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Abstract

The extensive financial benefit that a prosumer can reap from participating in P2P trading has been shown to be unprecedented by many recent studies. However, since the actual transfer of electricity occurs over the physical network, a key question that yet to answer is: *what is the repercussion of P2P trading on the power losses in grid-connected electricity networks?* To this end, this paper presents a detailed physical layer analysis of P2P trading to investigate its impact on the network losses. In this paper, P2P transaction losses is defined as one part of network losses and a strategy is proposed to trace P2P transaction losses using effective nodes' area concept. The other portion of network losses is labelled as grid contributed losses incurred due to the power supplied by the grid to satisfy other customers within and outside effective nodes' area. Finally, this paper utilises IEEE 8500-node distribution test feeder to capture the large-scale performance of P2P trading in comparison with the existing case, in which there is no P2P trading. Several case studies are considered and the first category of simulation results demonstrate that the P2P transactions do not change the network losses, compared to the non-P2P scenario, if prosumers do not have power dispatch flexibility. Further, It is observed from the second category of simulation results that flexible power dispatch of P2P prosumers can change the network losses at some time instants of a typical day. However, the variation in 24 hours network losses between P2P and non-P2P cases is found to be insignificant for a large-sized distribution network with notable residential customers for a typical sunny day.

Index Terms

Peer-to-peer (P2P) trading, physical layer, network losses, P2P transaction losses, grid contributed losses, non-P2P practice

I. Introduction

With significant adoption of distributed energy resources and advancement in communications, control, and internet-of-things (IoT), small-scale electricity consumers are becoming prosumers, proactive-consumers that can actively manage their production, consumption, and sharing of energy [1]. Traditionally, these small-scale prosumers are serviced in retail markets, where they are individually metered by retailers and incentivised only to optimise their own local energy usage. However, if coordinated properly, small-scale prosumers can be utilised not only to manage the energy demand more efficiently but also to enable a significant mix of clean renewable energy into the grid [2]. Nonetheless, such effective coordination can only be obtained when small-prosumers are fully incorporated into the local electricity market [3].

To this end, feed-in-tariff (FiT) scheme was introduced in the last decade to enable prosumers to participate in the energy market [4]. In FiT, a prosumer with distributed energy resources, such as rooftop solar photovoltaic (PV), can sell the excess

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energy to the grid. Further, it can also buy energy from the grid if there is an energy deficit. Presently, the benefits that most prosumers obtain from participating in FiT, however, has been proven to be insignificant [5]. As a consequence, some of the FiT schemes have recently been discontinued across the world, for example, in Australia [5], [6].

Given this context, peer-to-peer (P2P) trading has recently emerged as a potential market structure with prosumer-centric perspective to incorporate small-scale prosumers into energy trading [7]. In P2P trading, prosumers can actively trade energy with one another in real time and facilitate a sustainable and reliable generation and consumption of energy within the community. Compared to existing FiT schemes, the financial benefit that a prosumer can reap by participating in P2P trading is expected to be very large [3]. As a consequence, a number of strategies have been proposed to capture the decision-making process of different selsumers (prosumers that sell energy via P2P) and pursumers (consumers that purchase energy via P2P) on energy trading parameters to facilitate electricity transfer over the P2P network. Examples of such strategies include game theory [5], [8]–[12], auction [13], [14], contract theory [1], [15], multi-level optimisation [16]–[18], consensus theory [19]–[21], and blockchain [22]–[25].

Indeed, once all participating selsumers and pursumers decide on the amount of energy they want to trade in the market at their chosen prices, the actual transfer of electricity between them occurs over the physical distribution network. Now, electricity exchange is different from exchanging of other goods due to the physical laws and technical constraints for safe and efficient operation of the network. A completely decentralised transfer of electricity via P2P trading may compromise the network operation. Existing studies on transfer of energy over the physical electricity network and its subsequent impacts on the network can be divided into two general categories. The first category of studies include [26], [27] that focus on how uncoordinated exchange of energy can potentially violate the network voltage limit and thus compromise the safe and efficient operation of the network. To address the issue, the key measures that have been implemented is to regulate the amount of power that a prosumer can push into the network. For instance, in Queensland, Australia, there is a cap of 5 kW for every residential prosumer that it can push to the network [6]. This limit on the power can be decided by the network sensitivity analysis [26]. Besides, additional P2P control services are recommended in [27] to maintain the network voltages within the safe margin.

The aim of the second category of studies, which is the primary focus of this paper, is to understand the impact of local generation-based P2P trading on the network losses. Traditionally, local generation helps reduce the network losses [28], [29]. However, proper investigation is recommended in the current literature to analyse how P2P transactions impact the network losses. For example, in [30], the authors report that the unbalanced power flow nature associated with the distribution networks should be fundamentally integrated while determining P2P losses and propose a graph-based losses allocation framework. In [31], the authors emphasise that losses due to each transaction in P2P trading is crucial as transactions can happen among different entities. The P2P energy trading technique proposed in [32] develops a coordination mechanism between prosumers and the wholesale market that minimises the costs associated with the transaction losses due to P2P trading. A methodology is presented in [33] to allocate exogenous costs incurred because of power losses during bilateral transactions in distribution networks. Finally, in [34], authors argue that each prosumer needs to be charged for contributing to the transaction losses via P2P trading and propose to share the losses cost based on the electrical distance between the prosumers. Since prosumers inject

local power to carry out multi-later transactions, P2P transaction losses are obvious. However, grid contributed losses are also existed in grid-connected power networks due to the upstream grid supply to maintain the total network demand. To this end, this paper considers overall network losses as the summation of P2P transaction losses and grid contributed losses and urges to investigate the impact of P2P trading on the overall network losses compared to the scenario while no P2P transactions are conducted. This is important because the total network losses are usually compensated by the grid operators in practical power systems and the practice should remain the same even P2P business model comes into the local energy market. The major contributions of this paper can be summarised as follows:

- A succinct overview is provided on both virtual and physical layers of P2P trading to help the reader understand how P2P transactions are going to be carried out in a real network. Further, special attention has been paid towards the P2P power exchange over the grid-connected networks to analyse all the losses related to the grid-tied power transfer.
- A generalised mechanism is proposed to estimate the losses associated with P2P transactions using effective nodes' (nodes that consume P2P injected power) area concept. Once estimated, the grid contributed losses within and outside effective nodes area are also evaluated.
- A large-scale P2P trading is simulated on IEEE 8500-node distribution test feeder. To the best of the author's knowledge, this is the first paper which is simulating large-scale P2P transactions with an intention to signify the impact of several simultaneous P2P transactions on grid-tied networks.
- Numerous case studies are considered, with and without power dispatch flexibility of the P2P prosumers, to determine all the power losses. Finally, the P2P network losses are compared with that of the non-P2P practice to investigate the unexplored effect of P2P transactions on the total network losses for a typical day.

The rest of the paper is organised as follows. In Section II, the preliminaries of P2P energy trading are discussed. The analysis of the power losses due to P2P trading between prosumers is outlined comprehensively in the following section. In Section IV, simulation studies are carried out on unbalanced IEEE 8500-node test feeder to evaluate the performance of P2P trading and the results are compared with the existing non-P2P case. Finally, in Section V, the paper is concluded via summarising the findings followed by a brief discussion of potential future works.

II. P2P Trading - Preliminaries

In a P2P energy network, prosumers can share a part of their resources, such as renewable energy and storage, to attain certain energy-related objectives including renewable usage maximisation, electricity cost reduction, network losses reduction and peak load shaving. A prosumer can be a selsumer, a pursumer or both and can interact with other prosumers without any direct influence on its decision-making process from a third party. The network consists of two layers that include a virtual layer and a physical layer [35], as shown in Fig. 1.

