A New Method for Peer Matching and Negotiation of Prosumers in Peer-to-Peer Energy Markets

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***Abstract*—This paper presents a scalable mechanism for peer-to-peer (P2P) energy trading among prosumers in a smart grid. In the proposed mechanism, prosumers engage in a non-mediated negotiation with their peers to reach an agreement on the price and quantity of energy to be exchanged. Instead of concurrent bilateral negotiation between all peers with high overheads, an iterative peer matching process is employed to match peers for bilateral negotiation. The proposed negotiation algorithm enables prosumers to come to an agreement, given that they have no prior knowledge about the preference structure of their trading partners. A greediness factor is introduced to model the selfish behavior of prosumers in the negotiation process and to investigate its impact on the negotiation outcome. In order to recover the costs related to power losses, a transaction fee is applied to each transaction that enables the grid operator to recover incurred losses due to P2P trades. The case studies demonstrate that the proposed mechanism discourages greedy behavior of prosumers in the negotiation process as it does not increase their economic surplus. Also, it has an appropriate performance from the computation overheads and scalability perspectives.**

***Index Terms*—Decentralized algorithm, market design, multi-issue negotiation, peer-to-peer market, prosumer, smart grids, transaction fee.**

I. Introduction

A. Motivation and Problem Statement

THE transition from centralized to decentralized electricity networks has been accelerated in recent years. This has facilitated by fast deployment of distributed energy resources (DER), in line with grid modernization, initiated by the recent advances in information and communication technology. As a part of this transition, customers are becoming prosumers, proactive players who can manage their flexible resources in response to market signals [1]. Existing market paradigms do not facilitate the active participation of prosumers in energy markets. Hence, new liberalized market structures are needed to pave the path for the prosumers participation in energy markets. Within this context, new market structures have been proposed in recent studies to incorporate prosumers in energy trading through local transactive markets [2], and peer-to-peer (P2P) energy trading [3].

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P2P energy trading offers several advantages to prosumers including autonomy, their ability to express individual preferences, and a competition in a transparent market [4]. In the P2P trading, it is preferred to settle bilateral energy trade transactions through direct negotiation of peers with the minimum possible influence from a third party, while trading peers have no prior knowledge of the preferences of other peers [5]. There are several challenges in designing an appropriate mechanism for P2P trading of prosumers. At first, P2P trading incorporates a large number of prosumers with various and even conflicting interests. Hence, it is important to develop a fair and scalable negotiation mechanism that enables prosumers to participate in the market based on their preferences, without revealing their private information to a third party. Secondly, a challenge when implementing P2P markets is related to dealing with power losses in energy trading. Indeed, transactions between seller and buyer prosumers inevitably determine power losses, which entail an extra energy amount and cost that must be recovered by either the grid operator or each market player [6]. Hence, the aim of this paper is to address the aforementioned challenges by designing a fair and scalable negotiation mechanism for P2P energy trading between prosumers considering power losses in the transactions.

B. Related Works

Mechanism design for P2P energy trading has been reported in several recent works. According to the adopted technical approach for designing the market scheme, existing P2P energy trading methods can be divided in three groups namely, auction-based, game theory, and optimization-based [5]. In auction-based methods, market players participate in the market by submitting their offers/bids to an auctioneer [7]–[9]. Game theory can be used to model behavior and decisions of market participants through cooperative and non-cooperative games [10], [11]. Optimization-based approaches model the P2P trading as an optimization problem, which can be solved using different optimization techniques, such as consensus methods [12], and alternating direction method of multipliers (ADMM) [13].

In terms of the negotiation mechanism, the methods proposed in the literature can be divided into two categories based on the interaction of market participants; mediated and non-mediated negotiations [14]. In a mediated negotiation, a non-biased mediator facilitates the negotiation between market participants, while in a non-mediated negotiation, market

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participants directly negotiate with each other. The mediated negotiation forms as a many-to-one negotiation between prosumers and a third party. Morstyn *et al.* [15] proposed a bilateral contract network for P2P energy trading, which is designed based on many-to-one negotiation between prosumers and a supplier as an intermediary between the generators and the prosumers. In [16], a virtual agent is introduced as an intermediator on behalf of all prosumers to proceed the negotiation with an aggregator. Zhang *et al.* [17] employed a unilateral auction mechanism for P2P trading, in which a market operator is the mediator of the negotiation and constructs the P2P matching between producers and consumers. In [18], a non-profit platform is considered as a tool for the communication and negotiation of energy buildings within a community. However, decentralized implementation of P2P trading requires an algorithm for market settlement, which can be executed with the least influence from a third party. In the mediated methods, prosumers need to negotiate with a third party, instead of direct negotiation with their peers, which can raise scalability issues and may affect the fairness of the negotiation process.

The non-mediated negotiation is another type of negotiations, which can be formed as a many-to-many negotiation between all prosumers, or as a one-to-one negotiation between a seller and a buyer prosumer. Many-to-many negotiation requires a full P2P communication network which allows all agents to concurrently negotiate on their actions in the market. In [12], a P2P market structure based on a multi-bilateral economic dispatch formulation is presented, which enables prosumers to directly negotiate with each other for multi-bilateral trading. The peer-centric configuration in [19] and the fully decentralized market structure proposed in [20] are other examples of a P2P trading platform with many-to-many negotiation. However, this type of negotiation results in significant computational and communication overheads. In order to reduce the computation and communication complexities of the negotiation mechanism, decomposition techniques can be used to decompose the negotiation problem into several concurrent negotiations. The P2P frameworks in [21] and [22] employ the one-to-one negotiation as the negotiation strategy, in which prosumers engage in bilateral negotiations with peers to mutually agree on the energy quantity and price in the transactions. Nonetheless, designing a negotiation mechanism with a low computational complexity is a challenging task due to barriers in achieving a fair market outcome considering the greediness of prosumers. To that end, we propose an iterative peer matching process that decomposes the negotiation mechanism into several concurrent negotiations among seller and buyer prosumers taking into account their offers and greediness.

In resolving the challenges associated with grid-related aspects of P2P trading, several works employ the concept of transaction fee for trades in P2P markets to recover the costs incurred due to the energy transactions [8], [9], [13], [19], [23], [24]. In [8], a methodology based on the sensitivity analysis is presented to assess the impact of each trade on the network and to allocate additional costs associated with the network constraints to the users involved in the transaction. The power transfer distribution factor (PTDF) is used in [9] to calculate the transaction fee to avoid line flow congestion in bilateral trades. Baroche *et al.* [23] consider the electrical distance between zones as the base for transaction fee calculation. In [24], PTDF is employed to calculate the transaction fee, which needs to be paid by the energy buyers. The works in [9], [23], [24] only consider the distance in the transaction fee calculation and neglect the cost incurred to the network by power losses. The distribution locational marginal price (DLMP) is utilized in [13] and [19] for grid utilization charge calculation in P2P trades. However, in these works, the transaction fee is not used during the peer matching process, but it has been used during the negotiation to adjust prosumers' offers in the market. The calculation of the transaction fee at each iteration increases the computational complexity of the mechanism and may cause the market settlement to take a longer time.

Accordingly, in this paper a transaction fee, calculated based on power losses, is employed that enables the grid operator to recover the losses due to the P2P transactions. The transaction fees are estimated and sent to prosumers before the peer matching process. The transaction fee calculation does not need to occur at each iteration of the negotiation, which consequently avoids increasing the computational complexity of the mechanism.

