fig. 1, consisting of three main steps as following.

1) Extracting Hidden Information of Agents: The first step is to collect the information from all agents who are willing to participate in the P2P market. DSO extracts the information from the participating consumers and prosumers, such as ask and bid prices, amount of power to be traded, by sending two price signals to agents. First, DSO sends a feed-in tariff (FIT) price signal to all prosumers. If prosumers with surplus energy are willing to participate in the P2P market, they should respond to this signal by sharing the information of ask price and the amount of power to be traded with DSO; otherwise, prosumers cannot participate in the market for trading time interval. It is worth mentioning that the FIT price signal is defined as power purchase agreements between utilities and prosumers. In this paper, the FIT price signal is considered in a way to incentivize prosumers to trade their energy with the grid even if they lose all rounds of the auction in P2P market. Next, after gathering the information of price and amount of power from participating prosumers, DSO calculates DLMP and sends this price signal to consumers. It is worth noting that this price signal is calculated based on the forecast of consumers' consumption level and the generation output of utility-operated distributed generators (DGs), as well as prosumers ask price and amount of power. Then consumers use

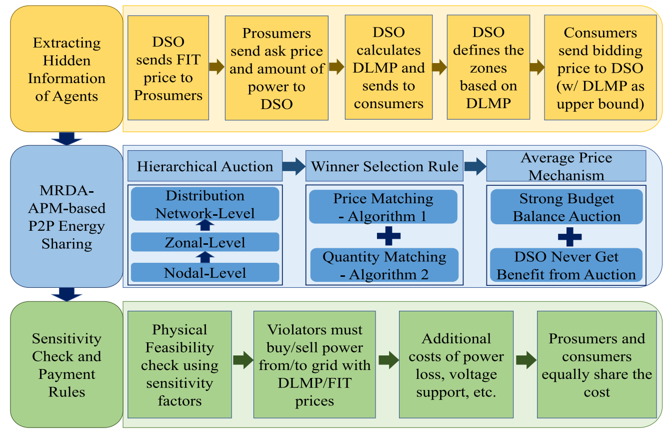


Fig. 1. Proposed P2P energy sharing framework in distribution network.

this price signal as the upper bound to decide and send the bidding price back to DSO. Finally, DSO obtains all required information for running the auction.

2) MRDA-APM-Based P2P Energy Sharing: After gathering all information from prosumers and consumers, including ask/bid prices, amount of surplus power, and requested demand, DSO starts the P2P energy trading with a hierarchical auction (MRDA). The hierarchical auction first starts from the nodal auction to balance the total demand of prosumers and consumers located in the same node. Next, prosumers and consumers trade in the zonal auction, and finally in distribution network (DN)-level auction. It should be noted that the zones are defined based on the criteria of similar DLMP values, including at least one prosumer, and the location in one neighborhood. Each agent is assigned with an identification (ID) number based on the node, zone, and DN number (e.g., N12Z3D1 denotes an agent located in node 12, zone 3 of first DN). The advantage of the MRDA design is to achieve more benefits by sharing energy with closest neighbors, save additional costs, and reduce the possibility of transaction rejection due to power loss, congestion, or voltage regulation. If agents fail to match in nodal, zonal, or DN-level auction, prosumers sell surplus power with the FIT price to the grid, and consumers purchase electricity from the grid with the DLMP price at their locations. Moreover, due to a large number of agents, the proposed MRDA-APM algorithm has other advantages of preserving the right of each market participant to benefit from the P2P market, through providing opportunities for all agents to participate in P2P market and keeping agents motivated to participate in next P2P market. More details and explanations will be explained in Section IV. It should also be mentioned that three auction rounds are needed to complete the MRDA-based P2P market.

In this paper, the cleared price of matched peers is the average of prosumer and consumer offering prices based on the APM. The preeminent advantage of the APM mechanism over traditional market-clearing prices is to enable the strong budget balance auction, in which all benefits from traded energy are equally dispersed among matched peers. Additionally, the MRDA-APM design satisfies other economic criteria such as individual rationality and truthfulness. It is worth noting that the framework doesn't involve the bidding strategy design for P2P market participants or consider more options from storage systems and demand response.

3) Sensitivity Check and Payment Rules: DSO is responsible for checking the security of transactions to determine whether the energy tradings between matched peers violate any network constraints or not, using sensitivity factors to block high-risk transactions. Once transactions satisfy the physical check, additional network costs, such as voltage regulation cost, power loss cost, etc., for every matched transaction, will be integrated into payments of both prosumers and consumers. These cost items can be calculated by the decomposition of DLMP components. Upon the final approval by DSO, prosumers and consumers split the additional cost, which the ratio could be adjusted by the market operator. In this paper, the simplest ratio is considered and assumed to be 50%.

III. Problem Formulation

The radial distribution network is represented as a graph (N, E), where N and E are the set of nodes and edges, respectively. The root node is numbered as 0, and the set of all other nodes is defined as $N^+ = N - \{0\}$. The set of nodes connected with DERs as prosumers is denoted as $S = \{1, 2, \ldots, N_s\}$, and all other nodes with demand are considered as consumers, with the set defined as $B = \{1, 2, \ldots, N_b\}$; and accordingly, $(S \cup B) = N^+$. Finally, it is assumed that DSO is responsible for determining the number and component of zones.

A. Entities in Multi-Round Double Auction

Entities in double auctions include sellers (prosumers), buyers (consumers), and the auctioneer (DSO). The indexes of n and m are denoted as prosumers and consumers, respectively.

1) Prosumers (Sellers): The ask price and amount of power to be traded in P2P market are denoted by Sp and Sq, respectively. The payoff of prosumer n from auction without considering additional costs, SW_n, is defined as:

$$SW_n = \begin{cases} \sum_{m=1}^{N_b} (\gamma_{nm} - Sp_n) \times Sq_{nm}, & \textit{if pros. n wins} \\ 0, & \textit{otherwise.} \end{cases} \tag{1}$$

where γ_{nm} is the auction cleared price of the successful transaction between prosumer n and consumer m.

