Dynamic Operating Envelope-enabled P2P Trading to Maximise Financial Returns of Prosumers

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***Abstract*—This paper presents a new dynamic operating envelope (DOE)-integrated peer-to-peer (P2P) trading scheme to increase the exchange of electricity from prosumers to a distribution network without jeopardising the network constraints. First, a DOE computation mechanism is designed to estimate the power export and import limits for prosumers at different time slots. Second, considering the DOE-estimated export and import limits, a network-aware P2P trading framework is developed utilising cooperative game theory. The key properties of the P2P coalition are studied, as well as the incentive-compatibility and stability are also confirmed. Finally, an algorithm is proposed that enables prosumers to form a stable and incentive-compatible network-aware P2P coalition and fairly distribute the total coalition benefit among themselves. With extensive simulations, it is demonstrated that the modelled P2P trading structure allows prosumers to export more electricity to the low-voltage (LV) network safely compared to existing techniques while keeping bus voltages and line loading within acceptable margins. Subsequently, by trading more power locally, prosumers can substantially mitigate their electricity costs.**

***Index Terms*—Peer-to-peer trading, dynamic operating envelope, network constraints, cooperative game, financial returns.**

NOMENCLATURE

j, (j, ji), z	Index of bus, branch, prosumer,
k, Δk	Index, length of each time slot,
$\mathcal{J}$, $\mathcal{I}$, $\mathcal{Z}$, $\mathcal{K}$	Set of buses, branches, prosumers, time slots,
S_j, P_j, Q_j	Complex, real, reactive power,
V_j, $(I_{j,ji})$	Voltage, branch current,
$\overline{V}_j$, $\underline{V}_j$	Maximum, minimum limit of V_j,
$P^{ld}_{z,k}$, $P^{sp}_{z,k}$	Load demand, solar PV power,
$\overline{P}^{ld}_{z,k}$, $\overline{P}^{sp}_{z,k}$	Maximum rating of $P^{ld}_{z,k}$, $P^{sp}_{z,k}$,
$P^{bc}_{z,k}$, $P^{bd}_{z,k}$	Charged, discharged power of the battery,
ρ^{bc}_z, ρ^{bd}_z	Charging, discharging capacity of the battery,
$S_{z,k}$, $\overline{S}_{z,k}$	State-of-charge, maximum $S_{z,k}$ of the battery,
ζ^{bc}, ζ^{bd}	Charging, discharging efficiency of the battery,
$c_{z,k}$, $d_{z,k}$	Binary variables,
$P^{ss}_{z,k}$, $P^{dy}_{z,k}$	Power surplus, deficiency,
$\mathcal{ZA}$, $\mathcal{ZB}$	Set of prosumers with $P^{ss}_{z,k}$, $P^{dy}_{z,k}$,
$\mathcal{ZX}$, $\mathcal{ZY}$	Set of safe, unsafe prosumers,
$P^{ex}_{z,k}$, $P^{im}_{z,k}$	Approved Power export, import,
$P^g_{1,k}$, $Q^g_{1,k}$	Supply real, reactive power,
$\overline{P}^g_{1,k}$, $\underline{P}^g_{1,k}$	Maximum, minimum limit of $P^g_{1,k}$,
$\overline{Q}^g_{1,k}$, $\underline{Q}^g_{1,k}$	Maximum, minimum limit of $Q^g_{1,k}$,
$V^{Re}_{j,\theta,k}$, $V^{Im}_{j,\theta,k}$	Real, imaginary part of phase V_j,
$I^{Re}_{j,\theta,k}$, $I^{Im}_{j,\theta,k}$	Real, imaginary part of phase $I_{(j,ji)}$,
$P^{io}_{z,k}$, $P^{do}_{z,k}$	Intended, dynamic limit operation,
$\mathcal{S}$, $\mathcal{SA}$, $\mathcal{SB}$	Set of P2P prosumers, sellers, buyers,
$P^{sa}_{z,k}$, $P^{sb}_{z,k}$	P2P selling, buying power,
$x^e_{z,k}$, $x^o_{z,k}$	Feed-in-tariff, time-off-use price,
$a_{z,k}$, $b_{z,k}$	Binary variables,
$CF^{sp}_{z,k}$	Cost with P2P,
$CF^{bu}_{z,k}$	Cost with BAU,
$C\hat{F}_{z,k}$	Cost difference between $CF^{bu}_{z,k}$ and $CF^{sp}_{z,k}$,
$\mathcal{G}$, $\mathcal{T}$, $\mathcal{W}(\mathcal{T})$	Proposed game, coalition, value of $\mathcal{T}$,
$\mathcal{T}_m$, $\mathcal{T}_n$	Any disjoint coalitions,
$\mathcal{T}_{mm}$, $\mathcal{T}_{nn}$	Any disjoint coalitions,
ϕ_z	Shapley value.

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I. INTRODUCTION

RECENTLY, the rapid uptake of small-sized distributed energy resources (DERs), that include solar photovoltaic (PV) systems, battery storage systems, and electric vehicles, has turned passive residential electricity consumers into active prosumers who can export their locally produced energy into the electricity grid [1]. To enable these prosumers to sell and buy energy among themselves with a profitable financial return, peer-to-peer (P2P) trading has turned up as a winsome feature of emerging local electricity markets (LEMs). At present, there is a growing interest in designing various P2P energy trading schemes with the purpose of supporting environmental suitability, self-sufficiency and autonomy, electricity bill reductions, demand-side flexible services, and quality of service improvements [2]. In general, recent studies focusing on P2P trading can mainly be grouped into two categories: financial P2P studies and physical P2P studies.

Financial studies of prosumer-centric P2P trading mainly focus on comprehensive peer-matching formats to negotiate and settle P2P selling and buying orders [3], satisfactory bilateral payment rules and regulations [4], integration of energy storage systems for optimally scheduling P2P decision-making strategies [5], fair payoff allocation and maximum energy usage expenditure reduction [6], developing policies to expedite the engagement of prosumers in P2P trading [7], and privacy-preserving and secure mechanisms to perform

P2P transactions [8]. Game theory has been one of the most common technical approaches adopted by recent financial P2P studies, as it can capture the decision-forming strategies of P2P prosumers efficaciously, whether acting independently (i.e., non-cooperatively) or as a part of a group (i.e., cooperatively) [2]. For instance, non-cooperative games are used in [9], [10], and [3] to study social attributes and behaviours of prosumers in P2P trading, apply P2P trading in multiple sharing regions, and capture P2P market competition, respectively. In these non-cooperative P2P frameworks, optimal solutions to the games are derived for individual rational prosumers.

On the contrary, the exercise of cooperative games is also evident in the existing literature to demonstrate how prosumers can benefit from working in groups. For example, a computationally-efficient P2P pricing model is proposed in [11]. A fair payoff allotment for prosumers in a P2P coalition is demonstrated in [12]. The climatic and stochastic analyses are also integrated into cooperative games in [13] and [14], respectively for better P2P market clearing solutions. Further, the authors in [15] develop a cooperative game considering prosumers' priorities of energy demand, price, and geographical distance in local communities. Analogous game models are also adopted in [16] and [17] to stabilise the P2P grand coalition while the energy demand is matched with the local energy supply and strategic decisions are formed.

Another important aspect of P2P trading that has received significant attention in recent literature is its impact on the physical network. This is important as a distribution network has its own inherent characteristics and is often constrained by technical limitations imposed by an authorised network operator [2]. Therefore, several studies have considered distribution network constraints while formulating P2P trading mechanisms. For instance, the authors in [18] propose a prosumer-blocking model to maintain the voltage and loading limits, enabling the P2P market to block a prosumer for a given trading instant through the voltage sensitivity analysis and power transfer distribution factor. An identical process is also practised in [19] to analyse the detailed implications of P2P trading on the physical network voltages. A consensus-based P2P approach is designed in [20] by considering the power set-points of P2P agents. A P2P-dominant distribution system structure is proposed in [21], in which P2P participants are charged to use the distribution network and network usage charges are computed by distributed locational marginal prices. Besides, the utilisation of reactive power management, interaction-driven power adjustment, and ancillary services to satisfy the distribution network constraints during the execution of P2P transactions is also discussed in [22], [23], and [24], respectively.

Although the aforementioned physical P2P trading models handle network constraints effectively, these models are usually bounded by the power set-points of the P2P participants, and strategic-oriented mechanisms are adopted to ascertain unimpaired network usage. In other words, P2P transactions, considering network usage charges, are optimised within the maximum pre-defined power export and import limits to ensure safe network operation. For example, at the low-voltage (LV) distribution level, the maximum set-point for power export is capped at 5 kW in different parts of the world [25]. This power set-point is in general conservative and usually designed considering worst-case scenarios (e.g., weak network, maximum local generation, and minimum power demand) – which may not occur often in well-functioning LV networks [26], and modern world scenarios may not be replicated [27]. As a result, prosumers' available production and modern solar PV inverters' capacities may be underutilised [28]. To use the available local resources and network capacities effectively, the concept of the dynamic operating envelope (DOE) has gained particular attention in recent years.

DOE can make efficient use of existing distribution network infrastructure while taking operational constraints into consideration [29]. In particular, it can be implemented at the connection points of prosumers and consumers to determine time-varying power export limits (also import limits) optimally to comply with the distribution network constraints [30]. The research on the derivation, application, and robustness of the DOE is getting momentum in recently published papers, e.g. [26], [28], [31], and [32] and some pilot projects, including Project EDGE [33] and Simply Energy VPP Project [34]. Although DOE has the potential to coordinate DERs separately from the rest of the network operation, its applications in the LEM to maximise prosumers' exports through P2P trading have not been studied. This is important as it can potentially shift the existing paradigm of P2P trading in this new era of the DOE by allowing prosumers to export more electricity than a set threshold and establishing the need for more innovative business models and customer engagement plans for financially attractive P2P trading.