C. Contributions and Organization of the Paper

This paper proposes a new method for the peer matching and negotiation of prosumers for P2P energy trading, where prosumers greedily participate in the market and try to maximize their economic surplus. The proposed method has two main steps, namely, peer matching and negotiation. At the beginning of the market, prosumers advertise their energy by submitting their offers to a public database. After reading offers from the database, prosumers select their trading partners by directly exchanging information with them in the peer matching process. Then, in the negotiation step seller and buyer prosumers directly negotiate with each other to reach agreement on the price and quantity of energy to be exchanged. For the negotiation, a mechanism is presented that guarantees a stable outcome acceptable by both parties. The transaction fee is defined based on the impact of each trade on the network power losses and is used in the peer matching process to incentivize prosumers to prioritize their trades based on their impact on the grid. The main contributions of this paper are following:

- We propose a new method for P2P energy trading among prosumers, which allows them to select their trading partners, and negotiate directly with them without any third-party intervention. The results of the proposed method are compared with the case of a centralized market settlement, and the decentralized methods with many-to-many negotiation.
- We design a non-mediated negotiation algorithm that is remarkably computationally-efficient as it does not require peers to directly solve an optimization problem at each iteration. Also, the greedy behavior of prosumers

in the negotiation is analyzed to evaluate how greediness can affect prosumers' surplus in the market.

- We define a transaction fee which enables the grid operator to recover the costs related to power losses in P2P transactions. This fee is utilized in the peer matching process to incite prosumers to select their trading partners based on the impact of their trades on the grid.

The rest of this paper is organized as follows: Section II presents the problem formulation; Section III describes market settlement algorithm, including the peer matching process, and the negotiation approach; Section IV provides the case studies and discusses the results. Finally, conclusions are summarized in Section V.

II. Problem Formulation

A. Assumptions

A distribution system is considered with an electrical and a communication network. The considered electrical network is a radial distribution network $\mathcal{G}(\mathcal{B}, \mathcal{L})$, consisting of a set of nodes with index $b \in \mathcal{B}$ and a set of lines with index $l \in \mathcal{L}$ connecting these nodes. Prosumers and the grid operator have two-way communication facilities and communicate through an appropriate communication platform. Different types of communication architectures can be employed for P2P trading, such as structured, unstructured, and hybrid architectures [25]. The adopted architecture should fulfill a set of performance metrics including latency, reliability, throughput, and security[1]. We consider a structured communication graph, such that each prosumer is able to negotiate with any other prosumer. However, the proposed method can be employed for the systems with the incomplete communication graph, in which the communication for information exchange is restricted to a preassigned communication graph. Blockchain and distributed ledger technologies can be used as the platform for information exchange in the communication layer [26], [27]. Each prosumer has the capability to negotiate, accept, and reject other prosumers' offers based on its preferences. Any accepted offer becomes the prosumer's commitment, which needs to be delivered through the electrical network. The market is a forward market, in which prosumers negotiate on the trade for the next time interval.

B. Market Objective

Let $\mathcal{N}$ be the set of prosumers in the market. At each time interval, prosumers participate in the market to trade power p_n with their peers. The aim of the market settlement is to find the optimal energy dispatch among prosumers such that their total economic surplus is maximized. Hence, the optimization problem can be modeled as

$$\max_{p_n} \sum_{n \in \mathcal{N}} E_n(p_n) \tag{1a}$$

$$\text{s.t.} \quad p_n = \sum_m p_{nm} \tag{1b}$$

$$\underline{p}_n \leq p_n \leq \overline{p}_n \tag{1c}$$

$$p_{nm} + p_{mn} = 0, \qquad \forall n, m \in \mathcal{N} \tag{1d}$$

$$p_{nm} \geq 0, \qquad \forall n \in \mathcal{N}_S \tag{1e}$$

$$p_{nm} \leq 0, \qquad \forall n \in \mathcal{N}_B \tag{1f}$$

where, E_n is the economic surplus of prosumer n. Prosumers participating in the P2P market are divided into two subsets $\mathcal{N}_S$ and $\mathcal{N}_B$ indicating seller and buyer prosumers, respectively. Prosumer n is a seller ($n \in \mathcal{N}_S$) if $p_n > 0$, and is a buyer ($n \in \mathcal{N}_B$), if $p_n < 0$. The sum of trades indicates the total generated/consumed power by the prosumer as in (1b), where m is index of any trading partner of prosumer n. It is assumed that prosumers have a range of flexibility for the power they want to trade in the market, as in (1c). Eq. (1d) imposes demand-supply constraint in each transaction. From the market design point of view, the aim is to design a market settlement mechanism, which allows the prosumers to negotiate with their peers, without any intervention of a third party in the negotiation process, to reach an agreement on the quantity and price of energy in each trade, while maximizing their economic surplus.

C. Prosumer Model

We consider a nonexclusive model for the prosumers, such that each prosumer can be equipped with different types of DER, and is able to manage the optimal set points of its assets, i.e. PV, storage and flexible loads. Prosumers are assumed to be economically rational who try to maximize their individual economic surplus through participating in P2P trading, either as a seller or a buyer. The economic surplus of each prosumer can be modeled by

$$E_n(p_n) = \sum_m \hat{\lambda}_{nm} p_{nm} - \frac{1}{2}\alpha_n p_n^2 - \beta_n p_n, \tag{2}$$

where, $\alpha_n, \beta_n > 0$ are two constants representing cost (utility) of prosumer, and $\hat{\lambda}_{nm}$ is the perceived per unit price of energy for the trade between prosumer n and m. This price indicates the final profit/cost of the prosumer in the market after paying the costs related to each transaction, i.e.

$$\hat{\lambda}_{nm} = \begin{cases} \lambda_{nm} - \tau_{nm}, & n \in \mathcal{N}_S \\ \lambda_{nm} + \tau_{nm}, & n \in \mathcal{N}_B \end{cases} \tag{3}$$

where λ_{nm} is the energy price in transaction between prosumer n and m, and τ_{nm} is the transaction fee paid by the prosumer n to the grid operator for recovering costs of power losses related to their trade. In (2), the first term refers to the received/paid money by the seller/buyer prosumer, while the second and third terms represent the generation cost for the seller prosumer, and willingness to pay for the energy of the buyer prosumer. For a seller prosumer, these terms reflect the cost of producing the power p_n, whereas for a buyer prosumer, these terms reflect the negative amount the buyer is willing to pay for the power $|p_n|$. More details on the modeling of cost (or willingness to pay) function can be found in [28].

[1]These performance metrics are defined in IEEE 1547.3-2007 for communication networks for integrating DER applications into power networks.

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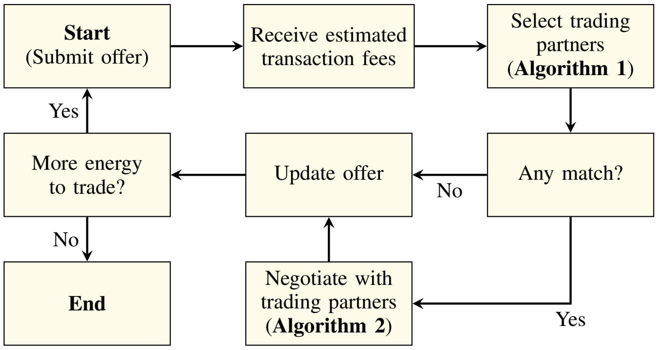

Fig. 1. Flowchart of market settlement algorithm.

Each prosumer tries to maximize its economic surplus individually. From the first and second order derivatives of (2) we have

$$\frac{\partial E_n(p_{nm})}{\partial p_{nm}} = \lambda_{nm} \pm \tau_{nm} - \alpha_n p_n - \beta_n = 0 \tag{4a}$$

$$\lambda_{nm} = \alpha_n p_n + \beta_n \pm \tau_{nm} \tag{4b}$$

$$\frac{\partial^2 E_n(p_{nm})}{\partial p_{nm}^2} = -\alpha_n < 0. \tag{4c}$$

Equation (4b) indicates the marginal (reservation) price of each prosumer at a given power p_n. For each seller prosumer, λ_{nm} obtained from this equation gives the minimum price that the seller is willing to accept to sell its energy, while for a buyer prosumer this price denotes the maximum price the buyer is willing to pay for the energy. Therefore, this equation will be used by the sellers and buyers to determine the minimum/maximum price that seller/buyer is willing to accept/pay for the power. However, prosumers may want to participate in the market using a different strategy rather than using their marginal cost/benefit function to increase their economic surplus. Hence, we define a greediness factor ($g > 0$), which will be used by prosumers to change their bidding strategy. For the sake of notational brevity, we use indices i and j for seller and buyer prosumers in subsets $\mathcal{N}_S$ and $\mathcal{N}_B$, respectively. In the rest of the paper, p_j refers to $|p_n|, \forall n \in \mathcal{N}_B$. Therefore, (4b) can be rewritten as:

$$\begin{cases} \lambda_{ij} = \alpha_i p_i + \beta_i(1+g_i) + \tau_{ij}, & \forall i \in \mathcal{N}_S \\ \lambda_{ji} = -\alpha_j p_j + \beta_j(1-g_j) - \tau_{ij}, \forall j \in \mathcal{N}_B \end{cases} \tag{5}$$

where g_i and g_j indicate greediness of seller and buyer prosumers, respectively. Using these factors, a seller prosumer increases its minimum acceptable price, and a buyer prosumer reduces its maximum payable price for any given power.