2) Consumers (Buyers): The bid price and amount of energy to be traded in P2P market are denoted by Bp and Bq, respectively. The payoff of consumer m from auction without considering additional costs, BW_m, is defined as:

$$BW_m = \begin{cases} \sum_{n=1}^{N_s} (Bp_m - \gamma_{mn}) \times Bq_{mn}, & \textit{if con. m wins} \\ 0, & \textit{otherwise.} \end{cases} \tag{2}$$

3) Auctioneer (DSO): Total social welfare of all peers, TW, is defined as the sum of payoffs of both prosumers and consumers in the auction, presented as below:

$$TW = \sum_{n=1}^{N_s} SW_n + \sum_{m=1}^{N_b} BW_m. \tag{3}$$

B. DLMP Formulation

For DSO, the market-clearing is formulated as a SOCP-based optimization problem with convex relaxation. The DLMP price signal is used as a tool based on existing literature such as [6], [32], for extracting hidden and private information of agents and calculating additional transaction costs.

1) Objective Function: The objective is to minimize the generation cost of utility-operated DGs, and the cost of purchasing power from the grid, which is shown as the first and second terms in (4), respectively. It is assumed that PV units are the only generation units controlled by prosumers.

$$min \sum_{t=1}^{T} \left[\sum_{i=1}^{N} \left(C_{i,t}^{g} \times P_{i,t}^{g} \right) + \left(C_{0,t}^{g} \times P_{0,t}^{g} \right) \right] \tag{4}$$

where $C_{i,t}^{g}$ and $C_{0,t}^{g}$ are the marginal cost of DGs and buying power from wholesale or retail markets, respectively. $P_{i,t}^{g}$ and $P_{0,t}^{g}$ are defined as the power related with two cost terms. The objective function is subjected to technical constraints such as voltage limits, line flow limits, generation limits, power balance, etc. The convex relaxation of constraints can be referred in [6]. Based on KKT conditions and duality analysis [6], nodal prices can be represented as following:

$$\pi_i = \omega_1.\pi_{A_i} + \omega_2.\mu_i + \omega_3.\mu_{A_i} + \omega_4.\eta_i + \omega_5.\eta_{A_i} \tag{5}$$

where π_i, μ_i, η_i are active power price, reactive power price, and contribution of complex power at node i. Index A_i refers to the ancestor node of i. More details about the calculation of dual variables ω_i, and the decomposition of DLMP can be referred to [6]. In this paper, DLMP price signals have two major impacts, 1) serving as the upper bound of consumers' bids; if violated, consumers may lose the auction and have to purchase power from the grid with DLMP price; and 2) including valuable price information about the power transition, such as power loss, voltage regulation, etc. In order to calculate the additional costs associated with every transaction, DLMP differences between seller and buyer nodes are considered.

IV. P2P Energy Sharing Mechanism

There are major challenges of directly applying the literature research of prosumers/consumers in wholesale/retail markets [34] into distribution networks, which have been explained thoroughly in Section I. In this paper, a hierarchical auction with three rounds of nodal, zonal, and DN-level auction (defined as MRDA) is proposed to address the challenges. The APM mechanism is also integrated into MRDA to enable a strong budget balance, in which the auctioneer (DSO) cannot benefit from running the auction and all the benefits are equally divided among prosumers and consumers. In this paper, the 15-minute time interval is considered for P2P energy exchanges. It should be mentioned that the design of time intervals depends on the size of system, the number of agents participating in the P2P market, and the auction design. The following subsections will elaborate the details regarding the auction winner selections in price and quantity matching, sensitivity check, and payments of agents considering extra network usage costs.

A. Winner Selection Based on Price and Quantity

Considering the wholesale market as a reference, after collecting all data from agents, DSO arranges the requests from prosumers and consumers in ascending and descending orders, respectively, as expressed below.

$$Sp_1 < Sp_2 < \cdots < Sp_n, \quad \forall n \in S \tag{6}$$

$$Bp_1 > Bp_2 > \cdots > Bp_m, \quad \forall m \in B \tag{7}$$

After this arrangement, DSO calculates the average price of all agents participating in the P2P market and selects the winners of auction. The MRDA-APM improves the process by introducing the mean price λ, which makes all market players equal in terms of their chances to win auction. A prosumer wins the auction if and only if $Sp_n < \lambda$; and from the consumer point of view, $Bp_m > \lambda$ should be satisfied.

$$\lambda = \frac{\sum_{n=1}^{N_s} Sp_n + \sum_{m=1}^{N_b} Bp_m}{N_s + N_b} \tag{8}$$

The MRDA-APM enables agents to first negotiate with their neighbors (at nodal level) based on their IDs, containing information of node, zone, and DN. It should be noted that the cleared transactions in nodal level only need to provide a very small amount of additional cost, comparing to the zonal and DN-level transactions which will procure larger additional cost. If there is no successful matching with any consumer, prosumer n fails in the nodal auction and will participate again in the zonal auction. If prosumer n fails again in the zonal auction, it will participate in DN-level auction (zone crossing condition). If prosumer n fails in all three auctions, it can sell surplus energy to the grid. This three-layer auction process preserves the rights for all agents to participate in the market so that no agents can sell or buy energy multiple times continuously within one-time interval.

Fig. 2 shows an example of how the proposed auction works. To compare with other auction mechanisms in literature, let us first assume prosumers sell surplus energy one by one in Fig. 2(a). In this scenario, prosumers sell surplus energy until their energy is sold out. For instance, prosumer 1 has sufficient surplus energy and asks for a lower price, which satisfies more than the need of the first customer. Then prosumer 2 cannot sell its energy until prosumer 1 completely sells all its energy. As a result, other prosumers must wait in line for their turn to sell energy and will be reluctant to participate in future P2P markets, since they may not benefit from P2P market in different time intervals. To fill this gap, the proposed peer matching mechanism preserves the rights of all agents to participate in the P2P market.