A. Virtual layer

The virtual layer is based on a secured information system that provides prosumers an access to energy-related information of other prosumers within the network. Essentially, in the virtual layer, the generation, demand, consumption, and pricing data

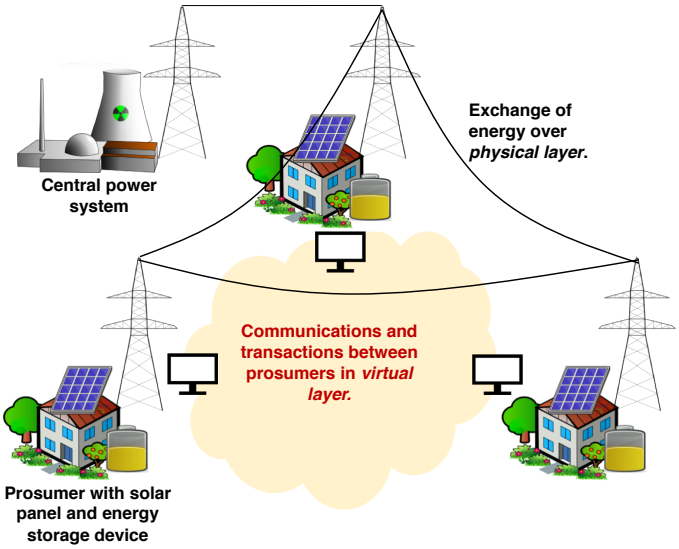


Fig. 1: A schematic diagram of P2P network consisting of virtual and physical layers.

of a peer are transferred from its smart meter over a secured communication network based on which buy and sell orders are created. Based on the created orders, a suitable market mechanism is used to facilitate energy trading. Once the market mechanism settles all buy and sell orders from selsumers and pursumers respectively, respective payments between the parties are made and the transfer of electricity is carried out over the physical layer.

B. Physical layer

The physical layer is responsible for the actual transfer of electricity from a selsumer to a pursumer after their financial settlement in the virtual layer. In a grid-connected network, this layer is representative of the distribution network provided and maintained by an independent system provider. Here, it is essential to note that although the amount of energy to be traded between a selsumer and a pursumer is decided by them following the market mechanism, it does not necessarily reflect that a direct transfer of electron from the same selsumer to the target pursumer is established to facilitate this trade as they may not be always directly connected by a single line.

To that end, there is a need for clear articulation of how electricity can be transferred over the physical layer within a P2P framework. To this end, this paper states that energy trading in the physical layer can be done in two ways: 1) transfer of power (watts) and 2) transfer of Negawatts.

1) Transfer of power: Once the settlement is done in the virtual layer, a selsumer pushes the agreed power amount to the distribution network (physical layer). A transactive meter [3] (a separate meter from traditional power meter to track P2P energy trading) tracks this electricity that has been pushed in response to a P2P settlement in the virtual layer. The pursumer, on the other hand, consumes the same amount of power from the distribution network, which is also recorded in its transactive meter as an energy amount traded via P2P.

Now, the power, which is consumed by the pursumer, does not necessarily be the power pushed by selsumer. This is due to the fact that power flow over the distribution network follows the law of physics, and therefore, the power pushed by selsumer could be consumed by different neighboring prosumers located closer to selsumer compared to the buying pursumer. However,

due to participating in the P2P trading, the payment to the selsumer for pushing its power to the network is made by pursumer in the virtual layer as P2P payment. On the other hand, when a pursumer is billed for using electricity by the retailer, it would not be billed for the amount recorded in its transactive meter for that period of time.

2) Transfer of Negawatts: Negawatts can be defined as the electric power saved by reducing electricity demand or consumption for a particular period of time [36]. Negawatts can be estimated by the difference between the baseline electrical load and the measured electrical consumption of a prosumer after scheduling and control. Transfer of Negawatts is beneficial to implement in scenarios when either there is a need for more surplus generation in a community or the prosumers need to supply to an aggregator in a supply constraint environment. Nonetheless, P2P trading via Negawatts is a new concept and a standard framework to enable the trading yet to be established. For details, please see [36]. Please note that while transfer of Negawatts could be a potential way to perform P2P trading in the future, it is still at an infant level. At present, majority of the P2P studies and pilot trials are based on the transfer of power. Hence, this paper also focuses on network related issues of P2P trading via transfer of power, especially its repercussion on the network losses.

Please note that the concept of hybrid P2P market is presented in [37], where the part of the market operation such as network analysis during P2P power transfer will be conducted by a nominated local market operator within the P2P community. This paper demonstrates this role of the P2P market operator to conduct power losses analysis for P2P trading.

III. Power Losses Analysis for P2P Trading

To determine the impact of P2P trading on the overall power losses, this section considers that whenever a prosumer has its own local generation and storage in a distribution network, it meets up most of its demand by internally and if there is any excess generation it may play the role of a selsumer (P2P prosumer) by selling it into the P2P market.

A. Prosumers' Decision-making Model

Let consider there are N houses, where $N = |\mathcal{N}|$ and each house $n \in \mathcal{N}$ acts as a prosumer. It is assumed that each prosumer is equipped with a rooftop photovoltaic (PV) system, a battery and some controllable loads. To meet its internal demand, prosumer n can use its PV generated and battery stored power. On the other hand, it can sell its excess power to the grid, to other prosumers or to charge its battery for future use. In order to handle all these activities, prosumers are assumed to have a smart meter that can (1) record the PV generation data, (2) determine the household demand, (3) record and manage the state-of-charge (SoC) of the battery, and (4) determine and record the amount of sold or purchased power.

It is considered that at any time instant t of the day, the PV power generation and demand of n prosumer are $G_{n,t}$ and $P^{\mathrm{d}}_{n,t}$ respectively, where $P^{\mathrm{d}}_{n,t}$ is the summation of base load, $P^{\mathrm{d+}}_{n,t}$, and controllable load, $P^{\mathrm{d++}}_{n,t}$, respectively. Let $P^{\mathrm{ch}}_{n,t}$ be the power required to charge the battery, whereas the battery discharges $P^{\mathrm{dis}}_{n,t}$ power. The operation of battery is determined by the SoC [38], which can be defined after charging and discharging as follows:

$$S^{\mathrm{ch}}_{n,t} = S_{n,t-1} + \eta(P^{\mathrm{ch}}_{n,t} \times \Delta t) \tag{1}$$

$$S^{\mathrm{dis}}_{n,t} = S_{n,t-1} - (\frac{P^{\mathrm{dis}}_{n,t}}{\eta} \times \Delta t) \tag{2}$$

where η is the battery efficiency.

are The household prosumers are categorised into types, such as Type 1 and Type 2, depending upon their power dispatch flexibility. Let the sets of Type 1 and Type 2 prosumers are denoted by $\mathcal{N}^{+}$ and $\mathcal{N}^{++}$ respectively, where $\mathcal{N}^{+}, \mathcal{N}^{++} \subset \mathcal{N}$ and $\mathcal{N} \setminus (\mathcal{N}^{+} \cup \mathcal{N}^{++}) = \{\phi\}$. It is assumed that each $n^{+} \in \mathcal{N}^{+}$ Type 1 prosumer does not use batteries for charging/discharging purposes and controllable loads. Consequently, $P^{\text{ch}}_{n^{+},t}, P^{\text{dis}}_{n^{+},t}, P^{\text{d++}}_{n^{+},t} = 0$. Please note that prosumers without battery and flexible loads are also labelled as Type 1 prosumers. These prosumers sell excess generation entirely by fulfilling their own demand. Alternatively, each $n^{++} \in \mathcal{N}^{++}$ Type 2 prosumer manages generation, demand and storage in the best possible way for monetary gains.