III. Market Settlement Algorithm

In designing the market settlement algorithm for P2P trading, the objective is to match seller and buyer prosumers for the negotiation and to design a non-mediated negotiation process that does not require any private information of peers. The market settlement algorithm from a prosumer's point of view is given in Fig. 1. The market settlement has two main steps, i.e. peer matching process and the negotiation step. In the peer matching step, prosumers submit their offers, and select their trading partners for the negotiation based on their offers and transaction fees. Then, in the negotiation step, prosumers negotiate with their trading partners to reach an agreement on the price and quantity of the energy in each trade. Then, prosumers update their offers based on the agreement in each round of the peer matching process and submit new offers if they need a new trading partner. In the proposed method, both the peer matching and negotiation steps are iterative. The iteration in the peer matching step appears for all prosumers simultaneously, while in the negotiation step, the iteration appears for each matched prosumers.

The following rules are considered for the market settlement process:

- The final price in the transaction between seller and buyer is bounded by their initial offers in the peer matching process.
- A seller and buyer can form a partnership if the seller has capability to provide the minimum demand of the buyer. Hence, sellers offer their maximum generation in their initial offers, while buyers initiate with offering their minimum demand requirement.
- The negotiation process has a deadline, and if prosumers cannot reach an agreement with their trading partners before the deadline, they cannot trade in the market and have to wait for the next round of the peer matching to find a new trading partner.
- There is a deadline for the peer matching process, and if prosumers cannot form any trading partnership before the deadline, they cannot trade in the P2P market.

Fig. 2 shows the information flow in the proposed method. It has to be pointed that, while there is a need for a public database for prosumers to submit their offers and read other prosumers offers, the peer matching and negotiation steps do not need any third party intervention, as explained in the rest of this section.

A. Peer Matching Process

For the peer matching process, we consider a greedy algorithm, in which each prosumer tries to select its trading partners such that the expected economic surplus is maximized. Peer matching step is an iterative process that forms all possibles trading pairs among prosumers. Each transaction in the market is subject to the power losses, which need to be compensated to maintain the demand-supply balance in the network. It is assumed that the grid operator injects the extra power required to recover the power losses, and in turn, charges prosumers based on their contribution in the network losses. For each line $l \in \mathcal{L}$, losses can be calculated as $\gamma^l (p^l)^2$, where γ^l is a constant parameter which gives the ratio of the line's resistance over the square of the network's nominal voltage (R^l/V_b^2), and p^l is the power flowing through that line [29]. In order to define the share of each transaction from the losses incurred in each branch, we need to know how the injected power by the seller is distributed across the network. Hence, we use the PTDF matrix, which quantifies the fraction of transacted power from a seller to a buyer that flows over a

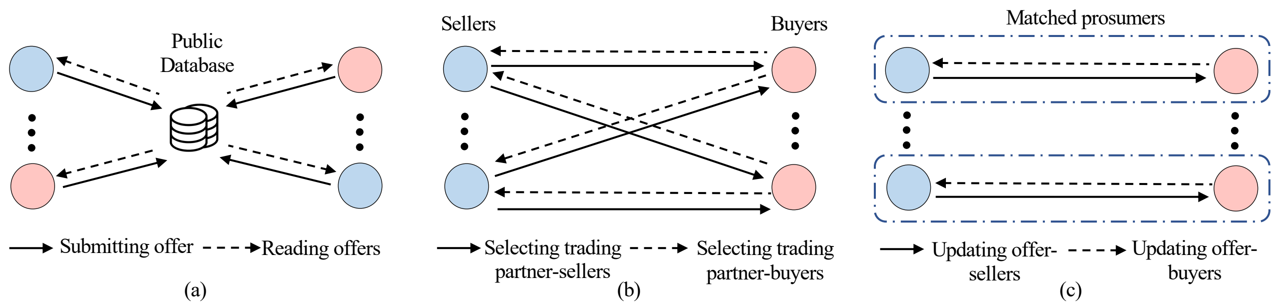

Fig. 2. Information flow in the proposed method; a) all prosumers submit their initial offers and read offers from the database, b) prosumers select their trading partners by exchanging their peer selection indices calculated using Algorithm 1, c) matched prosumers negotiate by exchanging their offers calculated using Algorithm 2.

given line and can be obtained using the line susceptance and the bus susceptance matrices [30]. Using the PTDF, the power flowing through line l due to transaction between prosumer i and j can be calculated as

$$p^l_{ij} = \phi^l_{ij} p_{ij}, \tag{6}$$

where, ϕ^l_{ij} denotes an element of PTDF matrix which indicates the incremental change in power that flows in line l due to power transfer between prosumer i and j. The total losses incurred by the transaction between prosumer i and j can be calculated by summing over losses in all lines

$$\chi_{ij} = \sum_{l \in \mathcal{L}} \gamma_l (p^l_{ij})^2. \tag{7}$$

The losses will be compensated by the grid operator and prosumers need to pay the cost related to their trades to the grid operator. The cost for compensating losses in each trade is modeled as a transaction fee, which is equally shared between the seller and buyer. The transaction fee for the trade between seller i and buyer j is calculated as

$$\tau_{ij} = \frac{\chi_{ij}}{2}\omega, \tag{8}$$

where, ω is a price coefficient indicated by the grid operator to set the price for the losses.

Definition: Let $\mathbf{A}^S$ represents the $\mathcal{N}_S \times \mathcal{N}_B$ peer selection matrix by sellers, where $\mathbf{A}^S_i$ is the i^{th} row indicating selected peer by seller i, and $a^S_{ij} \in \{0, 1\}$ indicates whether buyer j is selected by seller i or not. If $a^S_{ij} = 1$, seller i intends to form a partnership with buyer j, and otherwise, $a^S_{ij} = 0$. Similarly, $\mathbf{A}^B$, $\mathbf{A}^B_j$, and a^B_{ji} represent $\mathcal{N}_B \times \mathcal{N}_S$ peer selection matrix by buyers, the j^{th} row indicating selected peer by buyer j, and buyer decision to form partnership with seller i, respectively.

Remark: A partnership between seller i and buyer j is formed if and only if both seller and buyer simultaneously select each other as a trading partner, i.e. $a^S_{ij} = a^B_{ji} = 1$.

It is assumed that there is a platform which enables prosumers to submit their offers and inform other prosumers about their willingness to trade in the upcoming time slot. The offer of seller i and buyer j can be represented by $O_i = (p_i, \lambda_i)$, and $O_j = (p_j, \lambda_j)$, respectively. These offers are stored in a public database managed by the grid operator, which can be accessed by the prosumers for reading offers and selecting their trading partners (as shown in Fig. 2a).