As shown in Fig. 2(b), prosumer 1 can only sell partial of its surplus energy (based on the demand from consumer 1), and its remaining energy is transferred to the end of the prosumers list, waiting for new consumers. When first transaction is completed, prosumer 2 sells energy to consumer 2. This process continues until no consumers or prosumers on the list. The details of MRDA-APM price and quantity matching mechanism are shown in Algorithm 1, Algorithm 2 and Fig. 3, respectively. The benefit of matching in Fig. 2(b) is that prosumers and consumers cannot bid strategically to sell/buy all

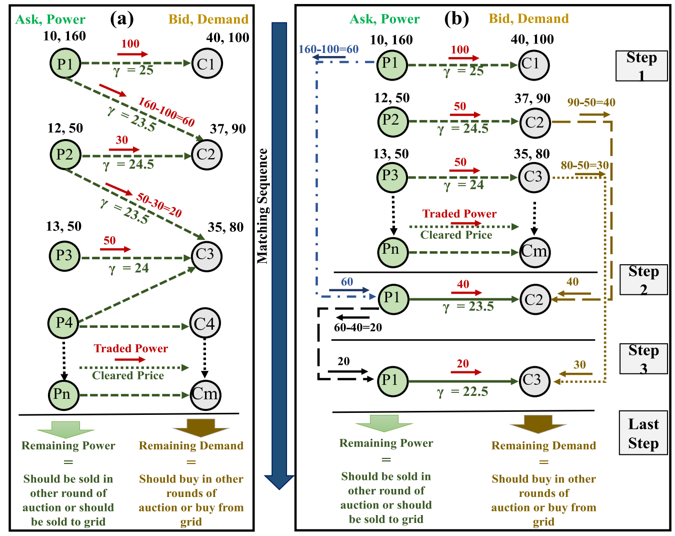


Fig. 2. The matching sequence example of MRDA at one time interval.

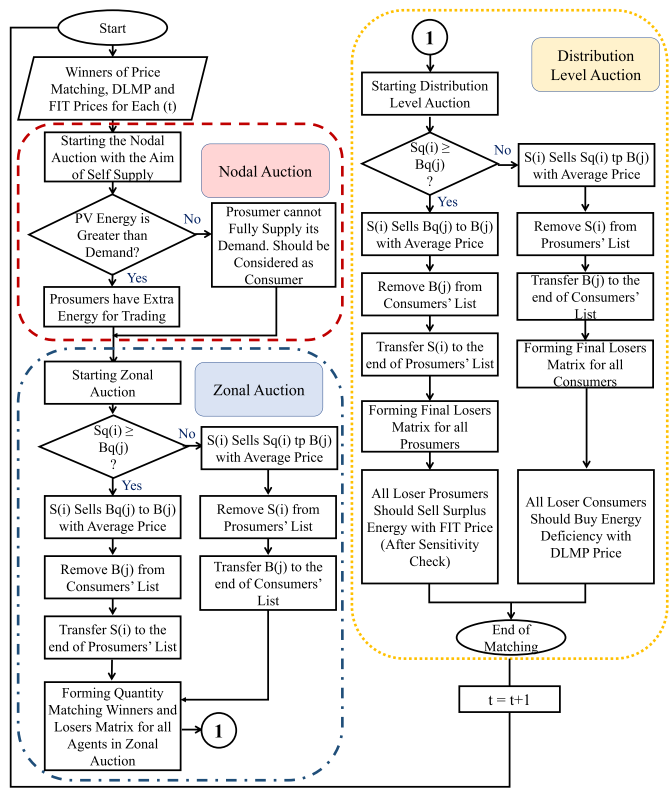


Fig. 3. The matching sequence flow chart for hierarchical quantity match.

surplus/needed energy. Moreover, MRDA increases the participation level of prosumers and consumers, as all agents have the chance to get benefit from P2P market.

For better elaborating the quantity matching sequence presented in Fig. 2, let us assume that there are 2 prosumers and 3 consumers in the P2P market, assuming that DSO has completed the price matching based on Algorithm 1. The surplus power of prosumers 1 and 2 are assumed to be 100 and 50 kw, respectively; and the demand of consumers 1, 2, and 3 are 25, 25, 50 kw, respectively. The first quantity matching happens between prosumer 1 and consumer 1 with 25 kw

Algorithm 1: MRDA-APM Price Match Algorithm

Input: Submitted ask and bid prices of agents, agents ID, DLMP and FIT prices for every time slot t

Output: Winners and Losers of price matching

Initialization;
Define set of pros. S_i (Sp_i, Sq_i, ID_i, $i = n \in N_s$)
Define set of cons. B_j (Bp_j, Bq_j, ID_j, $j = m \in N_b$)
Calculate λ based on (8)
Stage 1:
if $Sp_i \leq \lambda$ **then**
  $S_i \rightarrow$ Winner and do quantity match
else
  $S_i \rightarrow$ Considered as Loser and should sell power with FIT price to the grid
end
if $Bp_j \geq \lambda$ **then**
  $B_j \rightarrow$ Winner and do quantity match
else
  $B_j \rightarrow$ Considered as Loser and should buy power with DLMP price from the grid
end

Algorithm 2: MRDA-APM Quantity Match Algorithm in Each Round of Auction

Input: Winners of price matching (Algorithm 1), agents ID, DLMP and FIT prices for every time slot t