Given this context, the novelty of our proposed work stems from the proposition of a DOE-enabled P2P energy trading framework to increase prosumers' power export capabilities in the LEM compared to existing P2P approaches, enabling them to attain better financial returns without violating any network constraints. Unlike other existing P2P approaches, in this paper, the power export limits (and also the import limits) are set dynamically at different times using the optimal power flow (OPF). Then, with the assigned DOE, network-aware P2P coalitions are formed following the cooperative game structure, and monetary gains received by all participating prosumers are evaluated to assess the financial viability.

We note that while some prosumers may prefer to be self-sufficient, i.e., not willing to export/import, other prosumers may have the intention to generate more clean energy than they require [35]. They can use this energy to sell via P2P trading to receive greater monetary gains. Also, this can allow sole consumers to buy clean energy at decreased rates and reduce their electricity costs. The motivation for generating and using increased amounts of clean energy is also supported by the clean energy usage targets of governments in many parts of the world. For instance, the state government of Victoria, Australia, has set a target to go renewable by 50% by 2030 [36]. there is a need to ensure clean energy production, usage, and exchange among prosumers and consumers, and P2P trading can be a mechanism to exercise such clean energy exchange [37].

Accordingly, our paper contributes to the literature by making the following key contributions:

- A trading slot-ahead DOE approach is developed to determine time-varying power exchange limits for P2P prosumers, considering the technical constraints of the LV distribution network. This is done to maximise prosumers' local penetration into the corresponding network without violating network constraints and unlock better revenue streams for them in the LEM. The proposed DOE approach is also validated on an actual Australian LV distribution network.
- A network-aware cooperative P2P trading framework is proposed, whereby prosumers always take DOE-assigned power exchange quantities into consideration while they collaborate and decide on their P2P trading strategies as part of the constituted coalition. Further, the proposed DOE-facilitated P2P trading mechanism is demonstrated to be profitable and stable for all engaged prosumers.

We note that a cooperative game is also used in our recently published paper, [17] to design a P2P trading framework. However, in [17], a static power export limit [25] is assumed for prosumers in designing the scheme like other available literature, and major contributions are highlighted via the hardware-in-loop demonstration of the developed mechanism. Meanwhile, in this paper, we have developed a new dynamic exchange-enabled P2P trading model. In the proposed model, unlike [17], the power export of prosumers is maximised beyond a fixed limit without compromising the network's integrity. This is done by incorporating the concept of DOE into prosumers' P2P decision-making, which is shown to result in greater financial returns for the participants compared to existing trading schemes.

The rest of the paper organisation is arranged as follows: The system structure of the work is discussed in Section II. Section III explains the developed methodology to model the proposed DOE-based P2P trading framework. Simulation results are given in Section IV to assess the performance of the designed P2P trading compared to different existing models. In the end, Section V finalises the paper.

II. System Description

Assume a LV distribution network model in which small-sized prosumers are connected to different buses. It is assumed that a P2P market operator is responsible for maintaining the distribution network's safety during P2P trading, following a hybrid market structure for P2P trading [2]. Under such a market structure, the P2P market operator only provides the physical network information, e.g., power export and import limits of the network, computed using DOE in this paper, but does not influence the actual settlement of P2P trading quantities and prices. These trading parameters are entirely decided by the participating prosumers.

All prosumers are supposed to have a smart transactive meter to store solar PV, load demand, and storage data. The transactive meter can also evaluate the power surplus and power deficiency of the respective prosumer (please see detailed calculations in Subsection II-B). Both prosumers and the P2P market operator are also assumed to have accounts on a privacy-ensured distributed ledger platform, such as blockchain, where prosumers can share their power surplus and power deficiency information with the P2P market operator. The privacy of blockchain-based data sharing can be confirmed by using the privacy-preserving methodology discussed in [8].

A. Network Model

Let the buses' set of an LV distribution network be $\mathcal{J}$, where the index of each bus is indicated by $j \in \mathcal{J}$. Some of these buses contain prosumers and consumers. The branch interlacing two buses, j and ji, where $j, ji \in \mathcal{J}$, is denoted by $(j, ji) \in \mathcal{I}$ where $\mathcal{I}$ implies the set of branches.

Let the complex power and voltage of each bus in the considered LV distribution network be given by $S_j = P_j + jQ_j$ and $V_j = \mid V_j \mid \; e^{j\Phi}$; where P_j, Q_j signify real and reactive power of each bus $j \in \mathcal{J}$, respectively. The complex power flow through the branch $(j, ji) \in \mathcal{I}$ is symbolised by $S_{(j,ji)} = P_{(j,ji)} + jQ_{(j,ji)}$, where $P_{(j,ji)}$ and $Q_{(j,ji)}$ refer to real and reactive power flow by way of the branch $(j, ji) \in \mathcal{I}$, respectively. The branch flow model of the considered LV distribution network can mathematically be described as follows [24]:

$$P_{ji} = \sum_{(ji,jj)\in\mathcal{I}} P_{ji,jj} - \sum_{(j,ji)\in\mathcal{I}} (P_{j,ji} - R_{j,ji} \mid I_{j,ji} \mid^2) + G_{ji} \mid V_{ji} \mid^2, \tag{1}$$

$$Q_{ji} = \sum_{(ji,jj)\in\mathcal{I}} Q_{ji,jj} - \sum_{(j,ji)\in\mathcal{I}} (Q_{j,ji} - X_{j,ji} \mid I_{j,ji} \mid^2) + B_{ji} \mid V_{ji} \mid^2, \tag{2}$$

$$\mid V_{ji} \mid^2 = \mid V_j \mid^2 - 2(R_{j,ji}P_{j,ji} + X_{j,ji}Q_{j,ji}) + (R_{j,ji}^2 + X_{j,ji}^2) I_{j,ji}, \tag{3}$$

$$I_{j,ji} = \frac{P_{j,ji}^2 + Q_{j,ji}^2}{\mid V_j \mid^2} \tag{4}$$

where $P_{ji}, Q_{ji}, V_{ji}, G_{ji}$, and B_{ji} denote real power, reactive power, voltage, conductance, and susceptance of bus $ji \in \mathcal{J}$, respectively. $R_{j,ji}, X_{j,ji}, I_{j,ji}$, respectively, indicate resistance, reactance, and current flow through the branch $(j, ji) \in \mathcal{I}$.

B. Prosumer Model

Let $\mathcal{Z}$ be the set of prosumers, and the index of each prosumer is denoted by $z \in \mathcal{Z}$. The load demand and solar PV generation of each prosumer $z \in \mathcal{Z}$ at a given time instant, $k \in \mathcal{K}$, are signified by $P_{z,k}^{ld}$ and $P_{z,k}^{sp}$, respectively. These are constrained by the following constraints:

$$0 \le P_{z,k}^{ld} \le \overline{P}_z^{ld}; \quad \forall z \in \mathcal{Z},\ \forall k \in \mathcal{K}, \tag{5}$$

$$0 \le P_{z,k}^{sp} \le \overline{P}_z^{sp}; \quad \forall z \in \mathcal{Z},\ \forall k \in \mathcal{K} \tag{6}$$

where $\overline{P}_z^{ld}$ and $\overline{P}_z^{sp}$ imply maximum ratings of a prosumer's load demand and solar PV system, respectively.

Suppose $P_{z,k}^{bc}$ and $P_{z,k}^{bd}$ represent charged and discharged power of the battery storage system of each prosumer $z \in \mathcal{Z}$ at time $k \in \mathcal{K}$, which are limited by the maximum charging capacity ρ_z^{bc} and the maximum discharging capacity ρ_z^{bd}, respectively. The storage operation is maintained by the state-of-charge (SoC) $S_{z,k}$, and the SoC is also restricted by the maximum capacity $\overline{S}_z$. The battery storage system's charging efficiency and discharging efficiency are indicated by ζ^{bc} and ζ^{bd}, respectively. $c_{z,k}$ and $d_{z,k}$ are binary variables, i.e., $c_{z,k}, d_{z,k} \in [0,1]$, used to evade charging and discharging of the battery storage system simultaneously. That is, if $P_{z,k}^{bc} = 0$ ($c_{z,k} = 0$) at any storage operation period k, then $P_{z,k}^{bd} \neq 0$ ($d_{z,k} = 1$). Similarly, $P_{z,k}^{bd} = 0$ ($d_{z,k} = 0$) makes $P_{z,k}^{bc} \neq 0$ ($c_{z,k} = 1$) at k. If the storage neither charges nor discharges, $P_{z,k}^{bc}, P_{z,k}^{bd} = 0$ ($c_{z,k} = 0, d_{z,k} = 0$). Mathematically:

$$S_{z,k} - S_{z,k-1} - (\zeta^{bc} \times c_{z,k} \times P_{z,k}^{bc} \times \Delta k), \quad (7)$$
$$+(\frac{d_{z,k} \times P_{z,k}^{bd} \times \Delta k}{\zeta^{bd}}) = 0; \quad \forall z \in \mathcal{Z},\ \forall k \in \mathcal{K},$$
$$0 \leq S_{z,k} \leq \overline{S}_z; \quad \forall z \in \mathcal{Z},\ \forall k \in \mathcal{K}, \quad (8)$$
$$0 \leq (P_{z,k}^{bc} \times \Delta k) \leq \rho_z^{bc}; \quad \forall z \in \mathcal{Z},\ \forall k \in \mathcal{K}, \quad (9)$$
$$0 \leq (P_{z,k}^{bd} \times \Delta k) \leq \rho_z^{bd}; \quad \forall z \in \mathcal{Z},\ \forall k \in \mathcal{K}, \quad (10)$$
$$c_{z,k} + d_{z,k} \leq 1; \quad \forall z \in \mathcal{Z},\ \forall k \in \mathcal{K} \quad (11)$$

where Δk is the time length.