Before starting the peer matching process, all prosumers read offers from the database and receive the transaction fees for potential transactions from the grid operator. The peer matching process starts by buyers sending vectors of their selected peers to sellers. Let r denotes the index of iteration in the peer matching process, and R indicates the maximum number of allowable peer matching rounds. In each iteration r, after receiving offers from buyers, sellers start to select the best trading partners among them. Sellers arrange all available offers in descending order based on the perceived price for each transaction considering the transaction fees. Then, they will select their preferred trading partners based on the best available offers. In this step, each seller forms vector $\mathbf{A}^{S,r}_i$, which indicates the selected peer by the seller i at iteration r of the peer matching process. Similarly, after receiving offers from sellers, each buyer selects its trading partner and forms vector $\mathbf{A}^{B,r}_j$. If a partnership is formed, i.e. $a^{S,r}_{ij} = a^{B,r}_{ji} = 1$, offers of seller i and buyer j will be removed from the database. Then, peer matching iteration index will be updated and unmatched peers explore the database again to find their trading partners from the available offers. This algorithm repeats until there is no more potential partnership. It should be noted that there is a deadline for each round of peer matching process ($r = R$), and if prosumers cannot form any trading partnership before the deadline, they cannot trade in the P2P market. Prosumers who lose the P2P market can trade energy with the grid at the fixed rates, e.g. feed-in-tariffs and time of use prices for sellers and buyers prosumers, respectively. Algorithm 1 shows the peer matching process for both seller and buyer prosumers.

B. Negotiation Strategy

After the peer matching process, prosumers start a multi-issue negotiation to reach an agreement on the quantity and price of the energy in the transaction. The aim is to design a negotiation strategy that enables prosumers to come to an agreement, given that they have no prior knowledge about the preference structure of their trading partners. It should allow prosumers to make autonomous decisions by maximizing their economic surplus through a direct negotiation. The negotiation approach is based on an alternating offer production mechanism guaranteeing convergence to a unanimous feasible agreement [31]. Prosumers start the negotiation with an offer

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Algorithm 1: Peer matching Algorithm

——————— Algorithm for each seller $i \in \mathcal{N}_S$ ———————

Input: O_j^r, $a_{ji}^{B,r}$, τ_{ij} for any potential trading partner

while $Match = 0$ ***or*** $r \leq R$ **do**

  Arrange all $j \in \mathcal{N}_B^r$ in descending order such that: $\lambda_j - \tau_{ij} > \lambda_{j+1} - \tau_{ij+1}$

  for $j = 1$ *to* $\mathcal{N}_B^r$ **do**

    if $p_i \geq p_j$ **then**

      $1 \leftarrow a_{ij}^{S,r}$

    else

      $0 \leftarrow a_{ij}^{S,r}$

    end

    if $a_{ij}^{S,r} = a_{ji}^{B,r} = 1$ **then**

      $1 \leftarrow Match$

      Go to Algorithm 2

    end

  end

  Set $r + 1 \leftarrow r$

  Send $a_{ij}^{S,r+1}$ to the buyers

end

——————— Algorithm for each buyer $j \in \mathcal{N}_B$ ———————-

Input: O_i^r, $a_{ji}^{S,r}$, τ_{ij} for any potential trading partner

while $Match = 0$ ***or*** $r \leq R$ **do**

  Arrange all $j \in \mathcal{N}_S^r$ in ascending order such that: $\lambda_i - \tau_{ji} < \lambda_{i+1} - \tau_{ji+1}$

  for $i = 1$ *to* $\mathcal{N}_S^r$ **do**

    if $p_j \leq p_i$ **then**

      $1 \leftarrow a_{ji}^{B,r}$

    else

      $0 \leftarrow a_{ji}^{B,r}$

    end

    if $a_{ji}^{B,r} = a_{ij}^{S,r} = 1$ **then**

      $1 \leftarrow Match$

      Go to Algorithm 2

    end

  end

  Set $r + 1 \leftarrow r$

  Send $a_{ji}^{B,r+1}$ to the sellers

end

generating the highest possible economic surplus by setting their greediness factor to a high value and continue by decreasing their greediness to reach an agreement.

Fig. 3 depicts the interaction of a seller and a buyer prosumer. Each prosumer has an aspiration region, which indicates the area in the target economic surplus space within which a prosumer aspires to come to an agreement with its trading partner. Also, each prosumer has a marginal cost/benefit line, which reveals the minimum/maximum price for each amount of energy that each prosumer is willing to accept/pay. Prosumers neither propose nor accept any offer which is out of their aspiration zone. As stated in Section II-C, and equation (5), prosumers can use different greediness factors to adjust this line to increase their economic surplus. Depending on the greediness of trading peers, there are several potential agreement points in the zone of agreement. It should be noted that the zone of agreement is unknown to the negotiators as none of them knows their trading partner's aspiration region. Thus, the negotiation mechanism should allow prosumers to reach an agreement, which is in their acceptable zone of actions, considering that none of the peers has any explicit knowledge of the zone of agreement.

The negotiation mechanism is an iterative process with k as iteration index. The pseudocode for the negotiation process

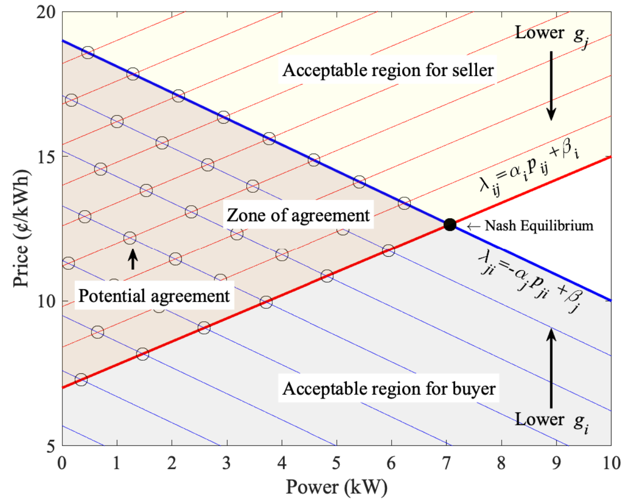

Fig. 3. Illustration of offers by seller and buyer prosumers during the negotiation.

is provided in Algorithm 2. After being matched with a peer, each seller $i \in \mathcal{N}_S$ and buyer $j \in \mathcal{N}_B$ first calculates its reservation price for the demanded/offered quantity by the buyer/seller using (9a) and (9b), respectively

$$\lambda_{ij,r}^k = \alpha_i p_{ji}^k + \beta_i (1 + g_i^k) + \tau_{ij} \tag{9a}$$

$$\lambda_{ji,r}^k = -\alpha_j p_{ij}^k + \beta_i (1 - g_j^k) - \tau_{ij}. \tag{9b}$$

Each prosumer checks if the price offered by the peer is in its aspiration zone or not, by comparing it with its reservation price

$$|\lambda_{ij,r}^k - \lambda_{ji}^k| < \epsilon, \forall i \in \mathcal{N}_S \tag{10a}$$

$$|\lambda_{ji,r}^k - \lambda_{ij}^k| < \epsilon, \forall j \in \mathcal{N}_B. \tag{10b}$$

If so, the seller and buyer accept the offer and update their power and price using (11) and (12) respectively

$$\begin{cases} p_{ij}^{k+1} &= \max(\underline{p}_i, p_{ji}^k) \\ \lambda_{ij}^{k+1} &= \alpha_i p_{ij}^{k+1} + \beta_i (1 + g_i^k) + \tau_{ij} \end{cases} \quad \forall i \in \mathcal{N}_S \tag{11}$$

$$\begin{cases} p_{ji}^{k+1} &= \min(\overline{p}_j, p_{ij}^k) \\ \lambda_{ji}^{k+1} &= -\alpha_i p_{ji}^{k+1} + \beta_j (1 - g_j^k) - \tau_{ij} \end{cases} \quad \forall j \in \mathcal{N}_B. \tag{12}$$

If the offered price by the peer is not close to the prosumer reservation price for the offered quantity, prosumers check if the offered quantity by the peer is the same as their offered quantity i.e.

$$|p_{ij}^k - p_{ji}^k| < \epsilon, \forall i \in \mathcal{N}_S \text{ and } \forall j \in \mathcal{N}_B. \tag{13}$$

If this is the case, seller accepts the offer only if $\lambda_{ji}^k \geq \lambda_{ij}^k$, and offer is acceptable for the buyer if $\lambda_{ij}^k \geq \lambda_{ji}^k$. Then, they update their prices by (14)

$$\lambda_{ij}^{k+1} = \lambda_{ji}^{k+1} = \frac{\lambda_{ij}^k + \lambda_{ji}^k}{2}. \tag{14}$$