Output: Winners and Losers of quantity matching in every round of auction

Stage 2:
for *Each node, zone, and whole DN* **do**
  while *set* $\{S_i\} = \phi$ *or* *set*$\{B_j\} = \phi$ **do**
    if $Sq_i \geq Bq_j$ **then**
      1. S_i sells Bq_j to B_j with average price
      2. Transfer B_j to pre-matching list and remove B_j from consumers list
      3. Transfer S_i with power of $Sq_i - Bq_j$ to the end of prosumers list
    else
      1. S_i sells Sq_i to B_j with average price
      2. Transfer S_i to pre-matching list and remove S_i from prosumers list
      3. Transfer B_j with demand of $Bq_j - Sq_i$ to the end of consumers list
    end
  end
  Form losers matrix for prosumers and consumers
  $R \leftarrow$ remaining consumers and prosumers list
end
Stage 3:
Do Step 2 for R until no prosumers or consumers remaining on the list

traded power. If traditional auctions in Fig. 2(a) are considered, the next matching order will be prosumer 1 with consumer 2 with 25 kw traded power, and prosumer 1 with consumer 3 with 50 kw traded power. As a result, during one trading time interval, prosumer 2 never receives benefits from P2P market. If this happens for more P2P time intervals, the motivation of prosumer 2 will be decreased, and as a result, there is possibilities that this prosumer will not participate in the upcoming P2P markets; and in the long term, prosumer 1 can increase the asking price and be the dominant winner for the upcoming P2P markets. However, considering the matching sequence in Fig. 2(b), the matching order is, prosumer 1 with consumer 1 with 25 kw traded power, prosumer 2 with consumer 2 with 25 kw traded power, and prosumer 1 with consumer 3 with 50 kw traded power. As it can be seen, this matching sequence motivates small-scale prosumers to participate more since they can benefit from the market. It should be noted that this mechanism also depends on the number of prosumers and consumers in the network.

Additionally, this matching sequence, as shown in detail in Fig. 3 (with assumption that there is either one prosumer or one consumer located at each node), prevents agents, like prosumer 1, from bidding intentionally lower to sell all their power. The proposed mechanism also enhances the cyber-resilience by not depending on the limited number of prosumers. For instance, if prosumer 1 is an attacker and intentionally reports 100 kw surplus power (but in reality it only has 5 kw surplus power, or is even a consumer), with traditional auctions the DSO must supply the load by purchasing power from the grid for the 90 kw deficiency. However, with the proposed matching sequence more prosumers are involved in P2P energy sharing markets and the system resiliency can be improved (by reducing the risk of cyber attacks), and DSO does not have to purchase more power from the upper grid or operate DGs to supply the load.

Apart from quantity matching, at each stage, the clearing price of matched peers is the average of prosumer and consumer bidding prices, defined as APM. The main advantage of the APM mechanism over traditional market clearing-prices is to enable strong budget balanced auctions, in which all benefits from traded energy in the P2P market are equally dispersed among matched peers, not the auctioneer or the central entity who runs the auction. However, DSO can indirectly benefit from P2P market by bringing small-scale prosumers into the market and keep them motivated to participate in all time periods when they have excess energy. Therefore, DSO can supply some of the load with prosumers' surplus energy (who are considered as final losers of the auction) and purchase less energy from the upper-level network with LMP price to minimize the operational cost. In the end, if the auction completes with no consumers, all prosumers should sell their remaining energy to the grid with FIT price; otherwise, if the auction completes with no prosumers, all consumers should purchase their remaining energy from the grid with DLMP price.

B. Sensitivity Check

After the completion of the auction, there will be a large number of transactions successfully matched in different rounds of auction. Next, DSO will check the physical feasibility of these transactions, preventing the power injections that may violate network constraints. In this paper, sensitivity factors are used to check the violation of physical network constraints.

$$Pf^p = M \times \Delta P_{inj}; \quad Pf^q = M \times \Delta Q_{inj} \tag{9}$$

$$\Delta V = R \times Pf^p + X \times Pf^q \tag{10}$$

$$SF_v = \frac{\partial \Delta V}{\partial \Delta P_{inj}} = R \times M \tag{11}$$

$$SF_{lp} = \frac{\partial Pf^p}{\partial \Delta P_{inj}} = M; \quad SF_{lq} = \frac{\partial Pf^q}{\partial \Delta Q_{inj}} = M \tag{12}$$

$$Pf_i^p = \sum_{i=1}^{N} SF_{lp,i} \times \Delta P_{inj,i} \tag{13}$$

$$PTDF_{ij}^E = Pf_i^p - Pf_j^p \tag{14}$$

$$P_{loss} = \sum_{i=1}^{N} R_l \times I_l^2 \approx \sum_{i=1}^{N} R_l \times Fl_l^2 \tag{15}$$

$$LF_i^p = \frac{\partial P_{loss}}{\partial \Delta P_{inj}} = \sum_{i=1}^{N} 2 \times Fl_i^p \times R_l \times \sum_{i=1}^{N} SF_{lp,i} \tag{16}$$

where M is the injection shift factor (ISF) that represents the sensitivity between nodal active (reactive) power injection ΔP_{inj} (ΔQ_{inj}) and active (reactive) line flow Pf^p (Pf^q), as shown in (9). In distribution network, voltage difference ΔV can be approximated using line flow and line resistant R and reactance X, as shown in (10). In (11), SF_v represents the sensitivity factor between voltage difference and nodal active power injection by DERs; and the second equation can be achieved by substituting (9) and (10) into (11). In (12), SF_lp and SF_lq represent the sensitivity factor between line flow and nodal active/reactive power injection; and the second equation can be achieved by substituting (9) into (12). Equation (13) represents the active power flow equals to the summation of all nodal active power injection multiplied by sensitivity factor. Then power transfer distribution factor (PTDF), $PTDF_{ij}^E$, can be obtained, which provides the sensitivity of active power flow in branch E with respect to one active power injection at bus i and the other active power withdrawn at bus j, as shown in (14). In (15), linear approximation of active power loss, P_{loss}, can be presented using active power flow in branches. Loss sensitivity factor, LF_i^p, represents the sensitivity between power loss and injected power at bus i, as shown in (16) [33]. After DSO's final approval of transactions, network costs will be added to the payment of all matched transactions. It should be noted that this paper only considers the active power cost.