The decision-making processes of both Type 1 and Type 2 prosumers are described in Algorithm 1. As can be seen from the first part of the algorithm, each n^{+} Type 1 prosumer only trades in the P2P market at the P2P price, $\lambda^{\text{p2p}}_{n^{+},t}$, if it is higher than the FiT rate, $\lambda^{\text{fit}}_{n^{+},t}$. Otherwise, they do not participate in P2P trading. Further, the decision-making mechanism of each n^{++} Type 2 prosumer is explained in the second part of Algorithm 1. They charge battery with excess generation for peak demand use first followed by the operation of controllable loads when necessary. Finally, they sell rest of the power surplus, if any, in the P2P market when $\lambda^{\text{p2p}}_{n^{++},t} > \lambda^{\text{fit}}_{n^{++},t}$. However, in case of higher P2P price signal, for instance, greater than peak demand price, $\lambda^{\text{g}}_{n^{++},t}$, each n^{++} Type 2 prosumer decides to sell most of its excess generation in the P2P market rather than storing it or turning its controllable loads on.

Let consider a toy example pertaining to the decision-making frameworks of Type 1 and Type 2 prosumers for a given time slot, in which PV generation is greater than the base demand, i.e., $G_{n,t} > P^{\text{d+}}_{n^{\cdot}t}$. The PV generation, base demand, controllable load and power required to charge the battery are 5 kW, 1 kW, 0.5 kW and 2 kW respectively. The summary of the outcomes of the decision-making approaches are provided in Table I. As is observed that the Type 1 prosumer sells 4 kW excess generation in the P2P market if it receives higher P2P price than the FiT rate. Alternatively, this prosumer continues to sell at the FiT price. On the contrary, the Type 2 prosumer trades only 1.5 kW via P2P as it stores power in the battery for future utilisation and also uses controllable loads. However, when the Type 2 prosumer is offered with the lucrative P2P price, it no longer charges the battery and activates the controllable loads. As a result, it can sell the entire 4 kW power surplus in the P2P market.

TABLE I: Decision-making process when $G_{n,t} > P^{\text{d+}}_{n^{\cdot}t}$

Types of prosumers	$\lambda^{\text{p2p}}_{n,t} < \lambda^{\text{fit}}_{n,t}$	$\lambda^{\text{p2p}}_{n,t} > \lambda^{\text{fit}}_{n,t}$	$\lambda^{\text{p2p}}_{n,t} > \lambda^{\text{g}}_{n,t},\ \lambda^{\text{fit}}_{n,t}$
Type 1: $G_{n^{+},t}$=5 kW, $P^{\text{d+}}_{n^{+},t}$= 1 kW	4 kW is sold at $\lambda^{\text{fit}}_{n^{+},t}$	4 kW is sold at $\lambda^{\text{p2p}}_{n^{+},t}$	4 kW is sold at $\lambda^{\text{p2p}}_{n^{+},t}$
Type 2: $G_{n^{++},t}$=5 kW, $P^{\text{d+}}_{n^{++},t}$= 1 kW $P^{\text{d++}}_{n^{++},t}$= 0.5 kW, $P^{\text{ch}}_{n^{++},t}$= 2 kW	1.5 kW is sold at $\lambda^{\text{fit}}_{n^{++},t}$	1.5 kW is sold at $\lambda^{\text{p2p}}_{n^{++},t}$	4 kW is sold at $\lambda^{\text{p2p}}_{n^{++},t}$

B. Network Model

Let consider a distribution network with M nodes, where $M = |\mathcal{M}|$. The nodes are connected in the network via a set of lines. Each line $l_{p,m}$ that connects node p and m, where $p, m \in \mathcal{M}$, has an impedance of $Z_{p,m} = \sqrt{R^2_{p,m} + X^2_{p,m}}\, \tan^{-1} \frac{X_{p,m}}{R_{p,m}}$, where $R_{p,m}$ and $X_{p,m}$ are the resistance and reactance of $l_{p,m}$ respectively. The losses due to flow of power from p to m is:

$$L^{\text{p,m}}_{p,t} = \left| \frac{V_p - V_m}{Z_{p,m}} \right|^2 \times \mathbb{R}(Z_{p,m}) \tag{3}$$

Algorithm 1 Decision-making Algorithm

for time slot $t = 1$ to T **do**
  for each $n^+ \in \mathcal{N}^+$ Type 1 prosumer **do**
    while $G_{n^+,t} \neq P^{\text{d+}}_{n^+,t}$ **do**
      if $G_{n^+,t} > P^{\text{d+}}_{n^+,t}$ **then**
        $P^{\text{+}}_{n^+,t} \leftarrow G_{n^+,t} - P^{\text{d+}}_{n^+,t}$
        if $(\lambda^{\text{p2p}}_{n^+,t} > \lambda^{\text{fit}}_{n^+,t})$ **then**
          Trade in the P2P market
        else
          Continue with FiT
        end if
      else
        $P^{\text{-}}_{n^+,t} \leftarrow P^{\text{d+}}_{n^+,t} - G_{n^+,t}$
        No P2P or FiT
      end if
    end while
  end for
  for each $n^{++} \in \mathcal{N}^{++}$ Type 2 prosumer **do**
    while $G_{n^{++},t} \neq P^{\text{d+}}_{n^{++},t}$ **do**
      if $G_{n^{++},t} > P^{\text{d+}}_{n^{++},t}$ **then**
        while $(\lambda^{\text{p2p}}_{n^{++},t} < \lambda^{\text{g}}_{n^{++},t})$ **do**
          $S^{\text{ch}}_{n^{++},t} \leftarrow$ on $\leq b_{n^{++}}$
          $P^{\text{d++}}_{n^{++},t} \leftarrow$ on
          if $(\lambda^{\text{p2p}}_{n^{++},t} > \lambda^{\text{fit}}_{n^{++},t})$ **then**
            Trade in the P2P market
          else
            Continue with FiT
          end if
        end while
        while $(\lambda^{\text{p2p}}_{n^{++},t} > \lambda^{\text{g}}_{n^{++},t}, \lambda^{\text{fit}}_{n^{++},t})$ **do**
          $S^{\text{ch}}_{n^{++},t} \leftarrow$ off
          $P^{\text{d++}}_{n^{++},t} \leftarrow$ off
          Trade in the P2P market
        end while
      else
        $S^{\text{dis}}_{n^{++},t} \leftarrow$ on $\leq b_{n^{++}}$
        $P^{\text{d++}}_{n^{++},t} \leftarrow$ off
        $P^{\text{-}}_{n^{++},t} \leftarrow P^{\text{d+}}_{n,t} - (G_{n^{++},t} + P^{\text{dis}}_{n^{++},t})$
        No P2P or FiT
      end if
    end while
  end for
end for

where V_p and V_m are voltages at node p and m.

Please note that (3) is used as the basis for calculation of all losses in this paper.

C. Overall Network Losses

Let assume that, at any given time slot t, the sets of selsumers (P2P prosumers) and pursumers (P2P consumers) in the network are denoted by $\mathcal{I}$ and $\mathcal{J}$ respectively, where $\mathcal{I},\ \mathcal{J} \subset \mathcal{M}$. Each selsumer $i \in \mathcal{I}$ has a power surplus of $E_{i,t},\ \forall i$ and each pursumer $j \in \mathcal{J}$ has a power deficiency of $P_{j,t},\ \forall j$. Now, when a trading contract is set in the virtual layer between a

selsumer i and pursumer j at t for $\rho_t^{i,j}$ kW of power, $\rho_t^{i,j}$ is injected to the network by the selsumer. Since there could be some customers in the distribution network who may not be interested to participate in P2P trading, that is, $\mathcal{M} \setminus (\mathcal{I} \cup \mathcal{J}) \neq \{\phi\}$, and in general, $\sum_{i=1}^{|\mathcal{I}|} E_{i,t} < \sum_{j=1}^{|\mathcal{J}|} P_{j,t}$ due to limited excess generation of the selsumers, the grid needs to supply a part of total energy demand of the network. As such, the overall network losses $L_{\text{tot},t}^{\text{p2p}}$ during P2P trading at t can be expressed as:

$$L_{\text{tot},t}^{\text{p2p}} = L_{\text{grid},t} + L_{\text{p2p},t} \tag{4}$$

In (4), $L_{\text{grid},t}$ is the grid contributed losses due to the flow of power from the upper grid over the network and $L_{\text{p2p},t}$ refers to P2P transaction losses due to the flow of power injected by the selsumers within the network.