In the case that a seller and a buyer have reached an agreement on the quantity, but the offered price by the peer is

Algorithm 2: Negotiation Algorithm

——— Algorithm for each seller $i \in \mathcal{N}_S$ ———

Initialization: $p_{ij}^k \leftarrow \overline{p}_i$, $\lambda_{ij}^k \leftarrow \alpha_i p_{ij}^k + \beta_i(1+g_i^k) + \tau_{ij}$, $k \leftarrow 1$

while $|O_{ij}^{k+1} - O_{ij}^k| < \epsilon$ *or* $k \leq K$ **do**
- Receive O_{ji}^k from the buyer
- Calculate $\lambda_{ij,r}^k$ using (9a)
- **if** $|\lambda_{ij,r}^k - \lambda_{ji}^k| < \epsilon$ **then**
  - Update p_{ij}^{k+1} and λ_{ij}^{k+1} using (11)
- **else**
  - **if** $|p_{ij}^k - p_{ji}^k| < \epsilon$ **then**
    - **if** $\lambda_{ji}^k \geq \lambda_{ij}^k$ **then**
      - Update λ_{ij}^{k+1} using (14)
    - **else**
      - Update λ_{ij}^{k+1} using (15a)
    - **end**
    - Set $p_{ij}^{k+1} \leftarrow p_j^k$ and $g_i^{k+1} \leftarrow g_i^k$
  - **end**
  - Update g_i^{k+1}, p_{ij}^{k+1}, and λ_{ij}^{k+1} using (16a), and (17)
- **end**
- Set $k+1 \leftarrow k$
- Send O_{ij}^{k+1} to the buyer

end

——— Algorithm for each buyer $j \in \mathcal{N}_B$ ———

Initialization: $p_{ji}^k \leftarrow \underline{p}_j$, $\lambda_{ji}^k \leftarrow -\alpha_j p_{ji}^k + \beta_j(1-g_i^k) - \tau_{ij}$, $k \leftarrow 1$

while $|O_{ji}^{k+1} - O_{ji}^k| < \epsilon$ *or* $k \leq K$ **do**
- Receive O_{ij}^k from the seller
- Calculate $\lambda_{ji,r}^k$ using (9b)
- **if** $|\lambda_{ji,r}^k - \lambda_{ij}^k| < \epsilon$ **then**
  - Update p_{ji}^{k+1} and λ_{ji}^{k+1} using (12)
- **else**
  - **if** $|p_{ij}^k - p_{ji}^k| < \epsilon$ **then**
    - **if** $\lambda_{ij}^k \leq \lambda_{ji}^k$ **then**
      - Update λ_{ji}^{k+1} using (14)
    - **else**
      - Update λ_{ji}^{k+1} using (15b)
    - **end**
    - Set $p_{ji}^{k+1} \leftarrow p_{ij}^k$ and $g_j^{k+1} \leftarrow g_j^k$
  - **end**
  - Update g_j^{k+1}, p_{ji}^{k+1}, and λ_{ji}^{k+1} using (16b), and (18)
- **end**
- Set $k+1 \leftarrow k$
- Send O_{ji}^{k+1} to the seller

end

not acceptable for them, they adjust their prices using (15) to incetivize the peer to continue the negotiation

$$\lambda_{ij}^{k+1} = \max(\lambda_{ij,r}^k, \lambda_{ij}^k - \mu_{\lambda,i}) \quad (15a)$$

$$\lambda_{ji}^{k+1} = \min(\lambda_{ji,r}^k, \lambda_{ji}^k + \mu_{\lambda,j}), \quad (15b)$$

where μ_λ is a small positive constant adjusting offered price. As the economic surplus of a prosumer obtained by agreement is higher than that without an agreement, if there is no agreement on neither the price nor the quantity, prosumers reduce their greediness factor using (16) to reduce the risk of no agreement solution at the end of the negotiation,

$$g_i^{k+1} = \max(0, g_i^k - \mu_{g,i}) \quad (16a)$$

$$g_j^{k+1} = \max(0, g_j^k - \mu_{g,j}), \quad (16b)$$

where μ_g is a tuning parameter for the greediness factor reflecting prosumer willingness to move toward the potential agreement. After updating the greediness factor, the seller and the buyer update their offered quantity and price using (17) and (18), respectively

$$\begin{cases} p_{ij}^{k+1} &= \max(\underline{p}_i, p_{ij}^k - \mu_{p,i}(p_{ij}^k - p_{ji}^k)) \\ \lambda_{ij}^{k+1} &= \alpha_i p_{ij}^{k+1} + \beta_i(1+g_i^{k+1}) + \tau_{ij} \end{cases} \quad \forall i \in \mathcal{N}_S \quad (17)$$

$$\begin{cases} p_{ji}^{k+1} &= \min(\overline{p}_j, p_{ji}^k + \mu_{p,j}(p_{ji}^k - p_{ij}^k)) \\ \lambda_{ji}^{k+1} &= -\alpha_j p_{ji}^{k+1} + \beta_j(1-g_j^{k+1}) - \tau_{ij} \end{cases} \quad \forall j \in \mathcal{N}_B, \quad (18)$$

where μ_p is the tuning parameter for offered energy. Once the new price and power are calculated, prosumers send their new offers to their trading peer. The negotiation ends if no changes occur during an iteration, or if it reaches the maximum number of iterations ($k = K$). Here, K is the deadline of the negotiation process, and if prosumers cannot reach an agreement with their trading partners, they have to wait for the next round of peer matching to find a new trading partner.

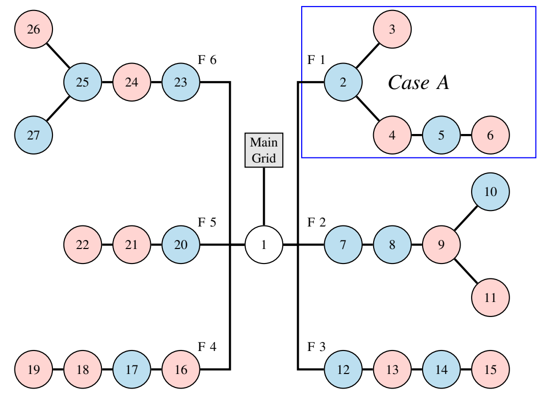

Fig. 4. 27 Bus LV distribution network model [32].

IV. Case Study

In this section, the feasibility and performance of the proposed mechanism for P2P energy trading are numerically analyzed. The case studies are carried out using the 27 bus distribution test system from [32]. The test system is illustrated in Fig. 4, and bus and branch data are same as [32]. We consider two cases of varied scales markets:

- *Case A:* A market with five players connected to different buses in feeder 1 to investigate the performance of the proposed method in the negotiation step and to analyze the impact of the greediness of players in the market.
- *Case B:* A market with 26 players connected to different buses in all feeders to demonstrate the impact of considering transaction fees and also the scalability of the proposed method. Moreover, this case is used to compare the performance of the proposed mechanism with the results of a centralized mechanism, simultaneous peer matching and negotiation, and many-to-many negotiation [20].

All case studies have been implemented using MATLAB on a computer with an Intel Core i7 of 2.6 GHz and 16 GB memory. Simulations are performed for one time slot with the duration equal to one hour.

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TABLE I
CONSTANTS PARAMETERS VALUES IN *Case A*

Parameter	ϵ	μ_λ	μ_g	μ_p	K	R	ω(¢/kWh^2)
Value	0.001	0.1	0.1	0.01	30	5	1.1

TABLE II
PARAMETERS OF PROSUMERS IN FEEDER 1

Bus No.	Prosumer Index	α (¢/kWh^2)	β (¢/kWh)	$\underline{p}$ (kW)	$\overline{p}$ (kW)	g^0 (¢/kWh)	p^0 (kW)
2	$i=1$	0.11	6.1	0	5	0.9	5
5	$i=2$	0.12	9.3	0	8	1	8
3	$j=1$	0.21	14.2	1	4	0.5	1
4	$j=2$	0.23	12.4	2	5	0.5	2
6	$j=3$	0.13	10.3	2	4	0.6	2

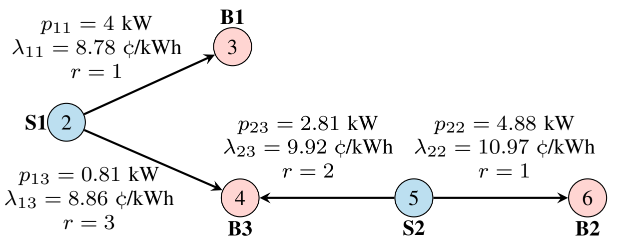

Fig. 5. P2P transactions in *Case A*; traded energy, price, and round of peer matching.