C. Payments and Allocation of Extra Costs

The MRDA-APM cleared prices can be integrated into nodal pricing schemes, which are based on marginal costs. For example, in PJM market, nodal price (NP) consists of system marginal energy price (SMP), e.g., locational marginal price (LMP), congestion price (CP) and loss price (LP) [35], [36].

$$NP = SMP + CP + LP \tag{17}$$

To integrate the proposed auction clearing price to distribution nodal pricing, SMP should be replaced with γ which indicates the cleared price of matched peers. Therefore, NP can be reformulated as below:

$$NP = \gamma + CP + LP \tag{18}$$

Additionally, matched peers should pay for power loss, voltage support, etc. The additional costs can be accessed by DLMP components from power injection by prosumers and power absorption by matched consumers. The payment of matched transactions confirmed by DSO can be presented as below:

$$SR_n = \sum_{m=1}^{N_b} SW_n - \sum_{m=1}^{N_b} \left(\frac{|DLMP_i - DLMP_j|}{2} \right) Sq_{nm} \tag{19}$$

$$BP_m = \sum_{n=1}^{N_s} BW_m + \sum_{n=1}^{N_s} \left(\frac{|DLMP_j - DLMP_i|}{2} \right) Bq_{mn} \tag{20}$$

where SR_n and BP_m denote to prosumers final revenue and consumers final payment, respectively. The first term of (19) and (20) denotes the traded energy benefit from P2P market. The second term of both equations is related to additional costs, which are equally split among matched peers.

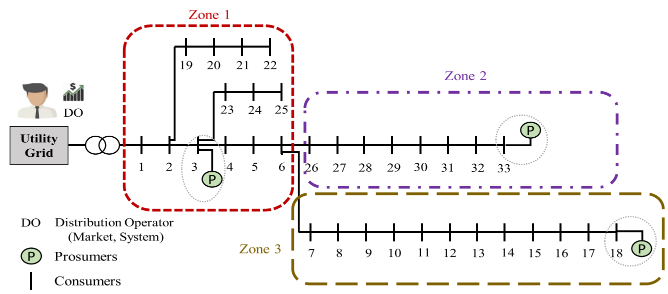


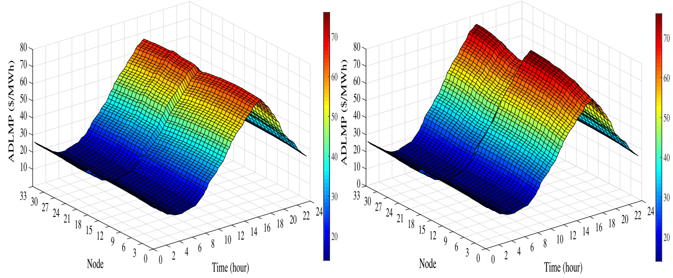
Fig. 4. 33-node distribution test system.

V. Numerical Results

The proposed P2P framework is first validated on the modified 33-node distribution test system [37] with pre-defined zones, as shown in Fig. 4. This test system has been used as a standard test system in various studies such as [33], [36], and [37]. Three 1,000 kW PVs are installed at nodes 3, 18, and 33, which represent three prosumers [33]. The nodes with load are considered as consumers. The network is clustered into 3 different zones, following the modification from [12]. All asks and bids are randomly generated and received by DSO. The hourly load data are obtained from [33], and PVs data are from CAISO for the first day of July 2019. Moreover, the hourly LMPs are from PJM, which can be referred to [33]. The time steps between each P2P market are set as $\Delta t = 15$ minutes for a whole day. Next, the framework is further tested in 141-node distribution system [38], [39] for scalability analysis and better explaining the benefits of defining the zones. Simulations are carried out on a PC with Intel Core i7-7700, 3.6 GHz CPU, and 16 GB RAM, with interfacing MATLAB and GAMS softwares.

A. DLMP Results

Based on the hourly forecasting data and LMP data from the wholesale market, DSO performs the DLMP calculation.



(a) DLMP w/ considering prosumers role (b) DLMP w/o considering prosumers role

Fig. 5. 33-node DLMP signals before and after P2P energy exchange.

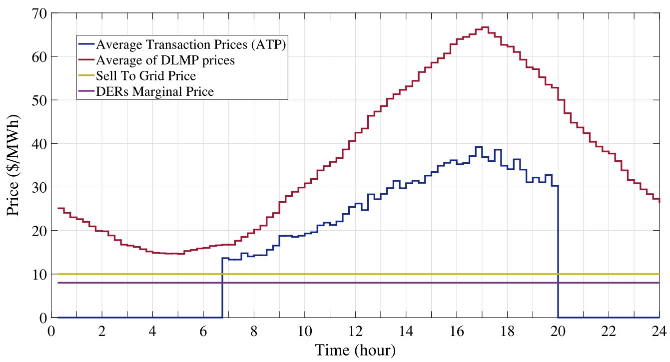


Fig. 6. Comparison of hourly prices w/o and w/P2P market.