1) P2P Transaction Losses ($L_{p2p,t}$): As shown in Fig. 2, the flow of power within a network follows the law of physics, which can be traced using power flow solution [31]. As a result, the power injected by a selsumer is going to be consumed by its closest neighbouring nodes in practice. These nodes are regarded as *effective nodes* in this paper. Therefore, $L_{\text{p2p},t}$ is determined by the physical distance that the injected power $E_{i,t},\ \forall i$ needs to travel on both sides of the line based on the loads and generation of effective nodes along the path. The total demand of all nodes within the effective nodes' area (Fig. 2) of selsumer i is assumed to be greater to the power $E_{i,t}$ injected by the selsumer i. In other words, for each selsumer i,

$$\sum_{k=1}^{|\mathcal{M}_{i,e}|} P_{k,t} \geq E_{i,t} \tag{5}$$

where $\mathcal{M}_{i,e}$ is the set of all effective nodes of selsumer i and $\mathcal{M}_{i,e} \subset \mathcal{M} \setminus \mathcal{I}$. $P_{k,t}$ is the power consumed by effective node $k \in \mathcal{M}_{i,e}$. Therefore, $E_{i,t}$ will be entirely consumed by i's effective nodes and there is no flow of i's injected power beyond its effective nodes' area. Let consider that the power losses due to the flow of $E_{i,t}$ through the effective node area at t is $L_{i,t}^{\text{p}}$.

Here, it is important to bear in mind that the power supplied by the grid to the nodes that are located beyond the effective nodes' area of i will also flow through and contribute to the losses within effective nodes' area. In this regard, if the losses due to the total flow of power, including grid's power and the injected power by i, to effective node $k \in \mathcal{M}_{i,e}$ is $L_{k,t}^{\text{tot}}$, the losses $L_{i,t}^{\text{p}}$ exclusively due to P2P transaction of power from selsumer i can be calculated as:

$$L_{i,t}^{\text{p}} = \frac{E_{i,t}}{\sum_{k=1}^{|\mathcal{M}_{i,e}|} P_{k,t}} \times \sum_{k=1}^{|\mathcal{M}_{i,e}|} L_{k,t}^{\text{tot}} \tag{6}$$

Thus, the total losses $L_{\text{p2p},t}$ due to P2P transaction by $|\mathcal{I}|$ selsumers is:

$$L_{\text{p2p},t} = \sum_{i=1}^{|\mathcal{I}|} L_{i,t}^{\text{p}} \tag{7}$$

2) Grid Contributed Losses ($L_{grid,t}$): The grid contributed losses $L_{\text{grid},t}$ is resulted from the flow of power from the grid to the entire distribution network. $L_{\text{grid},t}$ has two components: 1) losses $L_{\text{grid},t}^{\text{in}}$ due to the flow of power within effective nodes' area and 2) losses $L_{\text{grid},t}^{\text{out}}$ due to the flow of power outside effective nodes' area. Therefore,

$$L_{\text{grid},t} = L_{\text{grid},t}^{\text{in}} + L_{\text{grid},t}^{\text{out}} \tag{8}$$

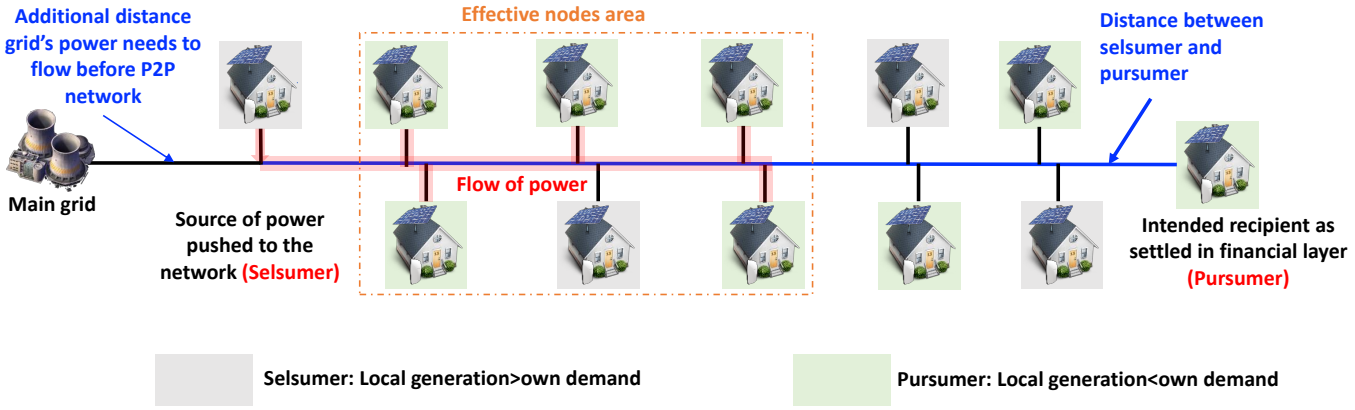


Fig. 2: The flow of power within the network regulated by the law of physics.

Clearly, the losses due to the flow of power within the effective nodes' area can be calculated from (6) and (7) as:

$$L^{\text{in}}_{\text{grid},t} = \sum_{i}^{|\mathcal{I}|} \left(\sum_{k=1}^{|\mathcal{M}_{i,e}|} L^{\text{tot}}_{k,t} \right) - L_{\text{p2p},t} \tag{9}$$

As for $L^{\text{out}}_{\text{grid},t}$, it is equal to the difference between total network losses due to supply of power within the network to meet the demand excluding local generation, storage dispatch as well as P2P injection and $L^{\text{in}}_{\text{grid},t}$. In other words,

$$L^{\text{out}}_{\text{grid},t} = L^{\text{d}}_{\text{tot},t} - L^{\text{eG}}_{\text{tot},t} - L_{\text{p2p},t} - L^{\text{in}}_{\text{grid},t} \tag{10}$$

where $L^{\text{d}}_{\text{tot},t}$ is the network losses for supplying the total demand of the household customers, $L^{\text{eG}}_{\text{tot},t}$ is the losses for supplying power equivalent to total local generation and storage dispatch.

Let consider a toy example to show how all losses associated with P2P trading can be calculated for a radial low-voltage (LV) network as given in Fig. 3. The load demand of nodes 2-6 are $P^{\text{d}}_{n,t} = \{2.5, 1.9, 0.8, 1.8, 3\}$ kW respectively at a given time t and all the loads are operating at 0.97 power factor. Node 1 represents the distribution transformer in connection to the upper grid. The line impedances are as follows:

$Z_{1,2} = 0.086 + j0.036$, $Z_{2,3} = 0.034 + j0.01$, $Z_{3,4} = 0.037 + j0.012$, $Z_{4,5} = 0.04 + j0.013$ and $Z_{5,6} = 0.033 + j0.009$.

Node 4 has a prosumer with a 5 kW_p PV system and it has 2.8 kW local generation for a given time instant t. Thus, it strikes a deal for $E_{4,t} = 2$ kW P2P transaction in the virtual layer with a pursumer at Node 6 and pushes 2 kW at its node finally. This injected power is consumed by Node 3 and Node 5 as $(P_{3,t} + P_{5,t}) > E_{4,t}$. Consequently, Node 3 and Node 5 are *effective nodes* in this context. The power flow solution provides the associated losses as follows:

$L_{\text{p2p},t} = 0.0058$ kW, $L_{\text{grid},t} = 0.0382$ kW, $L^{\text{p2p}}_{\text{tot},t} = 0.044$ kW.

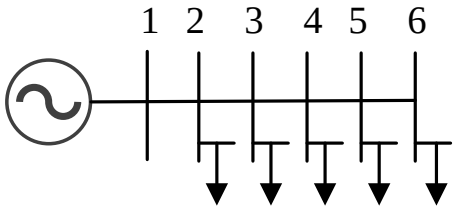


Fig. 3: A typical 0.4 kV distribution feeder.