Complying with the solar PV generation, load demand, and storage availability, the power status of each prosumer $z \in \mathcal{Z}$ at time $k \in \mathcal{K}$ is calculated as:

$$P_{z,k}^{st} = (P_{z,k}^{sp} + (d_{z,k} \times P_{z,k}^{bd})) \quad (12)$$
$$-(P_{z,k}^{ld} + (c_{z,k} \times P_{z,k}^{bc})); \quad \forall z \in \mathcal{Z},\ \forall k \in \mathcal{K}$$

If $P_{z,k}^{st} = 0$, prosumer z is self-sufficient. On the contrary, the prosumer has either power surplus (acting as a seller) $P_{z,k}^{ss}, \forall z \in \mathcal{ZA}$, or power deficiency (acting as a buyer) $P_{z,k}^{dy}, \forall z \in \mathcal{ZB}$, if $P_{z,k}^{st} \neq 0$, where $\mathcal{ZA} \subset \mathcal{Z}$ and $\mathcal{ZB} \subset \mathcal{Z}$ denote the sets of prosumers with power surplus and power deficiency, respectively. Now, $P_{z,k}^{ss}$ and $P_{z,k}^{dy}$ of each prosumer z at time $k \in \mathcal{K}$ can be expressed as:

$$P_{z,k}^{ss} = \max\{P_{z,k}^{st}, 0\}; \quad \forall z \in \mathcal{ZA},\ \forall k \in \mathcal{K}, \quad (13)$$
$$P_{z,k}^{dy} = \min\{P_{z,k}^{st}, 0\}; \quad \forall z \in \mathcal{ZB},\ \forall k \in \mathcal{K} \quad (14)$$

For example, for any z and k, if $c_{z,k} = 1$, $d_{z,k} = 0$, and $P_{z,k}^{ld} > P_{z,k}^{sp}$, from (12) we have $P_{z,k}^{st} < 0$. This means prosumer z is a buyer with power deficiency, i.e., $P_{z,k}^{ss} = 0$ in (13) and $P_{z,k}^{dy} \neq 0$ in (14), respectively.

Nonetheless, a prosumer z can intend to export/import $P_{z,k}^{ss}/P_{z,k}^{dy}$ amount of power into/from its connected bus at time $k \in \mathcal{K}$. We note that sole consumers also act as buyers by importing, along with prosumers with power deficiency, and belong to $\mathcal{ZB}$. However, the approved export amount $P_{z,k}^{ex}$, where $P_{z,k}^{ex} \leq P_{z,k}^{ss}$, and the approved import amount $P_{z,k}^{im}$, where $P_{z,k}^{im} \leq P_{z,k}^{dy}$, are determined through the DOE settings as described in III-A. With the approved $P_{z,k}^{ex}$ and $P_{z,k}^{im}$, indicated based on the standard generation reference sign conversion, prosumers can decide on their preferred P2P trading amounts. Please see Subsection III-B for detailed P2P trading settlements.

III. Proposed DOE-enabled Cooperative P2P Trading Model

This section explains how the DOE of a selected network is determined to evaluate the approved power amounts that prosumers can export into and/or import from their buses by maintaining network constraints within the prescribed margins. Afterwards, a network-aware P2P trading framework is developed using a canonical coalition game (CCG). In the proposed game, prosumers always trade energy with one another without violating the approved export and import limits assigned to them.

Fig. 1 illustrates the proposed DOE-based P2P trading model description, where the information of power deficiency and power surplus intended to be traded in the LEM by each prosumer is sent to the P2P market operator. We note that the intended power deficiency and power surplus amounts are not restricted by the existing static limits. With prosumers' data and relevant network data, the P2P market operator computes the DOE in two steps to ensure network integrity. In the first step, the P2P market operator solves an AC power flow (PF) to verify the network's compatibility to safely perform the intended trading between prosumers and consumers for the given parameters. If no violation occurs, e.g., voltage rise issue or excessive line loading, the indented amounts of prosumers and consumers are approved. Otherwise, an AC OPF solver is activated by the P2P market operator in the second step to determine the DOEs, i.e., maximum export and import limits for prosumers (and other consumers) to be traded via P2P without incriminating the network's integrity. The AC OPF formulation takes account of prosumer power limits, real and reactive power balance, power flow constraints, and technical and operational limits of the network to assign DOEs closest possible to the intended operation.

The approved export and import limits are sent to the prosumers and consumers, maintaining their privacy, so that they can decide on their preferred P2P trading quantities and prices collaboratively by forming the P2P coalition. The total benefit of the P2P coalition is maximised by following P2P market constraints, i.e., total selling and total buying quantities should be equal, any mismatch should be traded as per the existing tariff structure, and the P2P market price should be higher/lower than the selling/buying price of the existing tariff structure. Finally, the total cooperation benefit is evaluated and distributed among participating P2P prosumers.

A. Assignment of DOE

Firstly, an AC PF study is performed with intended power surplus $P_{z,k}^{ss}$, power deficiency $P_{z,k}^{dy}$, and considered network data. If no network constraint violation is observed, then $P_{z,k}^{ss}$ and $P_{z,k}^{dy}$ are approved to export and import, respectively. In other words, $P_{z,k}^{ex} = P_{z,k}^{ss}$ and $P_{z,k}^{im} = P_{z,k}^{dy}$ for all prosumers (i.e., $\forall z \in \mathcal{ZX}$ – where $\mathcal{ZX} \in \mathcal{Z}$ is the set of safe prosumers). However, if there exists any network constraint infringement – voltage rise or line loading phenomenon at some buses, for instance, an AC OPF problem is solved by considering the same data to evaluate the DOE settings, i.e., the maximum export/import limit of each individual prosumer to retain the

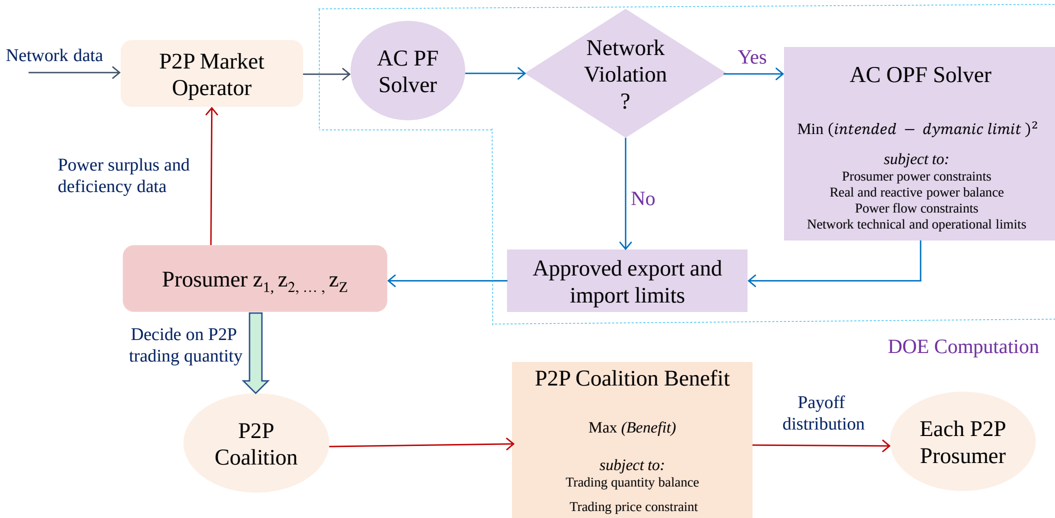

Fig. 1: The proposed DOE-based P2P trading model.

network integrity. In this case, $P^{ex}_{z,k} < P^{ss}_{z,k}$ and $P^{im}_{z,k} < P^{dy}_{z,k}$ for those prosumers who contribute to network constraints' violations (i.e., $\forall z \in \mathcal{ZY}$ – where $\mathcal{ZY} \in \mathcal{Z}$ is the set of unsafe prosumers). While $P^{ex}_{z,k} = P^{ss}_{z,k}$ and $P^{im}_{z,k} = P^{dy}_{z,k}$ for other prosumers whose export and import are safe for the network (i.e., $\forall z \in \mathcal{ZX}$).

Let the intended operation and dynamic operating limit for each prosumer at time $k \in \mathcal{K}$ be $P^{io}_{z,k}$ and $P^{do}_{z,k}$, respectively, where $P^{io}_{z,k}$ can be either $P^{ss}_{z,k}$ or $P^{dy}_{z,k}$. Prosumers cannot be compelled to export and import greater than intended $P^{ss}_{z,k}$ and $P^{dy}_{z,k}$ at any time $k \in \mathcal{K}$. This constraints are described by (15) and (16), respectively.

$$0 \leq P^{do}_{z,k} \leq P^{ss}_{z,k} \text{ [if } P^{io}_{z,k} = P^{ss}_{z,k}]; \quad \forall z \in \mathcal{Z},\ \forall k \in \mathcal{K}, \quad (15)$$

$$0 \geq P^{do}_{z,k} \geq P^{dy}_{z,k} \text{ [if } P^{io}_{z,k} = P^{dy}_{z,k}]; \quad \forall z \in \mathcal{Z},\ \forall k \in \mathcal{K} \quad (16)$$