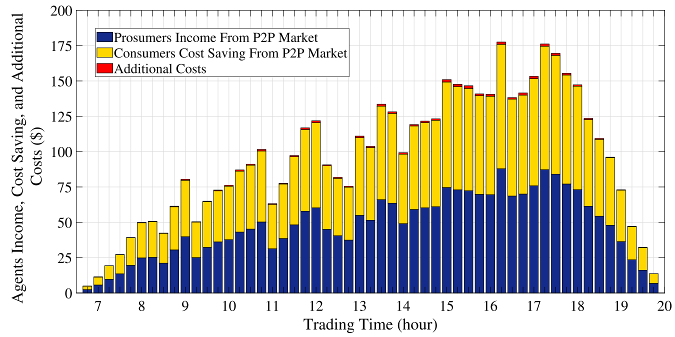
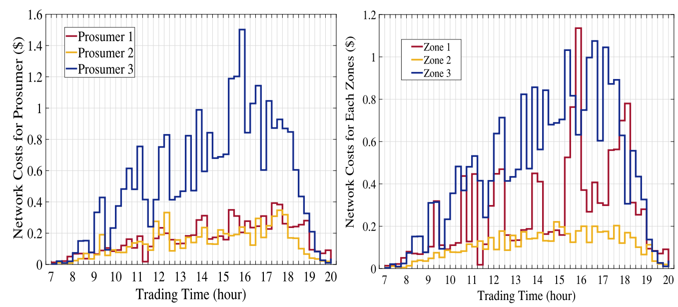


Fig. 7. Prosumers income, consumers cost saving, additional transaction costs in P2P market.



(a) Extra network costs of prosumers (b) Extra network costs of consumers

Fig. 8. Comparison of extra network costs.

Nodal prices of active power for all nodes with and without the participation of prosumers for 24 hours are shown in Fig. 5(a) and Fig. 5(b), respectively. Considering Fig. 5(b), the nodal prices vary between \$15/MWh and \$75/MWh, with the peak in the afternoon around 5 pm due to the peak demand. It should be mentioned that by prosumers participation in the P2P market, the DLMP prices decrease because of surplus energy injection to the grid and neighbors (maximum DLMP price based on Fig. 5(a) is \$66/MWh). Additionally, every 15 minutes, DSO sends these price signals to all consumers, and receives Bp_j, and Bq_j, which help determine the number of agents to participate in P2P market, and the amount of load to be supplied at these time slots.

B. P2P Transaction Prices vs. Traditional DLMP

The average P2P transaction prices for every time slot is shown in Fig. 6. The upper and lower bounds of asks and bids are the average DLMP price and FIT price, respectively, which varies from \$14.6/MWh to \$66.7/MWh. Moreover, in first 7 hours and last 4 hours, the average transaction prices for P2P energy trading is zero, due to zero surplus energy for prosumers to participate in P2P market.

C. Financial Benefits of Participating in P2P Market

To demonstrate how the proposed P2P market benefits both prosumers and consumers, different load and generation scenarios are considered for trading, as shown in Fig. 7. Three bars with different colors show prosumers' income and consumers' cost saving from the P2P market and additional costs associated with each peer for using the DN to trade energy. As MRDA-APM is strongly budget balanced, all traded energy and resulted income and cost saving at each time interval should be equal for both prosumers and consumers, as shown in Fig. 7. Take 1:30-1:45 pm as an example, total power traded at this time interval is 2.793 MW, and the income and cost saving for total prosumers and total consumers are the same of \$66.065, which validates the proposed double auction.

To reveal more details on network costs associated with transactions, Fig. 8(a) and Fig. 8(b) are depicted to present total network costs for each prosumer and all consumers in each zone at different trading hours, respectively. Considering 1:30-1:45 pm in Fig. 8(a), the total network cost is \$1.45 for all prosumers. Based on the formulation, network costs can be calculated based on DLMP differences between two nodes with DSO's final approval of energy transition. Based on Fig. 8(a), prosumer 3 has the highest network cost, due to the cleared prices between prosumer 3 and consumers in zone 3. In some hours, if prosumers 3 asks for higher prices, it can affect DLMP in that zone. As a consequence, DLMP differences become larger, and accordingly network costs increase.

According to the proposed methodology, both consumers and prosumers benefit from participating in the P2P market. Table II and Table III show the benefit improvement with and without participating in P2P market. Table II shows the P2P market benefits for each prosumer. If prosumers only sell surplus energy to the grid with the FIT price, the revenue for each prosumer will be \$378.9, \$393.1, and \$378.9, respectively. However, by participating in P2P market, prosumers can get more benefits. Furthermore, columns 3 and 4 of Table II show the benefit of participating in market without and with considering utility and additional costs. The benefit enhancements

TABLE II
REVENUE OF SELLERS W/O VS. W/P2P MARKET

Sellers	Benefit without P2P ($)	Benefit with P2P ($)		Benefit Improvement (%)
		w/o Utility and Extra Costs	w/ Utility and Extra Costs	
Pros. 1	378.9	1017.9	550.8	45.36
Pros. 2	393.1	702.4	507.7	29.15
Pros. 3	378.9	795.7	484.4	27.84

TABLE III
COST SAVING OF BUYERS W/O VS. W/P2P MARKET

Buyers	Cost without P2P ($)	Cost with P2P and Extra Network Costs ($)	Cost Saving Improvement (%)
Zone 1 Cons.	1783.5	615.82	65.47
Zone 2 Cons.	1841.4	320.12	82.61
Zone 3 Cons.	1772.2	390.74	77.95

for prosumers 1, 2, and 3 with participating in the P2P market and considering additional network costs and utility, are 45.36%, 29.15%, and 27.84%, respectively.

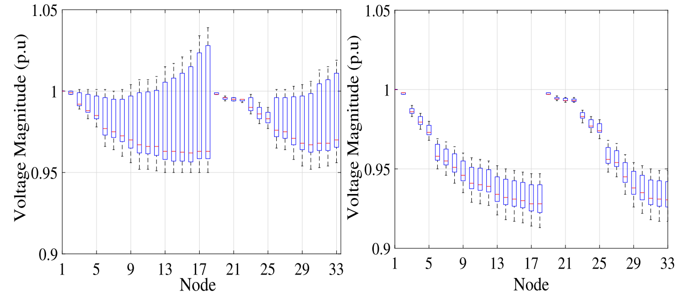
Different from prosumers, if consumers cannot get successfully matched with any prosumer in the auction, they have to purchase power from the grid with DLMP price. Table III shows different scenarios for consumers. For simplicity, the results of consumers cost are demonstrated by comparing aggregated consumers in each zone. If consumers in zones 1, 2, and 3 do not participate in the P2P market, their total cost of paying to receive power from DSO in that time period is $1783.5, $1841.4, and $1772.2, for each zone respectively. However, their cost will be reduced by participating in P2P market. Considering additional costs in consumers' payment, the total cost for zones 1, 2, and 3 is $615.82, $320.12, and $390.74, respectively; and with the cost saving improvement of 65.47%, 82.61%, and 77.59%, respectively.