A. Case A: Trading in Feeder 1

In the first case study, we assume that five prosumers, including two sellers and three buyers, are connected to different nodes of feeder 1. Table I lists the values of constant parameters in the algorithm, and Table II presents different parameters of the prosumers. Results for energy trading in this case are represented in Fig. 5, and Fig. 6 illustrates the convergence of offered powers by prosumers in different transactions. The peer matching process lasts for three rounds, in which in the first round there are two matches between seller 1-buyer 1, and seller 2-buyer 2. Then, in the second and third round of peer matching process buyer 3 is matched to seller 2 and 1, respectively. Each transaction has a unique price, which confirms that different from pool-based P2P market clearing (e.g., [11]), the proposed method allows to settle bilateral trade with product differentiation.

The evolution of offers by prosumers in the transaction between seller 2 and buyer 2 is represented in Fig. 7, which demonstrates how prosumers update their offers during the negotiation step. Both prosumers start offering greedily with a high value of g. The seller, for example, at the first iteration, offers its maximum power 8 kW at the price 20 ¢/kWh, and buyer offers 2 kW at price zero. Then, they continue negotiating with lowering their greediness and adjusting their offers. Once they reach their marginal cost/benefit curves, they start to adjust their offered power to concede to an agreement. Then, after reaching agreement on the power, they concede to agree on the price. They reach an agreement after $k = 23$ iteration. From Fig. 7, it can be verified that the final agreement occurs in the zone of agreement of prosumers.

Fig. 8 demonstrates how greediness of prosumers changes their final agreement in the transaction between seller 2 and buyer 2. For this case study, the results in the final agreement of prosumers are compared for different values of (g_i/g_j). Results verify that none of the prosumers can increase its economic surplus by acting greedily in the negotiation process. Considering that the economic surplus of prosumers in an agreement is higher than the one with no agreement, they prefer to concede to reach an agreement. Acting greedily in the negotiation can make the negotiation process longer, and prosumers may reach the negotiation deadline without any agreement. Therefore, the greedy behavior of prosumers can reduce their economic surplus at the end. The proposed negotiation approach allows prosumers to concurrently negotiate on the power and price without exchanging any private information (α, and β in this case). Since each prosumer is using a unique greediness factor, they cannot employ their opponent's offers to explore their private information.

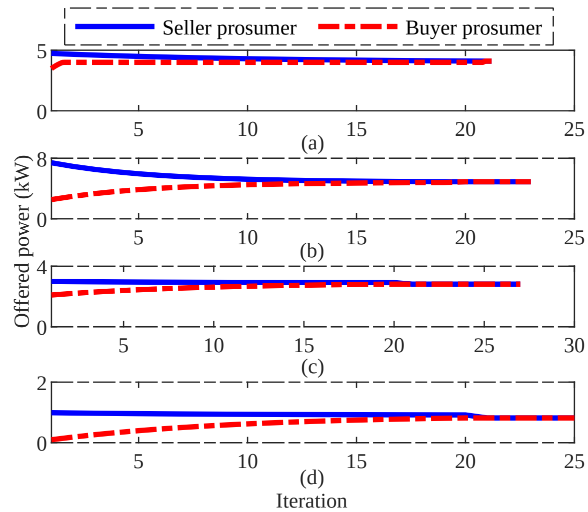

Fig. 6. Convergence of offered powers by seller and buyer prosumers; (a) Seller 1-Buyer 1, (b) Seller 2-Buyer 2, (c) Seller 2-Buyer 3, (d) Seller 1-Buyer 3.

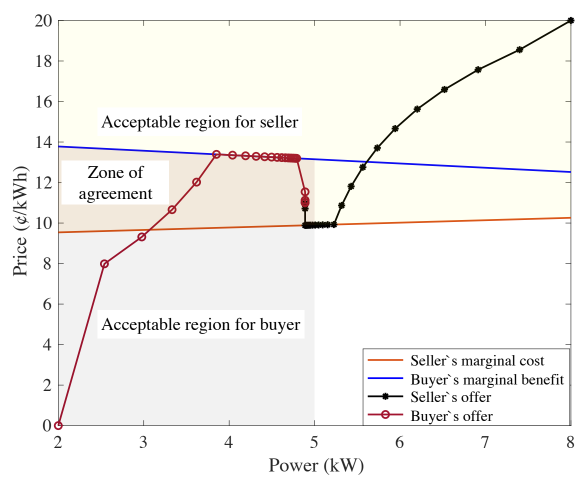

Fig. 7. Evolution of offers in the negotiation between seller 2 and buyer 2

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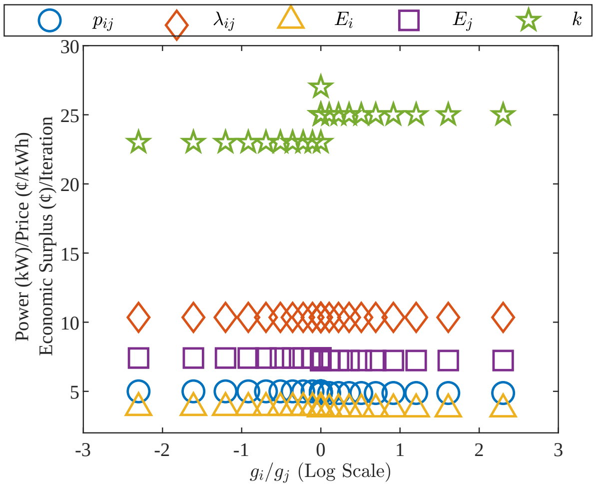

Fig. 8. Impact of prosumers greediness on the agreement between seller 2 and buyer 2; traded power, price, and economic surplus.

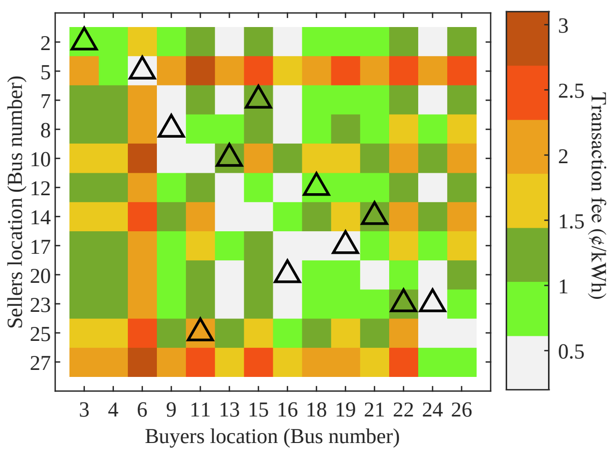

Fig. 9. Impact of transaction fee on the peer matching process. Each marker donates a match between seller and buyer.

B. Case B: Trading in All Feeders

In this case study, the proposed algorithm is implemented for all 26 players in the market. Fig. 9 demonstrates how loss-based transaction fee affects the peer matching process. Results are displayed for the first round of peer matching, in which 12 pairs are formed for the negotiation. It can be asserted that most of the pairs are formed based on the lowest available transaction fee. However, it should be noted that the transaction fee is not the only factor affecting the selection of a trading partner by a prosumer. As stated in Section III-A, prosumers select their trading partners based on the preserved price as in (3), and therefore, a seller/buyer prosumer may select a trading partner with a higher transaction fee, but a higher/lower offer. More importantly, to form a partnership between the seller and buyer, both of them should simultaneously select each other as the trading partner.