The real and reactive power balance formulations in the network are illustrated in (17) and (18), respectively, where $P^{g}_{j=1,k}$ and $Q^{g}_{j=1,k}$ refer to the real and reactive power supply from the upstream grid at a given time $k \in \mathcal{K}$. $P^{g}_{j=1,k}$ is constrained by minimum and maximum real power supply $\underline{P}^{g}_{j=1,k}$ and $\overline{P}^{g}_{j=1,k}$, respectively, such that $\underline{P}^{g}_{j=1,k} \leq P^{g}_{j=1,k} \leq \overline{P}^{g}_{j=1,k}$. Likewise, in the case of reactive power, $\underline{Q}^{g}_{j=1,k} \leq Q^{g}_{j=1,k} \leq \overline{Q}^{g}_{j=1,k}$, where $\underline{Q}^{g}_{j=1,k}$ and $\overline{Q}^{g}_{j=1,k}$ imply minimum and maximum reactive power supply, respectively. Besides, $P^{l}_{(j,ji),k}$ and $Q^{l}_{(j,ji),k}$ are real and reactive power losses in the branch $(j,ji) \in \mathcal{I}$, respectively. The real and reactive power deficiencies at bus $j \in \mathcal{J}$ are denoted by $P^{dy}_{j,k}$ and $Q^{dy}_{j,k}$, respectively.

$$P^{g}_{j=1,k} + \sum_{(j,ji)\in\mathcal{I}} P^{l}_{(j,ji),k} = \sum_{j\in\mathcal{J}} P^{dy}_{j,k}; \quad \forall k \in \mathcal{K}, \quad (17)$$

$$Q^{g}_{j=1,k} + \sum_{(j,ji)\in\mathcal{I}} Q^{l}_{(j,ji),k} = \sum_{z\in\mathcal{J}} Q^{dy}_{j,k}; \quad \forall k \in \mathcal{K} \quad (18)$$

The real and imaginary parts of phase currents exported or imported at each bus $j \in \mathcal{J}$ at time $k \in \mathcal{K}$ are represented by $I^{Re}_{j,\theta,k}$ and $I^{Im}_{j,\theta,k}$, respectively, where θ indicates phase index and is defined by $\theta \in \{a,b,c\}$. They are related with real part of phase voltage $V^{Re}_{j,\theta,k}$ and imaginary part of phase voltage $V^{Im}_{j,\theta,k}$ in (19) and (20), respectively, where $Q^{io}_{j,\theta,k}$ denotes the intended reactive power at phase θ of each bus $j \in \mathcal{J}$.

$$(V^{Re^2}_{j,\theta,k} + V^{Im^2}_{j,\theta,k}) I^{Re}_{j,\theta,k} = P^{do}_{j,\theta,k} V^{Re}_{j,\theta,k} + Q^{io}_{j,\theta,k} V^{Im}_{j,\theta,k}, \quad (19)$$

$$(V^{Re^2}_{j,\theta,k} + V^{Im^2}_{j,\theta,k}) I^{Im}_{j,\theta,k} = P^{do}_{j,\theta,k} V^{Im}_{j,\theta,k} - Q^{io}_{j,\theta,k} V^{Re}_{j,\theta,k} \quad (20)$$

The magnitude of each phase current θ through the branch $(j,ji) \in \mathcal{I}$ is limited by the capacity of the branch current flow $\overline{I}_{(j,ji)}$ as depicted in (21). Further, line and transformers limits that restrict branch power flows are provided in (22) and (23), respectively.

$$I^{Re^2}_{(j,ji),\theta,k} + I^{Im^2}_{(j,ji),\theta,k} \leq \overline{I}^{2}_{(j,ji)}; \quad \forall (j,ji) \in \mathcal{I}, \quad (21)$$

$$P^{2}_{(j,ji),\theta,k} + Q^{2}_{(j,ji),\theta,k} \leq (V^{Re^2}_{j,\theta,k} + V^{Im^2}_{j,\theta,k}) \overline{I}^{2}_{(j,ji)}, \quad (22)$$

$$(\sum_{\theta} P_{(j,ji),\theta,k})^2 + (\sum_{\theta} Q_{(j,ji),\theta,k})^2 \leq \overline{S}^{2}_{(j,ji)} \quad (23)$$

Similarly, the voltage magnitude is also abide by the maximum and minimum prescribed voltage limits – $\overline{V}_{j,\theta}$ and $\underline{V}_{j,\theta}$ respectively – as expressed in (24).

$$\underline{V}^{2}_{j,\theta} \leq (V^{Re^2}_{j,\theta,k} + V^{Im^2}_{j,\theta,k}) \leq \overline{V}^{2}_{j,\theta}; \quad \forall j \in \mathcal{J} \quad (24)$$

Considering constraints (15)(24), the proposed objective function, which minimises the sum of squared difference between $P^{io}_{z,k}$ and $P^{do}_{z,k}$, can be written as follows:

$$\min \sum_{z\in\mathcal{Z}} (P^{io}_{z,k} - P^{do}_{z,k})^2; \quad \forall k \in \mathcal{K} \quad (25)$$

$$\text{Subject to: (15)-(24)}$$

The following subsection describes how a CCG-based P2P trading mechanism is developed considering DOE outcomes.

B. Network-aware Cooperative P2P Trading

Under the proposed P2P trading scheme, prosumers and consumers trade at prices that are higher than the feed-in-tariff (FiT) rate but lower than the time-of-use (ToU) price set by the utility as per business-as-usual (BAU). This confirms that sellers (prosumers with power surpluses) earn more compared to the FiT scheme if they trade in the P2P market. Meanwhile, buyers (prosumers and consumers with power deficiencies) reduce their expenses compared to the retail price by buying energy from the P2P market. In other words, both sellers and buyers receive financial benefits in comparison with the BAU under utility.

Let $\mathcal{S}$ be a set of prosumers and consumers interested in P2P trading, where $\mathcal{S} \subset \mathcal{Z}$. Also, let $\mathcal{SA}$ and $\mathcal{SB}$ be sets of sellers and buyers , respectively, such that $\mathcal{SA} \cup \mathcal{SB} = \mathcal{S}$ and $\mathcal{S} \setminus (\mathcal{SA} \cup \mathcal{SB}) = \{\phi\}$. Assume $P^{sa}_{z,k}, z \in \mathcal{SA}$, and $P^{sb}_{z,k}, z \in \mathcal{SB}$, refer to the P2P selling and buying quantities at any time $k \in \mathcal{K}$, where $P^{sa}_{z,k}$ and $P^{sb}_{z,k}$ are bounded by approved export and import limits – such that $P^{sa}_{z,k} \leq P^{ex}_{z,k}$ and $P^{sb}_{z,k} \leq P^{im}_{z,k}$, respectively.

If $P^{sa}_{z,k} < P^{ex}_{z,k}$, $(P^{ex}_{z,k} - P^{sa}_{z,k})$ amount of power is exported at the FiT rate $x^e_{z,k}$. Likewise, $(P^{im}_{z,k} - P^{sb}_{z,k})$ amount of power is bought outside of the P2P settlement at the time-of-use (ToU) price $x^o_{z,k}$ in the case of $P^{sb}_{z,k} < P^{im}_{z,k}$ [38]. We assume that $x^o_{z,k}$ is higher than $x^e_{z,k}$ following the existing tariff structure in Victoria, Australia [39]. Nonetheless, if $x^s_{z,k}$ represents the P2P trading price, the electricity cost of each prosumer $z \in \mathcal{Z}$ at a given time $k \in \mathcal{K}$ is calculated as:

$$\begin{aligned} CF^{sp}_{z,k} = -a_{z,k} \times [(x^s_{z,k} \times P^{sa}_{z,k} \times \Delta k) + \\ (x^e_{z,k} \times (P^{ex}_{z,k} - P^{sa}_{z,k}) \times \Delta k)] - b_{z,k} \times [(x^s_{z,k} \times P^{sb}_{z,k} \times \Delta k) \\ +(x^o_{z,k} \times (P^{im}_{z,k} - P^{sb}_{z,k}) \times \Delta k)]; \quad \forall z \in \mathcal{S},\ \forall k \in \mathcal{K} \end{aligned} \tag{26}$$

where $P^{sa}_{z,k}, P^{ex}_{z,k} > 0$ and $P^{sb}_{z,k}, P^{im}_{z,k} < 0$. The binary variables $a_{z,k}$ and $b_{z,k}$ cannot be 1 simultaneously, i.e., $a_{z,k} + b_{z,k} \leq 1$ and $a_{z,k}, b_{z,k} \in [0, 1]$. If $a_{z,k} = 1$ and $b_{z,k} = 0$, the prosumer z acts as a seller, i.e., $z \in \mathcal{SA}$ as per (26). Contrarily, if $a_{z,k} = 0$ and $b_{z,k} = 1$, the prosumer z plays the role of a buyer, i.e., $z \in \mathcal{SB}$. The prosumer z decides not to sell or buy any power if $a_{z,k} = 0$ and $b_{z,k} = 0$, and hence, no cost is incurred, i.e., $CF^{sp}_{z,k} = 0$.

If $P^{sa}_{z,k}$ and $P^{sb}_{z,k}$ are traded at $x^e_{z,k}$ and $x^o_{z,k}$, respectively, as per BAU (where both $P^{sa}_{z,k}$ and $P^{sb}_{z,k}$ are bounded by the static limits), the equivalent cost becomes:

$$\begin{aligned} CF^{bu}_{z,k} = -a_{z,k} \times [(x^e_{z,k} \times P^{sa}_{z,k} \times \Delta k) + \\ (x^e_{z,k} \times (P^{ex}_{z,k} - P^{sa}_{z,k}) \times \Delta k)] - b_{z,k} \times [(x^o_{z,k} \times P^{sb}_{z,k} \times \Delta k) \\ +(x^o_{z,k} \times (P^{im}_{z,k} - P^{sb}_{z,k}) \times \Delta k)]; \quad \forall z \in \mathcal{S},\ \forall k \in \mathcal{K} \end{aligned} \tag{27}$$

The difference between $CF^{bu}_{z,k}$ and $CF^{sp}_{z,k}$ is the benefit, symbolised by $\hat{CF}_{z,k}$, attained by each prosumer $z \in \mathcal{S} \subset \mathcal{Z}$ at time $k \in \mathcal{K}$ from the P2P market, which is computed as follows:

$$\hat{CF}_{z,k} = CF^{bu}_{z,k} - CF^{sp}_{z,k}; \quad \forall z \in \mathcal{S},\ \forall k \in \mathcal{K} \tag{28}$$

Clearly, several sellers and buyers can decide to take part in P2P trading. In this paper, it is considered that all P2P prosumers (sellers and buyers) cooperate with each other at each P2P trading slot $k \in \mathcal{K}$, and the decision-making (influenced by the DOE settings) is formulated with the help of coalition game theory – particularly CCG structure. The formation, fundamental properties, and payoff distribution of the designed CCG-driven P2P framework are presented in Subsection III-B1, Subsection III-B2, and Subsection III-B3, respectively.