D. Voltage Comparison w/ and w/o P2P Energy Trading

To capture the voltage issues, two scenarios with and without P2P energy trading are considered to show voltage problems, as shown in Fig. 9(a) and Fig. 9(b) for the 33-node distribution system, and in Fig. 10(a) and Fig. 10(b) for 141-node distribution system, respectively. Comparing results in Fig. 9(b) and Fig. 9(a), the voltage variation without P2P trading as a benchmark is from 0.915 p.u. to 1 p.u., which is increased to the range of 0.95 p.u. and 1.04 p.u. with P2P trading. The reason is that when prosumers have surplus energy during certain times of a day, they participate in the P2P market; depending on whether they are successful in P2P matching or not, prosumers inject power to either supply consumers or sell to the grid, which causes voltages to increase. Additionally, for the 141-node test system, hour 12:30 pm is selected for better analysis of voltage values during the trading period.

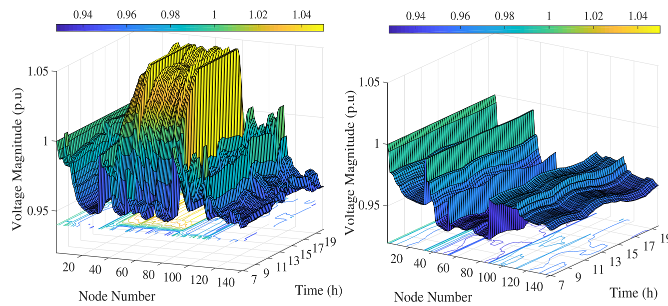
E. Simulation Results for 141-Node Distribution System

For scalability analysis and demonstrating how the zones can benefit both prosumers and consumers, 141-node real distribution system is considered for additional simulations. To



(a) Voltage values w/ P2P market (b) Voltage values w/o P2P market

Fig. 9. 33-node voltage magnitude before and after P2P energy exchange.



(a) Voltages with P2P (b) Voltages without P2P

Fig. 10. Voltage values w/o P2P energy sharing for 141-node distribution network during trading time.

TABLE IV
PROSUMERS LOCATION AND MAXIMUM CAPACITY

Prosumers Location	5	26	30	40,50 60,80	70,95 101,125	138
Capacity (MW)	0.2	0.5	0.75	1.5	1	0.75

validate how the proposed P2P framework works, 12 PV units representing prosumers, and 2 utility-operated DGs (each with the maximum capacity limit of 2 MW) are added to the 141-node system, as shown in Fig. 11. The location of prosumers and DGs and their maximum capacity limits are presented in Table IV. The entire distribution system is divided into 5 zones with the criteria of similar DLMP signals and location of agents. For better analysis, hour 12:30 pm is selected, and the DLMP signals, as well as voltage values, are presented in Fig. 12 and Fig. 13, respectively. Based on Fig. 12, it can be seen that when utility supplies the consumers' demand by purchasing power from upper grid or DGs, the DLMP signals are above $52/MWh. However, if the prosumers participate in the P2P market, then DLMP is reduced due to the cheaper energy supply by prosumers. In addition, the variations of DLMP for different zones depend on the density of prosumers in the zones, the number of prosumers participating in P2P market, the total demand of zones, and the auction design.

To elaborate how defining zones can benefit both prosumers and consumers, different scenarios are designed based on hour 12:30 pm results. The goal is to compare which option is more beneficial for prosumers, to negotiate either with a consumer with a lower bid price within the zone or another consumer with a higher bid price outside the zone. For instance, zone 1 and zone 4 are selected with average DLMP

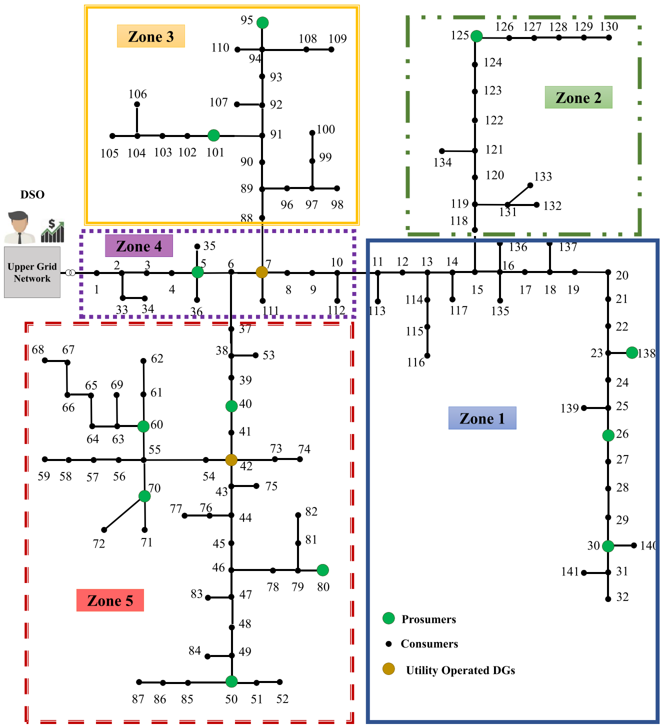


Fig. 11. 141-node distribution test system.