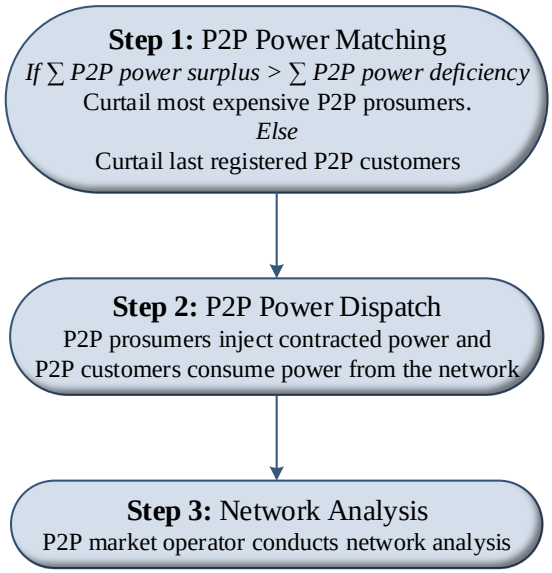


Fig. 4: The steps required to execute a physical layer P2P trading algorithm.

D. Network Losses Comparison

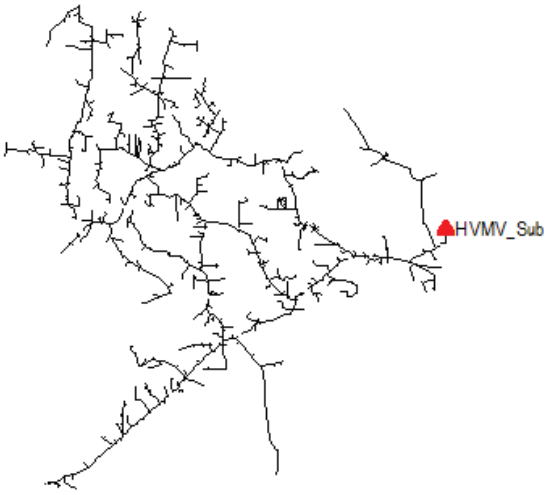
In this paper, *non-P2P practice* refers to the case in which no prosumer participates in P2P trading. Therefore, in non-P2P case, the excess generation of the prosumers are sold to the grid at the current FiT rate under the government policy. On the other hand, all the household customers have to buy electricity from the grid at the existing retail prices. $L_{\text{tot},t}^{\text{no-p2p}}$ is defined as the total incurred losses in the network with the non-P2P practice, which is compensated by the grid. Since non-P2P practice is already prevalent in many parts of the world, e.g., in Australia, this paper emphasises to compare $L_{\text{tot},t}^{\text{p2p}}$ with $L_{\text{tot},t}^{\text{no-p2p}}$ for the same network topology in order to investigate the consequence of P2P trading on the network losses.

IV. Large-scale P2P trading Simulation

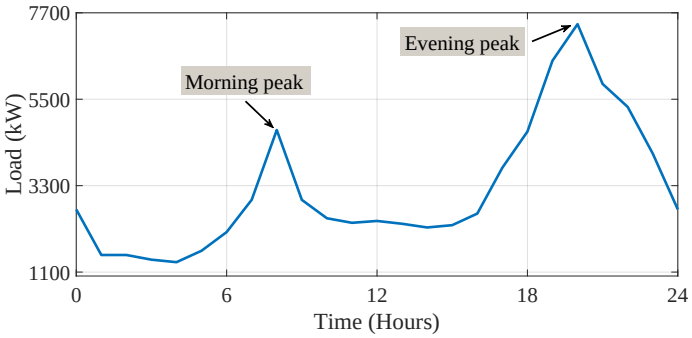
In this part, the P2P trading is simulated on IEEE 8500-node test feeder with unbalanced configuration, and the simulation results are provided for various scenarios to explore the performance of P2P trading on the grid-tied networks. The virtual P2P trading arrangements are made according to the decision-making model depicted in Subsection III-A and the consensus-based local market policy proposed in our previous paper [39]. As for the P2P physical layer trading, a step-by-step approach is briefly listed in Fig. 4. In Step 1, the total P2P traded power is matched. In other words, P2P power surplus and power deficiency are made the same. The unmet P2P prosumers and customers have to sell/buy energy to/from the grid at the existing prices. The following step deals with the P2P power dispatch, in which P2P prosumers inject virtually contracted power into their respective nodes and the customers consume P2P paid power from the network. Finally, the nominated network operator performs network analysis to investigate the impact of P2P trading on the power losses and node voltages. The analysis of the P2P market operator is demonstrated in this section by numerous simulation case studies and results.

A. System Description and Simulation Setup

IEEE 8500-node test feeder is a LV distribution network with 2354 loads. The detail description of this network can be found in [40]. The single-line diagram of the test feeder is given in Fig. 5a. In this study, it is assumed that all the unbalanced



(a) Single-line diagram of IEEE 8500-node test feeder.



(b) Household loads for a typical day.

Fig. 5: Household load profile of IEEE 8500-node test feeder for a typical day.

loads are household loads and the load profile of the network for a typical day is provided in Fig. 5b. All the household loads are working at 0.97 power factor and it is considered that 600 households of this test network have PV systems, i.e., prosumers. The maximum node voltage limit is set to 1.058 pu.

To simulate P2P transactions on the considered network, by means of OpenDSS-interfaced MATLAB environment, the following approaches are adopted:

- The number of prosumers with PV systems, ranging from 3 to 5 kW_p, are identified as selsumers (P2P prosumers) when they have excess power after meeting their own demands. The rest of the household loads are regarded as pursumers (P2P consumers). Some prosumers have battery capacity ranging from 2.4 to 10 kWh and some others have variable loads.
- It is assumed that the off-peak and peak electricity retail prices are 20 ¢/kWh and 35 ¢/kWh respectively [41] and the flat FiT rate is 10 ¢/kWh [42] during hours with power surplus. P2P participants have been permitted to negotiate prices on their own.
- A power flow analysis is conducted with the considered P2P configuration to determine the network losses.
- The network losses during grid-connected P2P trading is compared with the losses while there are no P2P transactions in the network to figure out the consequences of P2P trading on the network in term of losses.

B. Case Studies and Discussion

The framework considered for simulating P2P transactions based on the prosumers' power dispatch capability are depicted in Fig. 6.

1) P2P Trading without Prosumers' Power Dispatch Flexibility: In this study, it is assumed that the prosumers do not have/use any power dispatch flexibility., i.e., they do no have/use batteries and electric loads.

Scenario 1a: 0% P2P Penetration

In this scenario, it is considered that the prosumers are not interested in P2P trading, i.e., 0% P2P participation. Thus, Once local demand is fulfilled, each household sells its excess power to the grid by pushing it into the network. This injected

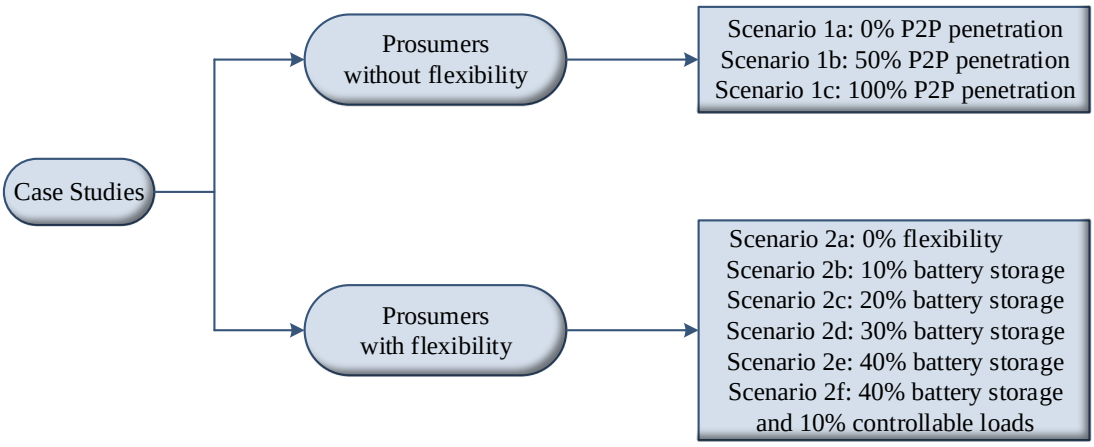


Fig. 6: Considered simulation framework.