1) Coalition Value Function: Let $\mathcal{G}$ be the proposed network-aware P2P coalition game, which can be defined as a characteristic function form such that:

$$\mathcal{G} = \{\mathcal{S},\ \mathcal{W}(\mathcal{S})\} \tag{29}$$

where $\mathcal{W}(\mathcal{S})$ represents a value function of $\mathcal{G}$ that assigns a real number, i.e., a procured numerical reward termed game value, to each network-aware P2P coalition $\mathcal{T} \subseteq \mathcal{S}$.

The procured numerical reward $\mathcal{W}$ – attained by the participating prosumers – at a given trading instant $k \in \mathcal{K}$ in the proposed P2P coalition $\mathcal{T}$ can be evaluated from the difference between the total electricity cost, i.e., $\sum_{z \in \mathcal{T} \subseteq \mathcal{S}} CF^{sp}_{z,k}$, in P2P coalition and the total electricity cost, i.e., $\sum_{z \in \mathcal{T} \subseteq \mathcal{S}} CF^{bu}_{z,k}$, as per BAU (where equivalent P2P quantities are traded at $x^e_{z,k}$ and $x^o_{z,k}$ prices). The total electricity cost difference is signified by $\sum_{z \in \mathcal{T} \subseteq \mathcal{S}} \hat{CF}_{z,k}$.

This paper seeks to maximise the procured numerical award, i.e., total electricity cost reduction, in (30) by following the power export and import constraints assigned by DOE (shown in (31) and (32), and described in detail in Subsection III-A) as well as the coalition trading quantity (total selling and total buying quantities should be equal) and price constraint (the P2P coalition price should be greater than the FiT rate but lesser than the ToU price to reward both sellers and buyers), as provided in (33) and (34), respectively. As such, the proposed coalition value function $\mathcal{W}(\mathcal{T})$ of $\mathcal{G}$ is defined as:

$$\mathcal{W}(\mathcal{T}) = \max \sum_{z \in \mathcal{T} \subseteq \mathcal{S}} \hat{CF}_{z,k}(\mathcal{T}); \quad \forall k \in \mathcal{K}, \tag{30}$$

Subject to:

$$P^{sa}_{z,k}(\mathcal{T}) \leq P^{ex}_{z,k} \leq P^{ss}_{z,k}; \quad \forall z \in \mathcal{S},\ \forall k \in \mathcal{K}, \tag{31}$$

$$P^{sb}_{z,k}(\mathcal{T}) \leq P^{im}_{z,k} \leq P^{dy}_{z,k}; \quad \forall z \in \mathcal{S},\ \forall k \in \mathcal{K}, \tag{32}$$

$$\sum_{z \in \mathcal{T}} P^{sa}_{z,k}(\mathcal{T}) = \sum_{z \in \mathcal{T}} P^{sb}_{z,k}(\mathcal{T}); \quad \forall k \in \mathcal{K}, \tag{33}$$

$$x^e_{z,k} < x^s_{z,k}(\mathcal{T}) < x^o_{z,k}; \quad \forall z \in \mathcal{S},\ \forall k \in \mathcal{K} \tag{34}$$

Since (30) refers to a reward paid to the P2P coalition $\mathcal{T}$, it can be distributed in any arbitrary fashion among the members of $\mathcal{T}$. Therefore, the proposed game $\mathcal{G}$ is a game with transferrable payoff. However, engaging prosumers may not always be interested establishing the coalition unless the proposed network-aware P2P coalition guarantees the benefits, i.e., cost reduction, in a stable manner at all times in $\mathcal{K}$. Hence, how the formulated P2P coalition abides by the cooperation benefits and stability properties of the CCG is authenticated in the next subsection.

2) Game Properties' Verification:

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2.1) Incentive-Compatibility [1]*:* The incentive-compatibility of CCG emphasises that any subgroup of players, i.e., P2P prosumers, cannot reap greater reward by leaving the grand coalition [40], [41], i.e., $\mathcal{T} = \mathcal{SA} \cup \mathcal{SB}, \forall \mathcal{T} \subseteq \mathcal{S}$. In other words, the CCG structure is by no means unprofitable for participating P2P prosumers. This is related to the super-additivity of the coalition value function [16]. Assume $\mathcal{T}_m$ and $\mathcal{T}_n$ are two disjoint coalitions, such that $\mathcal{T} = \mathcal{T}_m \cup \mathcal{T}_n$ and $\mathcal{T}_m \cap \mathcal{T}_n = \{\phi\}$. The value function of a CCG, i.e., $\mathcal{W}(\mathcal{T})$, satisfies the mathematical property of superadditive if the aggregation of solitary values of these two disjoint coalitions is less than the union value of two disjoint coalitions as defined in (35).

$$\mathcal{W}(\mathcal{T}_m \cup \mathcal{T}_n) \geq \mathcal{W}(\mathcal{T}_m) + \mathcal{W}(\mathcal{T}_n) \tag{35}$$

Theorem A: The coalition value function of our proposed network-aware P2P coalition, expressed in (30), is superadditive. Therefore, the collaboration is advantageous for all participating P2P prosumers.

Proof: If there exists no P2P coalition, i.e., if $\mid \mathcal{T} \mid= 0$, the value function $\mathcal{W}$ becomes zero, i.e., $\mathcal{W} = 0$, according to (30). Further, $\mathcal{W}$ is a function of total cost reduction if $\mid \mathcal{T} \mid\neq 0$. Since the participating prosumers seek to earn rewards from the proposed P2P coalition, the total cost reduction cannot be negative – which can otherwise incur more cost compared to BAU, and thus, prosumers are more likely to abandon the P2P coalition. As such, $\mathcal{W} \geq 0$, and it is a convex function.

Based on (30), the benefits gained in disjoint coalitions $\mathcal{T}_m$ and $\mathcal{T}_n$ can be written as follows:

$$\beta(\mathcal{T}_m) = \max \sum_{z \in \mathcal{T}_m \subset \mathcal{T} \subseteq \mathcal{S}} \hat{CF}_{z,k}(\mathcal{T}_m); \quad \forall k \in \mathcal{K}, \tag{36}$$

$$\beta(\mathcal{T}_n) = \max \sum_{z \in \mathcal{T}_n \subset \mathcal{T} \subseteq \mathcal{S}} \hat{CF}_{z,k}(\mathcal{T}_n); \quad \forall k \in \mathcal{K} \tag{37}$$

$$\text{Subject to: (31)} - \text{(34)}$$

The sum of two disjoint coalitions' value functions can be represented as follows:

$$\mathcal{W}(\beta_{\mathcal{T}_m}) + \mathcal{W}(\beta_{\mathcal{T}_n}) = \tag{38}$$

$$\mathcal{W}(\frac{\beta_{\mathcal{T}_m}}{\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}}(\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n})) + \mathcal{W}(\frac{\beta_{\mathcal{T}_n}}{\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}}(\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}))$$

For $0 \leq \frac{\beta_{\mathcal{T}_m}}{\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}}(\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}),\ \frac{\beta_{\mathcal{T}_n}}{\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}}(\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}) \leq 1$ and $\beta_{\mathcal{T}_m},\ \beta_{\mathcal{T}_n} \geq 0$, the convexity yields:

$$\begin{aligned} &\mathcal{W}(\frac{\beta_{\mathcal{T}_m}}{\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}}(\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n})) + \mathcal{W}(\frac{\beta_{\mathcal{T}_n}}{\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}}(\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n})) \\ &\leq \frac{\beta_{\mathcal{T}_m}}{\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}}\mathcal{W}(\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}) + \frac{\beta_{\mathcal{T}_n}}{\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}}\mathcal{W}(\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}) \\ &= \mathcal{W}(\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}) \end{aligned} \tag{39}$$

Thus, (38) can be rewritten as:

$$\mathcal{W}(\beta_{\mathcal{T}_m}) + \mathcal{W}(\beta_{\mathcal{T}_n}) \leq \mathcal{W}(\beta_{\mathcal{T}_m} + \beta_{\mathcal{T}_n}) \tag{40}$$

(40) suggests the enhancement of disjoint coalitions causes the reduction of $\mathcal{W}$, confirming the coalition value function of our proposed network-aware P2P coalition $\mathcal{T}$ is superadditive. Therefore, it is beneficial and incentive-compatible for all the members. ■

2.2) Stability: The stability of a coalition game is verified by the existence of the core, which is a set of payoff distributions with group and individual rationality. In other words, the core of a stable coalition game is a non-empty [17]. For a coalition game with a convex value function, i.e., $\mathcal{W}$, there exists a non-empty core if the value function is supermodular. For any P2P prosumer $z \in \mathcal{T} \subseteq \mathcal{S}$, assume $\mathcal{T}_{mm}$ and $\mathcal{T}_{nn}$ are two coalitions – such that $\mathcal{T}_{mm} \subset \mathcal{T}_{nn} \subset \mathcal{T}$ with $\mathcal{T}_{mm} \cap \{z\} = \mathcal{T}_{nn} \cap \{z\} = \{\phi\}$. The conduction for the supermodular value function is:

$$\mathcal{W}(\mathcal{T}_{mm} \cup \{z\}) - \mathcal{W}(\mathcal{T}_{mm}) \leq \mathcal{W}(\mathcal{T}_{nn} \cup \{z\}) - \mathcal{W}(\mathcal{T}_{nn}) \tag{41}$$

Theorem B: Our proposed network-aware P2P coalition always has a non-empty core. Hence, it is stable.