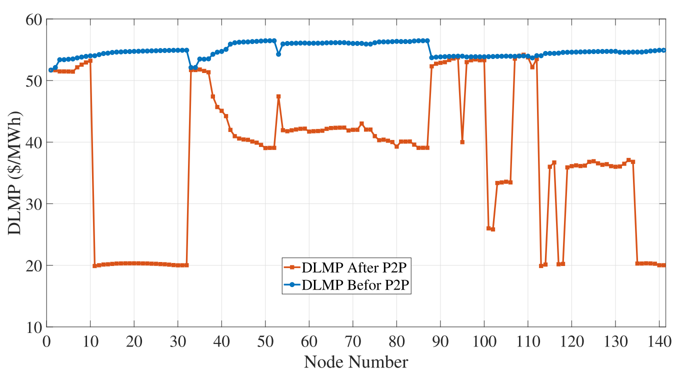


Fig. 12. DLMP price signals in hour 12:30 pm.

prices of $20/MWh and $53/MWh, respectively. Moreover, the operational cost for prosumers is $10/MWh. Two scenarios are proposed to perform the economic analysis for energy trading within and outside the zone. The first scenario can be considered as our proposed model, and the second scenario can be considered as the traditional auction as stated in [16].

In the first scenario, both agents within zone 1 are negotiating with offering prices of $15/MWh (prosumer) and $18/MWh (consumer). Based on the average price mechanism, agents' cleared price is $16.5/MWh. The extra cost for this transaction is calculated based on DLMP differences, which is $0.23/MWh. For simplicity, assuming there is 1 MWh energy flow, and DLMP at prosumer and consumer node is $20.04/MWh and $20.5/MWh, respectively. Total net revenue of prosumer in zone $1 = 16.5 - 10 - 0.23 = \$6.27$; and total cost saving for consumer in zone $1 = 20 - 16.5 + 0.23 = \$3.73$. In the second scenario, agents are negotiating outside their zone (DN-level auction) with offering prices of $15/MWh (prosumer) and $45/MWh (consumer). Based on the average price mechanism, agents' cleared price is $30/MWh, and extra cost for this transaction is $16.5/MWh. Total net revenue of prosumer in zone $1 = 30 - 10 - 16.5 = \$3.5$; and total cost saving for consumer in zone $4 = 53 - 30 + 16.5 = \$39.5$. Based on the results from scenarios 1 and 2, it can be seen that if prosumers negotiate within zones, then the net revenue is higher, compared to the scenario that prosumers trade energy with consumers outside the zone even with higher bid prices. This analysis clearly demonstrates the effectiveness of the proposed model in this paper over the matching presented by [16].

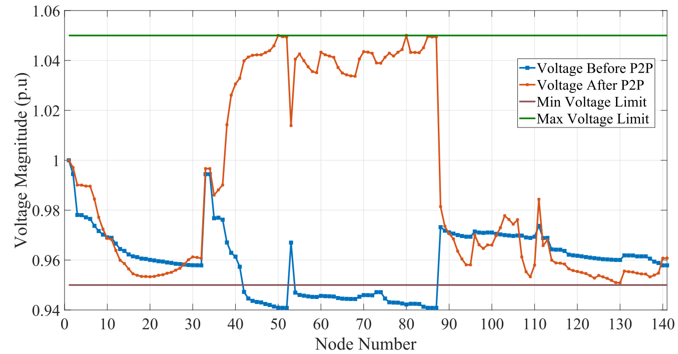


Fig. 13. Voltage magnitudes in hour 12:30 pm.

Besides the presented scenarios, trading outside the zones might be beneficial in some specific scenarios, which mainly depends on the bid prices of agents. For instance, prosumers bid close to the operational cost and consumers bid close to the DLMP signal. However, this scenario is not beneficial (from economic perspective) for agents, since prosumers prefer to maximize their welfare by bidding reasonably high compared to operational cost, and consumers prefer to bid lower for welfare maximization and more cost savings. It is worth mentioning here that if prosumers still have surplus energy after zonal auctions (completely supplying the loads in zonal level), they can negotiate with consumers outside the zones since both peers can benefit from P2P market. But again, this scenario depends on agents behavior and their power/demand amount.

The computational time of the proposed P2P framework depends on calculating the DLMP and P2P matchings in the hierarchical nodal, zonal, and DN-level auction. It should be mentioned that the total computational time for calculating the DLMP and P2P matching of the 141-node test system is 1.6 and 0.25 minutes, respectively, which is more efficient compared to the iterative-based P2P mechanisms. It should also be mentioned that the simulation time depends on the participation level of prosumers, DSO calculating DLMP, and trading time intervals.

VI. Conclusion

This paper proposes a framework for P2P energy exchange in the active distribution network. The framework utilizes the multi-round double auction with an average pricing mechanism, which preserves the rights of agents for negotiation, and gives the priority to neighboring nodes for energy exchange during the multi-round auction. The proposed MRDA-APM also satisfies the auction criteria from economic perspective. Moreover, this paper integrates additional network costs for each transaction, such as power loss cost, voltage regulation cost, etc., into the payments of all prosumers and consumers, through DLMP component decomposition. Simulation results demonstrate the advantage and benefits for not only prosumers and consumers but also DSO (reliable operation and reduce peak hour generation) from the proposed P2P market.

The proposed framework is based on assumptions to provide an alternative with advantages in certain areas, rather than totally replacing other market mechanisms. The possible future research directions include, 1) considering the impact of P2P energy sharing on integrated transmission and distribution network and considering realistic assumptions such as polynomial bid prices for agents; 2) extension of the proposed model by considering the uncertainty of renewable generation and its impact on DLMP and real-time auction models; 3) inclusion of energy storage to address renewable energy curtailment issues, comparing the performance of different energy storage systems, e.g., hydrogen and battery, and analyzing the local markets with considering P2P and hydrogen market; and 4) considering fully distributed P2P market with distributed DLMP and distributed auction with the aim of privacy-preserving of agents.

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