To evaluate the scalability of the proposed method, the execution time and the number of iterations required for the peer matching and negotiation for both *Case A* and *B* are compared in Table III. It should be noted that the given number

TABLE III
IMPACT OF NUMBER OF PROSUMERS ON THE EXECUTION TIME OF THE PROPOSED METHOD

	Peer matching		Negotiation	
	No. iterations	time (s)	No. iterations	time (s)
Case A	3	0.05	22	1.02
Case B	4	0.05	24	1.12

TABLE IV
COMPARISON OF THE PROPOSED METHOD WITH MANY-TO-MANY NEGOTIATION METHODS PRESENTED IN [19] AND [20]

Negotiation	1 seller-14 buyers		12 sellers-14 buyers	
model	No. iterations	time (s)	No. iterations	time (s)
[19]	84	13.03	301	94.73
[20]	198	11.21	825	14.13
This work	341	12.38	346	4.68

of iterations and the required time for the negotiation in Table III denote the maximum number of iterations and time for all of the peers. As it can be perceived, both the peer matching and negotiation steps can be executed in a short time, without any need to solve complex problems. Furthermore, results reveal that increase in the number of peers in the market increases the number of peer matching rounds. However, it does not have any significant impact on the negotiation time of each transaction. This is due to the fact that all negotiations occur in parallel and increase in the number of matched peers in the market does not change the negotiation time between peers. This, in turn, increases the scalability of the proposed method and makes it capable of being utilized in systems with a large number of prosumers.

In another case study, the proposed method is compared with the case of many-to-many negotiation between all peers to investigate how the negotiation model affects the execution time and the number of iterations. For this case study, besides the structure considered for *Case B*, a new case is considered, in which seller 1 is assumed to be a large-scale prosumer, which is the only seller in the market and in each round of the peer matching process, it is matched to one of the 14 buyers. For the many-to-many negotiation, the developed methods in [19] and [20] are employed. The peer-centric configuration in [19] is based on a many-to-many negotiation, in which peers optimize their objective function and select those trades which are optimal with respect to their preferences. The bilateral trading platform in [20] is also a many-to-many negotiation, where direct gradient method is used to solve prosumers local problems.

Results in Table IV show that in the first case, when there is only one seller in the market, the many-to-many negotiation approaches need less number of iterations for convergence than our proposed method. However, the negotiation time for all methods is almost the same. It has to be pointed out that this case can be considered as the worst case scenario for the proposed method since it needs the highest possible rounds of peer matching. At the same time, this case is a special case of many-to-many negotiation, with only one seller in the market. However, in the *Case B*, when the number of sellers increases, the proposed method has a better per-

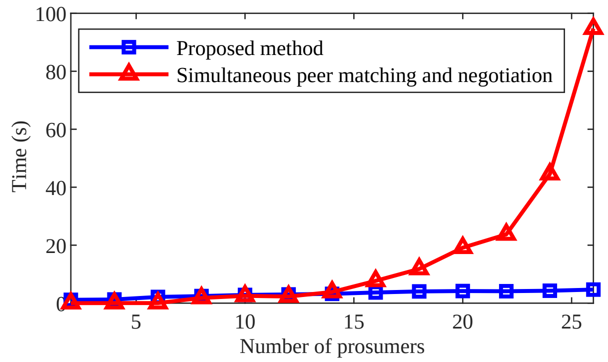

Fig. 10. Comparison of the execution time in the proposed method and the simultaneous negotiation and peer matching.

formance than many-to-many negotiation approaches. In the peer-centric method, prosumers need to solve an optimization problem at each iteration, which makes the market settlement to take a longer time. The bilateral method in [20] reduces the negotiation time by using direct gradient method for solving prosumers' objective function. However, compared to the proposed method, this method needs a higher number of iterations for convergence. As results in Table IV illustrate, the negotiation method proposed in this paper decreases the negotiation time significantly. This is due to the fact that prosumers are not concurrently negotiating with each other and can reach an agreement in a shorter time. Also, the economic surplus maximization problem is transformed to a set of operations as in (9a) to (18), which allows prosumers to update their offers without solving any optimization problem, which in turn enhances the computational efficiency of the algorithm. It can be inferred from the results that in the case that there is an extreme difference between the number of seller and buyer prosumers in the market, the many-to-many negotiation may yield better outcomes than the proposed method in terms of the execution time, as demonstrated by the simulation results. However, for a system with a large number of prosumers, the proposed method can reduce the execution time significantly, as shown in Table IV.

In the proposed method, the peer matching and negotiation steps occur sequentially. The motivation for separating these two steps is to enhance the computational efficiency of the algorithm. In order to show how this separation affects the results of the market settlement, we compare our method with the case of simultaneous peer matching and negotiation between peers. Fig. 10 shows the execution time for the market settlement, considering different number of prosumers in the market. Results demonstrate that in the case of simultaneous negotiation and peer matching, an increase in the number of prosumers in the market increases the execution time significantly. This is due to the fact that the negotiation step is an iterative process, and increasing the number of involved peers in the negotiation raises the number of iterations and the required time for the convergence [33]. Hence, we implement the peer matching process before the negotiation step to limit the number of trading partners of each prosumer, and consequently, speed up the negotiation process. However, prosumers

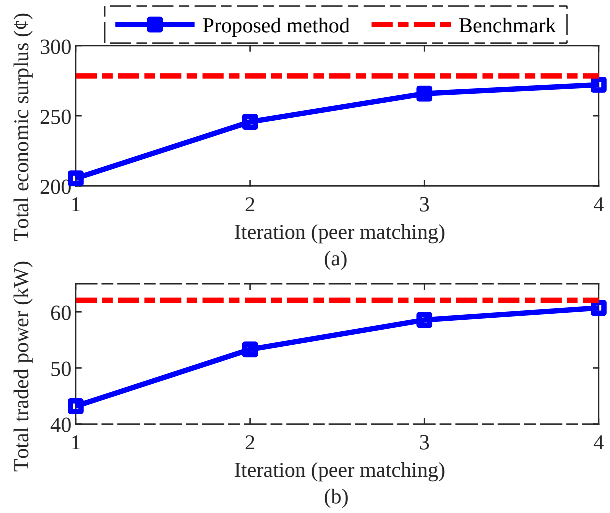

Fig. 11. Comparison of the results in the proposed method with the centralized optimization; a) total economic surplus, b) total traded power.

may achieve better results, in terms of the economic surplus and the traded energy, in case of simultaneous peer matching and negotiation between all peers. Hence, to minimize the loss of economic surplus, we make the peer matching process iterative to allow the prosumers to be matched with different trading partners, and to increase their economic surplus.

In general, methods that enable prosumers to select their trading partners and negotiate with them simultaneously can reach roughly the same results as the centralized optimization (see [19] and [20]). Therefore, we consider a centralized optimization as the benchmark for comparison. The centralized method can be considered as a many-to-one negotiation, in which a central operator collects all information from prosumers and clears the market. Results are shown in Fig. 11, and illustrate that the proposed method can reach approximately the same results as the centralized method. However, as in the proposed method there is no central entity for the peer matching and prosumers do not negotiate simultaneously, there is a small loss in the total economic surplus (3% in this case). Given the advantages of the proposed method, in terms of its scalability and low computation overheads, the loss in the economic surplus is not significant and can be compromised.

V. Conclusion

This paper proposes a new method for P2P energy trading among prosumers. The proposed method uses an iterative peer matching process to match prosumers for the negotiation, taking into account the losses in the network. A negotiation mechanism is designed, which enables prosumers to negotiate with their trading partners on the price and amount of energy without revealing their private information. Case studies show that the proposed method is computationally efficient and is applicable to systems with different scales. Also, compared to many-to-many negotiation, the proposed method needs a shorter time for the market clearing process. Furthermore, it is demonstrated that the peer matching process in influenced by the considered transaction fee and prosumers incorporate the costs related to losses in the trade in selecting their trading partners.

A limitation of the proposed method is that the peer matching step may take a long time in systems where there is an extreme difference between number of seller and buyer prosumers. However, the negotiation time in the proposed method is not affected by the number of prosumers. Hence, when the number of prosumers in the market increases, there is a trade-off between the increased time in the peer matching and reduced time in the negotiation process.