Proof: Since $\mathcal{T}_{mm} \subset \mathcal{T}_{nn}$ for two coalitions $\mathcal{T}_{mm} \subset \mathcal{T}$ and $\mathcal{T}_{nn} \subset \mathcal{T}$, the following relation can be derived for any P2P prosumer $z \in \mathcal{T}$:

$$(\mathcal{T}_{mm} \cup \{z\}) \subset (\mathcal{T}_{nn} \cup \{z\}) \tag{42}$$

As the number of P2P prosumers increases, the P2P transactions among prosumers are also proliferated in the coalition in $\mathcal{T}$. Note that all P2P transactions are always compliant with network and price constraints, as demonstrated in (31)-(34). Nevertheless, the increased number of P2P transactions causes cooperative prosumers to earn greater financial reward, i.e., more electricity cost reduction, contrasting to BAU. As such, the value function of our proposed network-aware P2P coalition is increased, confirming the coalition value function (the convexity is proved while proofing *Theorem A*) – proposed in (30). This results in:

$$\mathcal{W}(\mathcal{T}_{mm}) \leq \mathcal{W}(\mathcal{T}_{nn}); \quad \text{if } \mathcal{T}_{mm} \subset \mathcal{T}_{nn}, \tag{43}$$

$$\mathcal{W}(\mathcal{T}_{mm} \cup \{z\}) \leq \mathcal{W}(\mathcal{T}_{nn} \cup \{z\}); \tag{44}$$

$$\text{if } (\mathcal{T}_{mm} \cup \{z\}) \subset (\mathcal{T}_{nn} \cup \{z\})$$

Clearly, it is obvious from (44) - (43) that $\mathcal{W}(\mathcal{T}_{nn} \cup \{z\}) - \mathcal{W}(\mathcal{T}_{nn}) \geq\ \mathcal{W}(\mathcal{T}_{mm} \cup \{z\}) - \mathcal{W}(\mathcal{T}_{mm})$, implying the value function is supermodular. Therefore, our proposed network-aware P2P coalition is stable. ■

3) Payoff Allocation: Since the proposed network-aware P2P coalition satisfies the non-empty core criterion, the total payoff of the coalition, i.e., the coalition value, is required to be allocated among P2P prosumers. This paper adopts the Shapley value theorem for fair payoff distribution. In accordance with the marginal contribution – symbolised by $\mathcal{W}'(\mathcal{T}) = \mathcal{W}(\mathcal{T} \cup \{z\}) - \mathcal{W}(\mathcal{T})$ – of each prosumer z to P2P coalition $\mathcal{T} \subseteq \mathcal{M}$, the Shapley value $\phi_z(\mathcal{W})$ – evaluated in (45) – assigns the remuneration.

$$\phi_z(\mathcal{W}) = \sum_{\mathcal{T} \subseteq \mathcal{S} \setminus \{z\}} \frac{\mid \mathcal{T} \mid!(\mid \mathcal{S} \mid - \mid \mathcal{T} \mid -1)!}{\mid \mathcal{S} \mid!}[\mathcal{W}'(\mathcal{T})] \tag{45}$$

where $\mid \mathcal{T} \mid$ and $\mid \mathcal{S} \mid$ denote prosumers' number in the network-aware P2P coalition $\mathcal{T}$ and in the P2P prosumers' set $\mathcal{S}$, respectively. Once the P2P coalition value is optimally

[1]In this paper, we have adopted the incentive compatibility definition used in cooperative game theory [40], [41].

Algorithm 1 Proposed DOE-enabled P2P trading algorithm

for each target P2P trading slot $k \in \mathcal{K}$ **do**
  for each prosumer $z \in \mathcal{Z}$ **do**
    Calculate $P^{ss}_{z,k}, z \in \mathcal{ZA} \subset \mathcal{Z}$,
    and $P^{dy}_{z,k}, z \in \mathcal{ZB} \subset \mathcal{Z}$, in (13) and (14).
  end for
  Perform PF analysis with $P^{ss}_{z,k}, \forall z \in \mathcal{ZA}$, and $P^{dy}_{z,k}, \forall z \in \mathcal{ZB}$.
  if No network violation **then**
    for each prosumer $z \in \mathcal{Z}$ **do**
      $P^{ex}_{z,k} = P^{ss}_{z,k}$ and $P^{im}_{z,k} = P^{dy}_{z,k}$
    end for
  else
    for each prosumer $z \in \mathcal{Z}$ **do**
      Determine $P^{ex}_{z,k} \leq P^{ss}_{z,k}$ and $P^{im}_{z,k} \leq P^{dy}_{z,k}$ by solving (25) considering constraints (15)-(24).
    end for
  end if
  for each P2P prosumer $z \in \mathcal{S} \subset \mathcal{Z}$ **do**
    if $P^{sa}_{z,k} \neq 0$ and $P^{sb}_{z,k} = 0$ **then**
      P2P prosumer $z \in \mathcal{SA} \subset \mathcal{S}$ acts as a P2P seller, where $P^{sa}_{z,k} \leq P^{ex}_{z,k}$.
    end if
    if $P^{sa}_{z,k} = 0$ and $P^{sb}_{z,k} \neq 0$ **then**
      P2P prosumer $z \in \mathcal{SB} \subset \mathcal{S}$ acts as a P2P buyer, where $P^{sb}_{z,k} \leq P^{im}_{z,k}$.
    end if
  end for
  if $\sum_{z \in \mathcal{SA}} P^{sa}_{z,k} \neq 0$ and $\sum_{z \in \mathcal{SB}} P^{sb}_{z,k} \neq 0$. **then**
    Perform cooperative P2P trading by establishing a network-aware P2P coalition in $\mathcal{S} = \mathcal{SA} \cup \mathcal{SB}$.
    for any P2P coalition $\mathcal{T} \subseteq \mathcal{S}$ **do**
      Determine $\mathcal{W}$ by solving $\mathcal{W}(\mathcal{T})$ in (30) considering constraints (31) - (34).
      Allocate $\mathcal{W}$ between P2P prosumers in (45).
    end for
  else
    No cooperative trading between prosumers.
  end if
end for

determined in (30), the (45) is used to evaluate the allotted Shapley value to each P2P prosumer.

C. The Proposed Algorithm

The proposed DOE-facilitated cooperative P2P trading algorithm is displayed in Algorithm 1. It incorporates distribution network export and import limits while conducting P2P trading among cooperative prosumers following the hybrid market structure of P2P trading [2].

For each P2P trading slot $k \in \mathcal{K}$, power surplus $P^{ss}_{z,k}, z \in \mathcal{ZA}$, and power deficiency $P^{dy}_{z,k}, z \in \mathcal{ZB}$, of each prosumer z, where $\mathcal{ZA}, \mathcal{ZB} \subset \mathcal{Z}$ are calculated in (13) and (14), respectively. An AC PF is performed with intended $P^{ss}_{z,k}, \forall z \in \mathcal{ZA}$, and $P^{dy}_{z,k}, \forall z \in \mathcal{ZB}$, and considered network data. If no network violation is observed, $P^{ss}_{z,k}$ and $P^{dy}_{z,k}$ are approved to export and import respectively for all prosumers, i.e., $P^{ex}_{z,k} = P^{ss}_{z,k}, \forall z \in \mathcal{ZX}$ and $P^{im}_{z,k} = P^{dy}_{z,k}, \forall z \in \mathcal{ZX}$, where $\mathcal{ZX} \subset \mathcal{Z}$. However, if there exists any network constraint infringement, an AC OPF problem is solved to determine $P^{ex}_{z,k}$ and $P^{ex}_{z,k}$ for all prosumers by solving (25) considering constraints (15)-(24), which assigns $P^{ex}_{z,k} < P^{ss}_{z,k}$ and $P^{im}_{z,k} < P^{dy}_{z,k}$ for those prosumers who can create network violations (i.e., $\forall z \in \mathcal{ZY} \subset \mathcal{Z}$). Contrarily, $P^{ex}_{z,k} = P^{ss}_{z,k}$ and $P^{im}_{z,k} = P^{dy}_{z,k}$ for other prosumers whose export and import are not detrimental for the physical network (i.e., $\forall z \in \mathcal{ZX} \subset \mathcal{Z}$).

With approved $P^{ex}_{z,k}$ and $P^{im}_{z,k}$, $\forall z \in \mathcal{Z}$, the P2P sellers' set $\mathcal{SA}$ and the P2P buyers' set $\mathcal{SB}$ among P2P prosumers in $\mathcal{S} \subset \mathcal{Z}$ are identified such that $\mathcal{SA} \cup \mathcal{SB} = \mathcal{S}$ and $\mathcal{S} \setminus (\mathcal{SA} \cup \mathcal{SB}) = \{\phi\}$. In $\mathcal{SA}$, the P2P selling quantity $P^{sa}_{z,k} \neq 0, \forall z \in \mathcal{SA}$ (where $P^{sa}_{z,k} \leq P^{ex}_{z,k}, \forall z \in \mathcal{SA}$), and P2P buying quantity $P^{sb}_{z,k} = 0, \forall z \in \mathcal{SA}$. In contrast, $P^{sa}_{z,k} = 0, \forall z \in \mathcal{SB}$, and $P^{sb}_{z,k} \neq 0, \forall z \in \mathcal{SB}$ (where $P^{sb}_{z,k} \leq P^{im}_{z,k}, \forall z \in \mathcal{SB}$), in $\mathcal{SB}$. Now, a network-aware P2P coalition is formulated following the CCG structure $\mathcal{T} \subseteq \mathcal{S}$, such that $\mathcal{S} = \mathcal{SA} \cup \mathcal{SB}$ and $\mathcal{S} \setminus (\mathcal{SA} \cup \mathcal{SB}) = \{\phi\}$. The coalition value $\mathcal{W}$ is determined by solving the coalition value function $\mathcal{W}(\mathcal{T})$ in (30) considering constraints (31) game (34). Finally, $\mathcal{W}$ is allocated between P2P prosumers adopting the Shapley value theorem in (45).