TABLE II: Supply and losses in Scenario 1a.

Time Slot	Virtual P2P Transactions	P2P Supply (kW) [a]	P2P Losses (kW) [b]	Local Supply (kW) [c]	Upper Supply (kW) [d]	Grid Losses (kW) [e]	Network Losses (kW) [f]
1 am	0	0	0	0	1535.04	111.36	111.36
2 am	0	0	0	0	1472.39	109.61	109.61
3 am	0	0	0	0	1415.93	108.37	108.37
4 am	0	0	0	0	1352.17	106.93	106.93
5 am	0	0	0	0	1643.36	114.34	114.34
6 am	0	0	0	0	2118.26	130.44	130.44
7 am	0	0	0	0	2940.18	163.31	163.31
8 am	0	0	0	0	4716.29	281.18	281.18
9 am	0	0	0	5.27	2933.43	152.77	152.77
10 am	0	0	0	82.99	2386.96	129.14	129.14
11 am	0	0	0	515.15	1839.24	104.96	104.96
12 pm	0	0	0	726.16	1675.49	103.00	103.00
1 pm	0	0	0	669.86	1659.94	102.66	102.66
2 pm	0	0	0	470.78	1764.92	103.90	103.90
3 pm	0	0	0	157.40	2136.98	111.23	111.23
4 pm	0	0	0	0.34	2588.66	140.54	140.54
5 pm	0	0	0	0	3756.85	216.95	216.95
6 pm	0	0	0	0	4676.36	195.04	295.04
7 pm	0	0	0	0	6481.62	506.08	506.08
8 pm	0	0	0	0	7411.17	648.23	648.23
9 pm	0	0	0	0	5889.16	427.54	427.54
10 pm	0	0	0	0	5304.86	362.64	362.64
11 pm	0	0	0	0	4117.43	252.07	252.07
12 am	0	0	0	0	2694.85	157.95	157.95

[a] P2P transacted power injected by the selsumers
[b] Losses due to P2P transacted power (P2P transaction losses)
[c] Power injected by grid's paid prosumers
[d] Power required by the downstream customers deducting local supply
[e] Losses due to local and upper supplied power (grid contributed losses)
[f] Overall losses incurred in the network (the summation of P2P transaction losses and grid contributed losses)

power is consumed by the neighbouring households with power deficit. Table II describes that from 9 am to 4 pm, there are excess generation, i.e., PV generation $>$ load demand, but the total power surplus are not enough to satisfy the entire network demand. Consequently, the upstream grid supplies the deficit to balance the the total network demand. In fact, it is solely grid's responsibility to satisfy all the household customers, including prosumers, for the hours without PV production, e.g., 5 pm- 8

TABLE III: Supply and losses in Scenario 1b.

Time Slot	Virtual P2P Transactions	P2P Supply (kW) [a]	P2P Losses (kW) [b]	Local Supply (kW) [c]	Upper Supply (kW) [d]	Grid Losses (kW) [e]	Network Losses (kW) [f]
1 am	0	0	0	0	1535.04	111.36	111.36
2 am	0	0	0	0	1472.39	109.61	109.61
3 am	0	0	0	0	1415.93	108.37	108.37
4 am	0	0	0	0	1352.17	106.93	106.93
5 am	0	0	0	0	1643.36	114.34	114.34
6 am	0	0	0	0	2118.26	130.44	130.44
7 am	0	0	0	0	2940.18	163.31	163.31
8 am	0	0	0	0	4716.29	281.18	281.18
9 am	22	1.94	0.1	3.33	2933.43	152.67	152.77
10 am	152	40.18	2.1	42.82	2386.96	127.04	129.14
11 am	554	254.67	11.35	260.48	1839.24	93.61	104.96
12 pm	651	358.76	15.39	367.39	1675.49	87.61	103.00
1 pm	634	331.59	14.61	338.27	1659.94	88.05	102.66
2 pm	545	232.52	10.81	238.26	1764.92	93.09	103.90
3 pm	378	76.41	3.70	80.99	2136.98	107.53	111.23
4 pm	7	0.12	0.01	0.22	2588.66	140.53	140.54
5 pm	0	0	0	0	3756.85	216.95	216.95
6 pm	0	0	0	0	4676.36	195.04	295.04
7 pm	0	0	0	0	6481.62	506.08	506.08
8 pm	0	0	0	0	7411.17	648.23	648.23
9 pm	0	0	0	0	5889.16	427.54	427.54
10 pm	0	0	0	0	5304.86	362.64	362.64
11 pm	0	0	0	0	4117.43	252.07	252.07
12 am	0	0	0	0	2694.85	157.95	157.95

[a] P2P transacted power injected by the selsumers
[b] Losses due to P2P transacted power (P2P transaction losses)
[c] Power injected by grid's paid prosumers
[d] Power required by the downstream customers deducting local and P2P supply
[e] Losses due to local and upper supplied power (grid contributed losses)
[f] Overall losses incurred in the network (the summation of P2P transaction losses and grid contributed losses)

am, in this study. The hourly incurred network losses are also provided in Table II.

Scenario 1a is used as a *base non-P2P scenario* in this subsection and the outcomes of other scenarios are compared with it to analyse the impact of P2P penetration.

Scenario 1b: 50% P2P Penetration

This case study considers the same network topology as Scenario I, in which 50% of the prosumers, i.e., 300, wish to involve in the P2P trading market. Others prefer to continue trading with the grid at the FiT rate. The P2P participation of 300 prosumers has allowed 352 household customers to purchase electricity at P2P prices in the virtual layer during P2P trading periods (9 am- 4 pm).

Table III illustrates different supply and losses at every hour of the same day considered in Scenario Ib. Since prosumers trade in the P2P market, various number of P2P transactions are conducted in the virual layer. For example, 152, 554 and 651 P2P transactions are executed at 10 am, 11 am and 12 pm respectively. These transactions have directed the selsumers to inject 40.18 kW, 254.67 kW and 358.76 kW power into the network for P2P trading purposes respectively, and thus, 2.1 kW, 11.35 kW and 15.39 kW P2P transaction losses are created. However, during these periods, these selsumers did not trade with the grid. Thus, grid's paid local supply have decreased to 42.82 kW, 260.48 kW and 367.39 kW respectively. Due to the fact

of unchanged total number of prosumers, i.e. 600 (300 P2P and 300 grid's paid), with identical PV and load data, the power supplied by the upper grid have remained unvaried. As a consequence, same overall network losses are obtained. For instance, both Scenario 1a and Scenario 1b exhibit 104.96 kW and 103 kW overall network losses at 11 am and 12 pm respectively. Hence, no additional network losses is incurred if some of the existing prosumers participate in P2P trading while others carry on with the FiT scheme.

TABLE IV: Supply and losses in Scenario 1c.