References

[1] A. Dimeas, S. Drenkard, N. Hatziargyriou, S. Karnouskos, K. Kok, J. Ringelstein, and A. Weidlich, "Smart houses in the smart grid: Developing an interactive network." *IEEE Electrific. Mag.*, vol. 2, no. 1, pp. 81–93, 2014.

[2] S. Yin, J. Wang, and F. Qiu, "Decentralized electricity market with transactive energy–a path forward," *Electr. J.*, vol. 32, no. 4, pp. 7–13, 2019.

[3] T. Sousa, T. Soares, P. Pinson, F. Moret, T. Baroche, and E. Sorin, "Peer-to-peer and community-based markets: A comprehensive review," *Renew. Sust. Energ. Rev.*, vol. 104, pp. 367–378, 2019.

[4] T. Morstyn, N. Farrell, S. J. Darby, and M. D. McCulloch, "Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants," *Nat. Energy*, vol. 3, no. 2, pp. 94–101, 2018.

[5] W. Tushar, T. K. Saha, C. Yuen, D. Smith, and H. V. Poor, "Peer-to-peer trading in electricity networks: an overview," *IEEE Trans. Smart Grid*, vol. 11, no. 4, pp. 3185–3200, 2020.

[6] A. I. Nikolaidis, C. A. Charalambous, and P. Mancarella, "A graph-based loss allocation framework for transactive energy markets in unbalanced radial distribution networks," *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 4109–4118, 2018.

[7] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, "Designing microgrid energy markets: A case study: The brooklyn microgrid," *Appl. Energy*, vol. 210, pp. 870–880, 2018.

[8] J. Guerrero, A. C. Chapman, and G. Verbič, "Decentralized p2p energy trading under network constraints in a low-voltage network," *IEEE Trans. Smart Grid*, vol. 10, no. 5, pp. 5163–5173, 2018.

[9] M. Khorasany, Y. Mishra, and G. Ledwich, "Auction based energy trading in transactive energy market with active participation of prosumers and consumers," in *Proc. Australian Univ. Power Eng. Conf.* IEEE, 2017, pp. 1–6.

[10] A. Paudel, K. Chaudhari, C. Long, and H. B. Gooi, "Peer-to-peer energy trading in a prosumer-based community microgrid: A game-theoretic model," *IEEE Trans. Ind. Elec.*, vol. 66, no. 8, pp. 6087–6097, 2018.

[11] W. Tushar, T. K. Saha, C. Yuen, P. Liddell, R. Bean, and H. V. Poor, "Peer-to-peer energy trading with sustainable user participation: A game theoretic approach," *IEEE Access*, vol. 6, pp. 62 932–62 943, 2018.

[12] E. Sorin, L. Bobo, and P. Pinson, "Consensus-based approach to peer-to-peer electricity markets with product differentiation," *IEEE Trans. Power Syst.*, vol. 34, no. 2, pp. 994–1004, 2018.

[13] K. Zhang, S. Troitzsch, S. Hanif, and T. Hamacher, "Coordinated market design for peer-to-peer energy trade and ancillary services in distribution grids," *IEEE Trans. Smart Grid*, vol. 11, no. 4, pp. 2929–2941, 2020.

[14] R. Zheng, T. Dai, K. Sycara, and N. Chakraborty, "Automated multilateral negotiation on multiple issues with private information," *INFORMS J. Comput.*, vol. 28, no. 4, pp. 612–628, 2016.

[15] T. Morstyn, A. Teytelboym, and M. D. McCulloch, "Bilateral contract networks for peer-to-peer energy trading," *IEEE Trans. Smart Grid*, vol. 10, no. 2, pp. 2026–2035, 2018.

[16] A. G. Azar, H. Nazaripouya, B. Khaki, C.-C. Chu, R. Gadh, and R. H. Jacobsen, "A non-cooperative framework for coordinating a neighborhood of distributed prosumers," *IEEE Trans. Ind. Inf.*, vol. 15, no. 5, pp. 2523–2534, 2018.

[17] Z. Zhang, R. Li, and F. Li, "A novel peer-to-peer local electricity market for joint trading of energy and uncertainty," *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1205–1215, 2019.

[18] S. Cui, Y.-W. Wang, Y. Shi, and J.-W. Xiao, "A new and fair peer-to-peer energy sharing framework for energy buildings," *IEEE Trans. Smart Grid*, 2020.

[19] J. Kim and Y. Dvorkin, "A p2p-dominant distribution system architecture," *IEEE Trans. Power Syst.*, vol. 35, no. 4, pp. 2716–2725, 2019.

[20] M. Khorasany, Y. Mishra, and G. Ledwich, "A decentralized bilateral energy trading system for peer-to-peer electricity markets," *IEEE Trans. Ind. Elec.*, vol. 67, no. 6, pp. 4646–4657, 2020.

[21] S. Chakraborty, T. Baarslag, and M. Kaisers, "Automated peer-to-peer negotiation for energy contract settlements in residential cooperatives," *Appl. Energy*, vol. 259, p. 114173, 2020.

[22] C. Etukudor, B. Couraud, V. Robu, W.-G. Früh, D. Flynn, and C. Okereke, "Automated negotiation for peer-to-peer electricity trading in local energy markets," *Energies*, vol. 13, no. 4, p. 920, 2020.

[23] T. Baroche, P. Pinson, R. L. G. Latimier, and H. B. Ahmed, "Exogenous cost allocation in peer-to-peer electricity markets," *IEEE Trans. Power Syst.*, vol. 34, no. 4, pp. 2553–2564, 2019.

[24] A. Paudel, L. P. M. I. Sampath, J. Yang, and H. B. Gooi, "Peer-to-peer energy trading in smart grid considering power losses and network fees," *IEEE Trans. Smart Grid*, pp. 1–1, 2020.

[25] O. Jogunola, A. Ikpehai, K. Anoh, B. Adebisi, M. Hammoudeh, H. Gacanin, and G. Harris, "Comparative analysis of p2p architectures for energy trading and sharing," *Energies*, vol. 11, no. 1, p. 62, 2018.

[26] C. Dang, J. Zhang, C.-P. Kwong, and L. Li, "Demand side load management for big industrial energy users under blockchain-based peer-to-peer electricity market," *IEEE Trans. Smart Grid*, vol. 10, no. 6, pp. 6426–6435, 2019.

[27] S. Wang, A. F. Taha, J. Wang, K. Kvaternik, and A. Hahn, "Energy crowdsourcing and peer-to-peer energy trading in blockchain-enabled smart grids," *IEEE Trans. Syst. Man, Cybern., Syst.*, vol. 49, no. 8, pp. 1612–1623, 2019.

[28] G. Hug, S. Kar, and C. Wu, "Consensus+ innovations approach for distributed multiagent coordination in a microgrid," *IEEE Trans. Smart Grid*, vol. 6, no. 4, pp. 1893–1903, 2015.

[29] G.-X. Luo and A. Semlyen, "Efficient load flow for large weakly meshed networks," *IEEE Trans. Power Syst.*, vol. 5, no. 4, pp. 1309–1316, 1990.

[30] A. J. Wood, B. F. Wollenberg, and G. B. Sheblé, *Power generation, operation, and control*. John Wiley & Sons, 2013.

[31] A. Rubinstein, "Perfect equilibrium in a bargaining model," *Econometrica: J. of the Econometric Society*, pp. 97–109, 1982.

[32] R. Ahmadi Kordkheili, S. A. Pourmousavi, M. Savaghebi, J. M. Guerrero, and M. H. Nehrir, "Assessing the potential of plug-in electric vehicles in active distribution networks," *Energies*, vol. 9, no. 1, p. 34, 2016.

[33] M. Khorasany, Y. Mishra, B. Babaki, and G. Ledwich, "Enhancing scalability of peer-to-peer energy markets using adaptive segmentation method," *J. Mod. Power Syst. Clean Energy*, vol. 7, no. 4, pp. 791– 801, 2019.

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