IV. Case Study

This section presents numerical analysis to investigate the performance of our proposed network-aware P2P trading model in comparison with some existing techniques. We note that since the implementation needs access to all network data and information, which are not readily available for different networks, we have employed our LV distribution network (please see Fig. 2) as the test network.

In Subsection IV-A, the physical network compatibility of our proposed P2P trading is compared with the unrestricted method (Method I) considering both low and high local penetration (as provided in [26]), the prosumer-blocking method (Method II) [18], and the power-adjustment method (Method

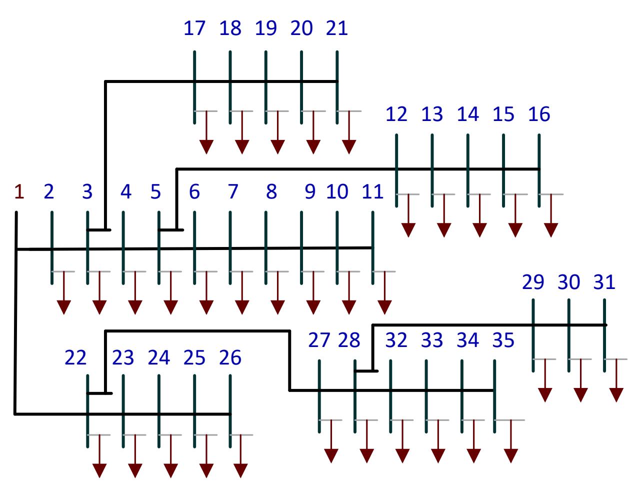

Fig. 2: A 0.4 kV Australian distribution network.

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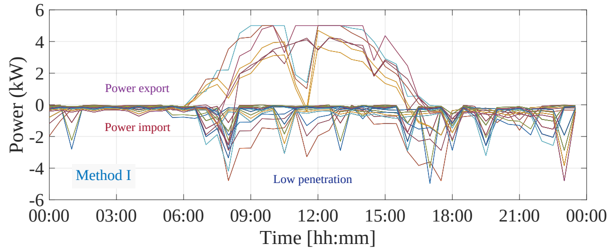
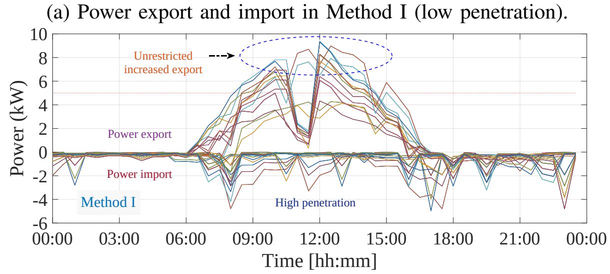
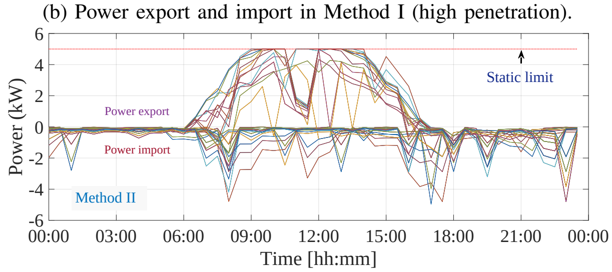


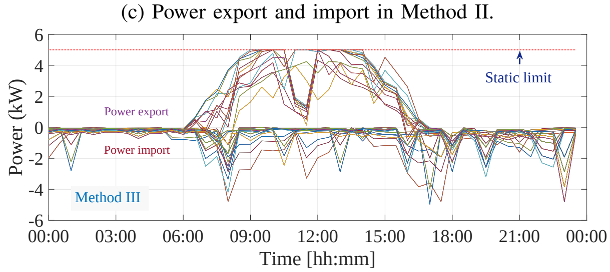
(a) Power export and import in Method I (low penetration).



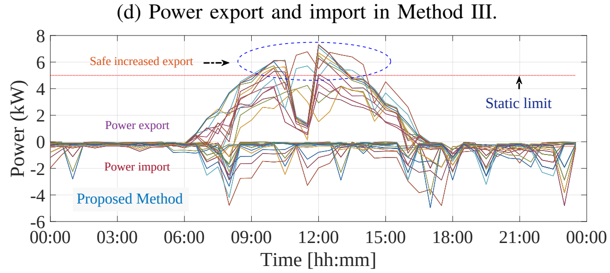
(b) Power export and import in Method I (high penetration).



(c) Power export and import in Method II.

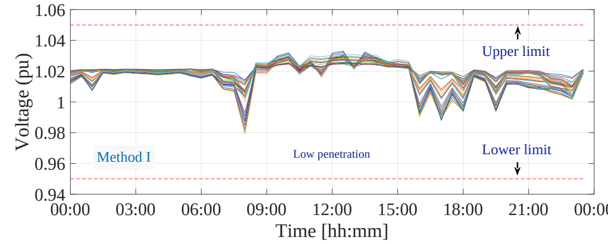


(d) Power export and import in Method III.

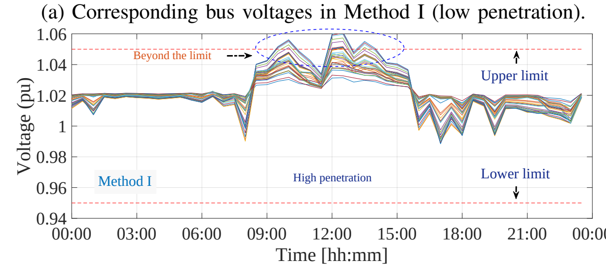


(e) Power export and import in our proposed method.

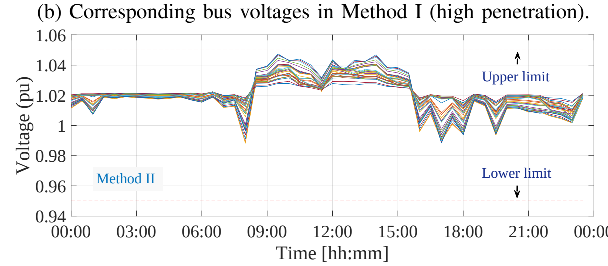
Fig. 3: Residential power export and import in our proposed method versus existing methods over the course of a typical day in Australia.



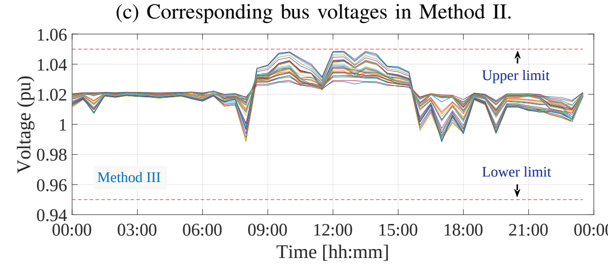
(a) Corresponding bus voltages in Method I (low penetration).



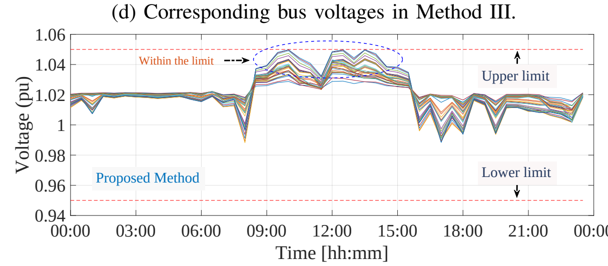
(b) Corresponding bus voltages in Method I (high penetration).



(c) Corresponding bus voltages in Method II.



(d) Corresponding bus voltages in Method III.



(e) Corresponding bus voltages in our proposed method.

Fig. 4: Corresponding bus voltages of the considered LV distribution network in our proposed method versus existing methods over the course of a typical day in Australia.

III) [23]. In Method I, no restriction is considered for solar PV system setup and local export. In Method II, the maximum solar PV system capacity is considered to be 5 kW, and thus, local export stays within 5 kW. Method III uses the existing distribution system limit, which is considered to be 5 kW based on the existing Australian LV limit. Whereas, in Subsection IV-B, the financial viability of our proposed P2P trading is compared with Method IV – in which power surplus and power deficiency are traded at FiT and ToU prices, respectively, as per the current BAU demonstrated in [38], and with the conventional CCG method adopted for local energy trading in [12] (Method V). In both Method IV and Method V, 5 kW is considered as the power export limit following the existing Australian limit.