Time Slot	Virtual P2P Transactions	P2P Supply (kW) [a]	P2P Losses (kW) [b]	Local Supply (kW) [c]	Upper Supply (kW) [d]	Grid Losses (kW) [e]	Network Losses (kW) [f]
1 am	0	0	0	0	1535.04	111.36	111.36
2 am	0	0	0	0	1472.39	109.61	109.61
3 am	0	0	0	0	1415.93	108.37	108.37
4 am	0	0	0	0	1352.17	106.93	106.93
5 am	0	0	0	0	1643.36	114.34	114.34
6 am	0	0	0	0	2118.26	130.44	130.44
7 am	0	0	0	0	2940.18	163.31	163.31
8 am	0	0	0	0	4716.29	281.18	281.18
9 am	53	5.27	0.27	0	2933.43	152.50	152.77
10 am	317	82.99	4.34	0	2386.96	124.8	129.14
11 am	1115	515.15	22.97	0	1839.24	81.99	104.96
12 pm	1311	726.16	31.14	0	1675.49	71.86	103.00
1 pm	1277	669.86	29.52	0	1659.94	73.14	102.66
2 pm	1095	470.78	21.88	0	1764.92	82.02	103.90
3 pm	762	157.40	7.63	0	2136.98	103.6	111.23
4 pm	17	0.34	0.02	0	2588.66	140.52	140.54
5 pm	0	0	0	0	3756.85	216.95	216.95
6 pm	0	0	0	0	4676.36	195.04	295.04
7 pm	0	0	0	0	6481.62	506.08	506.08
8 pm	0	0	0	0	7411.17	648.23	648.23
9 pm	0	0	0	0	5889.16	427.54	427.54
10 pm	0	0	0	0	5304.86	362.64	362.64
11 pm	0	0	0	0	4117.43	252.07	252.07
12 am	0	0	0	0	2694.85	157.95	157.95

[a] P2P transacted power injected by the selsumers
[b] Losses due to P2P transacted power (P2P transaction losses)
[c] Power injected by grid's paid prosumers
[d] Power required by the downstream customers deducting P2P supply
[e] Losses due to local and upper supplied power (grid contributed losses)
[f] Overall losses incurred in the network (the summation of P2P transaction losses and grid contributed losses)

Scenario Ic: 100% P2P Penetration

In this part, it is considered that all 600 prosumers decide to participate in the P2P market, i.e., 100% P2P participation, during power surplus periods (9 am- 4 pm) and sell entire amount of their excess generation. It is also assumed that the household customers prefer to purchase power from the P2P prosumers first and then from the grid (if necessary). As a consequence, all 600 prosumers have got the opportunity to trade in the P2P trading market, allowing 712 household customers to buy electricity from the prosumers.

The increased number of P2P transactions due to the higher P2P penetration, caused by 600 prosumers' participation, are demonstrated in Table IV. For instance, P2P transactions grow from 634 (Scenario 1b) to 1277 (Scenario 1c) at 1 pm, resulting in 14.91 kW increase in P2P transaction losses. On the other hand, the grid's paid local power supply becomes zero as all

600 prosumers inject mutually contracted power at P2P rates. Since Scenario 1c also uses the equivalent PV and load data as Scenario 1a and Scenario 1b, the total supplied power by the upper grid, and hence, the overall network losses remain unchanged. For instance, 102.66 kW overall network losses are observed in all three scenarios at 1 pm. Other trading periods also convey the uniform message that overall network losses does not vary if all the existing prosumers take part in the P2P trading market.

2) P2P Trading with Prosumers' Power Dispatch Flexibility: In this case study, it is assumed that some prosumers have battery storage and controllable loads and opt for using their power dispatch flexibility. Six scenarios are considered for network losses comparison between P2P and non-P2P scenarios as follows:

- Scenario 2a: 0% prosumers have flexibility
- Scenario 2b: 10% prosumers have battery storage
- Scenario 2c: 20% prosumers have battery storage
- Scenario 2d: 30% prosumers have battery storage
- Scenario 2e: 40% prosumers have battery storage
- Scenario 2f: 40% prosumers have battery storage and 10% prosumers have controllable loads

Scenario 2a represents the *base scenario*, where there is 100% P2P penetration without any power dispatch flexibility. This scenario has been described in details in Subsection IV-B1. In scenarios 2b-2e, the percentages of prosumers with battery storage have been varied from 10% to 40%. Finally, Scenario 2f considers that 10% prosumers have controllable loads while another 40% prosumers have battery storage.

It is assumed that non-P2P prosumers with battery storage facilities simply store their excess generation for peak demand use and they do not use controllable loads at peak demand periods. On the contrary, P2P prosumers seek for higher price contracts from the P2P market. P2P prosumers with battery storage facilities are assumed to have a tendency to sell their excess generation to the other prosumers in the P2P market if they are offered with prices greater than off-peak/peak rates. Similarly, P2P prosumers who have controllable loads do not use those loads if other prosumers offer higher P2P prices compared to off-peak/peak rates.

The network simulation has been performed for the entire 24 hours of a typical day and the results are shown in Fig. 7, Fig. 8 and Fig. 9 respectively. In these figures, the horizontal axis indicates the considered six cases and the MW network losses is represented by the vertical axis. Each case contains both P2P non-P2P network losses. As demonstrated in Subsection IV-B1, no variation in network losses is noticed, if the prosumers do not have any flexibility (Scenario 2a). Interestingly, this is not true in other cases, in which prosumers are provided with flexibility for managing their local power. In sunlight periods, one example is depicted by Fig. 7, the P2P network losses are fewer than the non-P2P network losses. This is due to the fact that whenever the P2P prosumers get preferred P2P price signals, they sell their excess power to the contacted prosumers instead of storing them in the storage or running controllable loads. In physical process, as a result, they inject increased amount of local power into the network. Consequently, the amounts of supply power required from the upstream grid are decreased, thus, the network losses are reduced in comparison with non-P2P practice in those P2P intervals.

On the other hand, Fig. 8 exhibits higher P2P network losses compared to the non-P2P practice at a peak demand period,

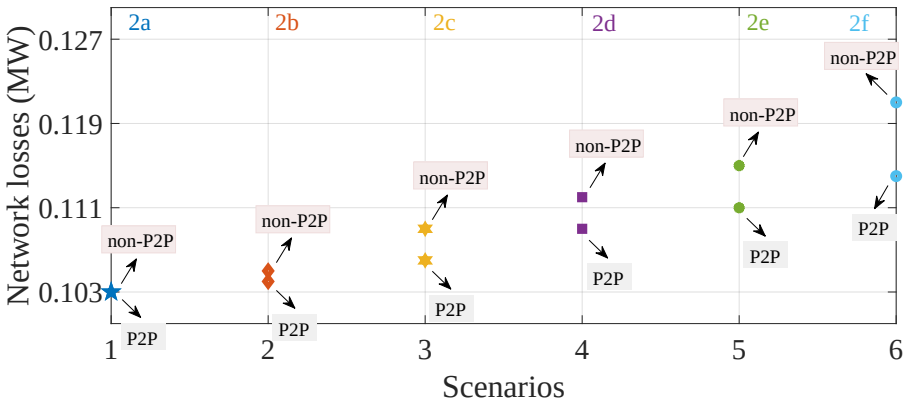


Fig. 7: P2P and non-P2P network losses incurred at a sunlight period, for example, at 12 pm.

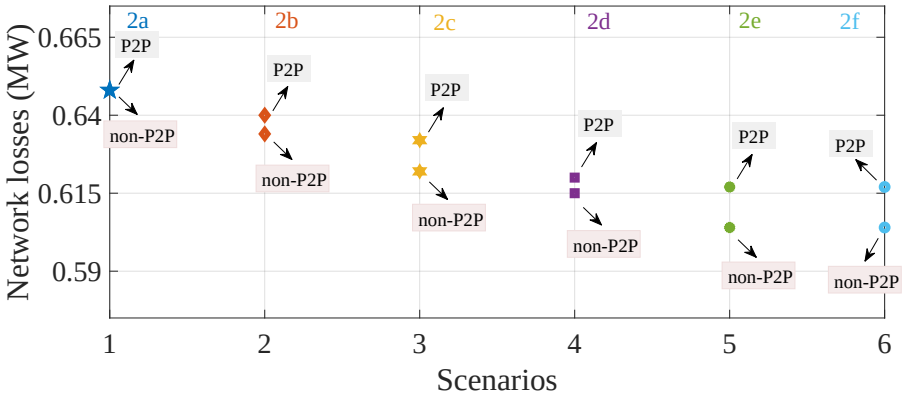


Fig. 8: P2P and non-P2P network losses incurred at a peak demand period, for example, at 8 pm.

such as 8 pm. This is because at a peak demand period, all the non-P2P prosumers with battery storage discharge their stored power to reduce their demand. However, since some P2P prosumers did not store enough excess power due to selling them during sunlight periods or have already used their battery stored power for P2P trading before peak demand times, these P2P prosumers are satisfied by the grid. Due to larger quantity of power supply from the upstream grid compared to the non-P2P case, the network losses are more in P2P scenario. Please note that both P2P and non-P2P prosumers turned off their controllable loads at 8 pm in this study.

Fig. 9 illustrates the total 24 hours network losses incurred for P2P and non-P2P scenarios at all six cases. While the considered distribution network has around 5.1 MW daily network losses in base case, only few kW differences between non-P2P and P2P network losses are observed at Scenarios 2b-2f over a course of 24 hours. For instance, the variations are approximately 7 kW, 22 kW, 12 kW, 18 kW and 10 kW respectively. Therefore, although prosumers' flexibility can change network losses in some time slots of a typical day, there is no substantial variation in the total 24 hours network losses for a large-sized distribution network with notable household customers.

3) Discussion on Power Losses: Since P2P trading involves a number of individuals from a network and the P2P payment is going to be finalised separately, the issue of P2P losses are raised by some authors in [30], [31], [34]. Indeed, P2P transactions are going to incur some losses as the prosumers are also instructed to inject P2P exchanged power in its respective nodes. Therefore, this paper proposes a mechanism of estimate P2P transaction losses from overall network losses in grid-tied systems.

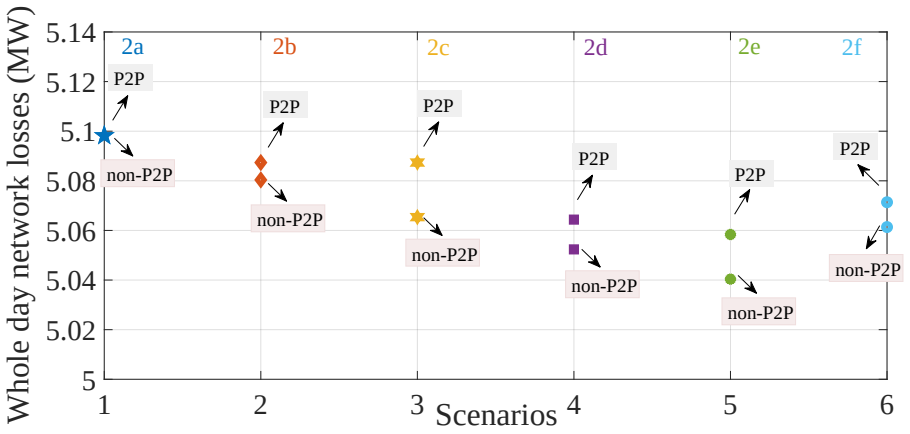


Fig. 9: Total P2P and non-P2P network losses incurred over the course of a typical day.

However, the grid operators require to compensate the overall network losses not the P2P transaction losses separately.

Given this context, diverse case studies are provided in this paper to figure out how network losses differs due to the existing prosumers' involvement in grid-connected P2P trading. The simulation results indicate that there exists P2P transaction losses but the overall network losses does not change if the prosumers do not have any flexibility of local power dispatch (no battery storage, no controllable loads). This is because they inject their excess power into the network at all conditions, i.e., either P2P or FiT rates, following the same physical process. Further, it is also noticed from the simulation results that considering the prosumers' flexibility to change local supply/demand profiles for P2P financial benefits can change the network losses at some time slots of a typical day. However, the difference between total P2P and non-P2P network losses for the entire 24 hours of a typical day is not too prominent to impact considerably large-sized distribution networks such as IEEE 8500-node test feeder.

4) Status of Node Voltages: The voltage status of all the households of the considered network are also checked in this study. Fig. 10 captures the node voltages during peak P2P trading periods, when 600 prosumers have injected higher quantities of power surplus into the network. As is seen that no node voltage violates the prescribed upper voltage limit, 1.058 pu. Hence, all P2P transactions, settled virtually by all the prosumers, can be acceptable for the safe network operation.

However, as advised in [26], [27], [43]–[46], care must be taken by the grid operators to avoid undesired rise in the network voltages which is likely to be caused by the extensive P2P penetration. This is because P2P trading market may attract new non-PV households to become prosumers by offering substantial financial benefits. In that perspective, the grid operators may require to limit the number of prosumers for safe voltage regulation based on their network configurations.

5) The Implications for Stakeholders: P2P trading can impact the stakeholders in energy sectors in different ways. For example:

- Distribution network operators: Considering the fact that P2P transactions may not change the daily network losses to a significant amount, the network operators may allow the existing prosumers to participate in P2P trading market based on the local market policy. However, the regulatory bodies have to analyse the issue of node voltage rise and overall network related costs before approving P2P transactions.
- Retailers: If the prosumers take part in P2P transactions, the retailers may lose some revenues due to the bilateral financial flow of P2P trading. However, the role of the retailers will remain important. This is due to the fact that both non-P2P

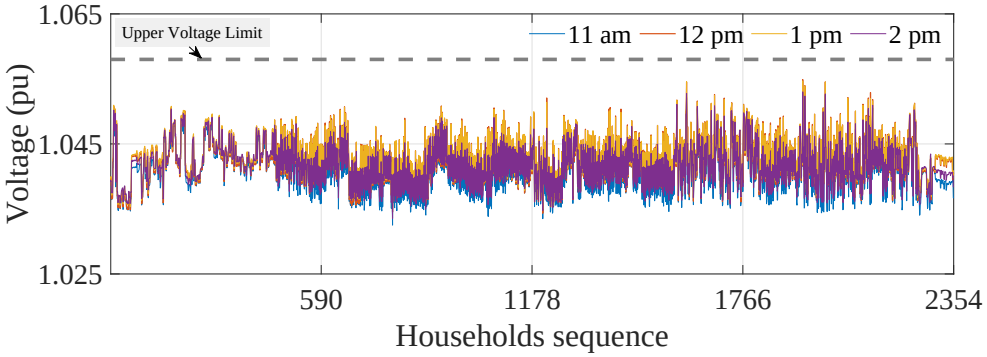


Fig. 10: Node voltages of the all the households during higher P2P penetration (11 am-2 pm).

and P2P customers will need to rely on the retailers for their energy in days when the local supply is not enough to meet the total demand of the prosumers, for example, due to cloudy days, increased demand, P2P communication server down.

- Upstream bodies: Depending upon the flexible power dispatch of P2P participants, the upstream producers may have to supply more or less power to the downstream customers. That will eventually impact their revenues.

V. Conclusion

This paper presents the impact of the P2P energy trading on the power losses in grid-tied networks. To do so, all the power losses associated with the physical layer of P2P trading have been analysed in great details. Mechanisms are proposed to trace P2P transaction losses and grid contributed losses from the network losses incurred during P2P trading. Then the large-scale P2P transactions are performed on IEEE 8500-node distribution test feeder for various case studies. Finally, the results are compared with the existing net-metering practice, in which no P2P tradings are taken place, with an intention to judge the performance of P2P trading. The first category of case studies do not consider prosumers' power dispatch flexibility and the simulation results show that P2P transactions do not change the network losses in comparison with the non-P2P case. However, different network losses are observed at some time slots of a typical day in the second category of case studies, where prosumers are provided with battery storage and controllable loads. Importantly, insignificant variation in total distribution network losses (24 hours) is found between P2P and non-P2P scenarios at all case studies for a typical day.

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