Fig. 2 displays the one-line layout of a 3-phase 0.4 kV standard Australian LV distribution network with 34 houses per

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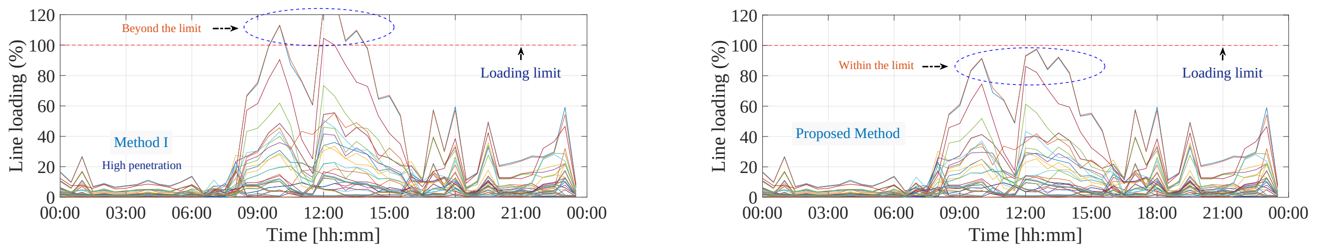

(a) Line current loading in Method I (high penetration).

(b) Line current loading in our proposed method.

Fig. 5: Percentage line current loading of the considered LV distribution network in our proposed method versus Method I over the course of a typical day in Australia.

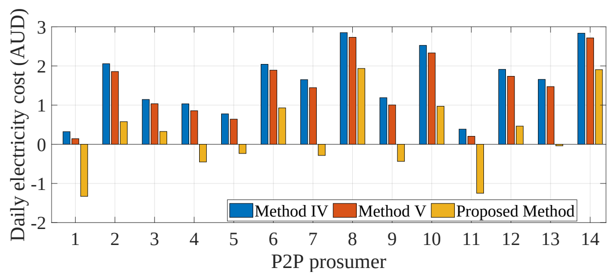

Fig. 6: Comparative daily electricity cost analysis between existing methods and our proposed method in Australian dollars.

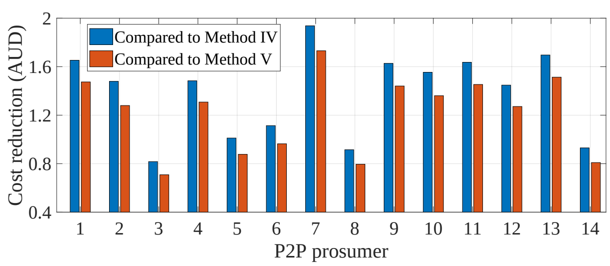

Fig. 7: Daily electricity cost minimisation in our proposed method compared to existing methods in Australian dollars.

phase – one house is considered to be connected at each bus, and bus 1 (i.e., $j = 1 \in \mathcal{J}$) denotes the distribution sub-station. In total, there are 102 single-phase houses in the 3-phase network [42]. Houses $3, 5, 8, 12, 14, 16, 18, 21, 23, 24, 27, 29, 32,$ and 35 of each phase (42 houses in total) are assumed to be prosumers. The studied LV distribution network is modelled on the OpenDSS-interfaced MATLAB platform using the YALMIP toolbox [43], and the AC OPF problem is solved with IPOPT v3.12.9 [44]. The network data are taken from a similar network model used in [27] – where upper and lower voltage constraints are defined as $\overline{V}_{j,\theta} = 1.05$ pu and $\underline{V}_{j,\theta} = 0.95$ pu.

Based on the available houses' data, the magnitudes of $P^{ss}_{z,k}, \forall, z \in \mathcal{ZA}, k \in \mathcal{K}$, for prosumers, acting as sellers, are varied between 0 kW and 10 kW. On the other hand, the magnitudes of $P^{dy}_{z,k}, \forall, z \in \mathcal{ZB}, k \in \mathcal{K}$, for prosumers and other houses, acting as buyers, are to be altered from 0 kW to 5 kW. The considered ToU tariff and FiT rates assume the variation in off-peak, shoulder, and peak ToU prices between 15 ¢/kWh and 50 ¢/kWh with a daily fixed supply charge of $\$1.1$, and FiT rates between 5 ¢/kWh and 7.1 ¢/kWh [39]. It is assumed that one third of the prosumers (14 houses in total) decide to take part in the P2P coalition every 30 minutes (min) apart, and the allocated Shapley value to each P2P prosumer is calculated using the MatTuGames toolbox [45].

A. *Physical Network Performance Analysis*

In this part, power exported and imported by all sellers and buyers in our proposed method and their impacts on the corresponding bus voltage profiles and line loading of the considered LV distribution network, illustrated in Fig. 2, are analysed and compared with some existing methods, i.e., Method I, Method II, and Method III, described earlier.

Method I provides satisfactory performance, i.e., no voltage violation throughout a typical day, if the local penetration is considerably low (around 10% houses export, for example), as noticed from Fig. 3a and Fig. 4a. As such, no restriction is required to maintain the network's integrity. However, Fig. 3b and Fig. 4b demonstrate that high unrestricted local penetration (caused by 40% houses, for instance) can create voltage rise issue in the network, i.e., beyond 1.05 pu, at diverse time instants over the course of 24 hours, and thus require attention for safe network operation. Method II overcomes the over-voltage phenomenon by blocking some houses from exporting power at those target time periods, as seen from Fig. 3c and Fig. 4c. Another existing method (Method III) also controls bus voltages by lowering local penetration interactively, as captured in Fig. 3d and Fig. 4d.

However, Figs. 3c, 3d reveal that local exports are limited by a static limit – which is 5 kW in Australia for instance [25]. Contrarily, our proposed method exports between 5 kW and 7.5 kW (more than the static limit but in a restricted way) during peak local penetration periods, as exhibited in Fig. 3e, resulting in higher local power injections (can lead to enhanced P2P trading quantities) contrasting to Figs. 3c, 3d. The impact of the increased power export through our proposed method on bus voltage profiles is depicted in Fig. 4e, which confirms that our proposed method keeps all bus voltages across all trading slots within upper and lower limits.

Further, unlike unrestricted the method, as shown in Fig. 5a, daily line current flows are within the prescribed maximum loading margin, i.e., 100%, as illustrated in Fig. 5b. Therefore, our proposed method demonstrates superior physical network performance in comparison with existing methods.

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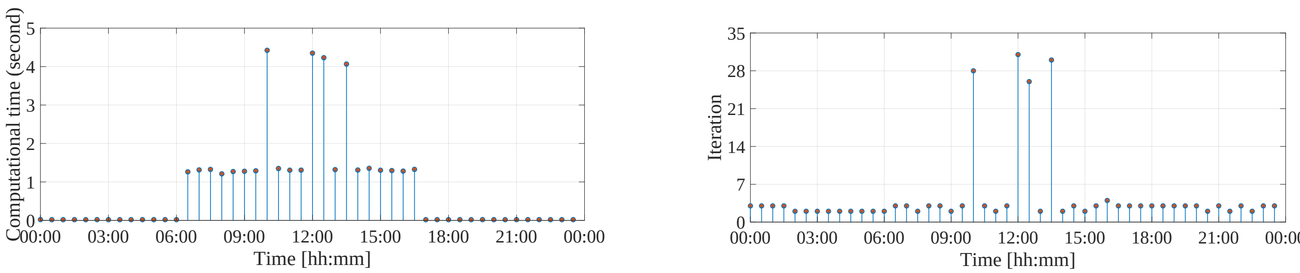

(a) Computational time required in our proposed method.

(b) Iteration required in our proposed method.

Fig. 8: Computational time and iteration required to converge our proposed method over the course of a typical day in Australia.

B. Financial Performance Analysis

In this part, P2P prosumers are assigned their economic benefits, and our proposed method's performance is compared with two other available methods, i.e., Method IV and Method V. P2P prosumers are indexed in Figs. 6-7 in accordance with their physical location (connected phase and bus) in the considered LV distribution network.

As is observed in Fig. 6, prosumer 5a (situated at phase a of bus 5: P2P prosumer 2), prosumer 16a (situated at phase a of bus 16: P2P prosumer 6), P2P prosumer 21c (situated at phase c of bus 21: P2P prosumer 8), P2P prosumer 23c (situated at phase c of bus 23: P2P prosumer 9), and P2P prosumer 27b (situated at phase b of bus 27: P2P prosumer 11) are typically billed \$2.06, \$2.04, \$2.85, \$1.19, and \$0.39, respectively, on a daily basis in BAU (Method IV). These costs scale down to \$1.86, \$1.89, \$2.73, \$1, and \$0.2, respectively, if an existing CCG algorithm (Method V) is adopted. Our proposed method brings down these costs further to \$0.58, \$0.93, \$1.94, $\$-0.44$, and $\$-1.25$, respectively, enabling P2P prosumer 9 and P2P prosumer 11 to gain \$0.44 and \$1.25, respectively (i.e., their bills are zero).

Fig. 7 captures the daily electricity cost minimisation via our proposed method. In particular, our proposed method provides \$1.28, \$0.96, \$0.79, \$1.44, and \$1.45 cost savings to P2P prosumer 2, P2P prosumer 6, P2P prosumer 8, P2P prosumer 9, and P2P prosumer 11, respectively, in comparison with Method V. These figures increase further by approximately \$0.2, \$0.15, \$0.13, \$0.19, and \$0.18 more if the comparison is made with Method IV. Besides, other participating P2P prosumers also reduce their energy expenses significantly by dint of our proposed method, as presented in Fig. 7. Thus, our proposed method outperforms both existing methods remarkably in terms of rewarding P2P prosumers.

C. Convergence Analysis

The results of the convergence analysis of the proposed method based on computational time and number of iterations are shown in Fig. 8. As is observed from Fig. 8a, the execution time of AC PF varies between 17.7 milliseconds (ms) and 20 ms from 5:00 pm to 6:00 am, in which there are no P2P transactions. From 6:30 am to 4:30 pm, P2P transactions are performed, and it takes around 1.28 seconds (sec) on average to clear the coalition payoff distribution, while the range of computational time of the AC PF remains the same if no network issues are noticed. However, for intervals of 9:30 am, 12:00 pm, 12:30 pm, and 1:30 pm, voltage rise issues are found, and hence, AC OPF-based DOE is executed to determine the operating limits. This involves higher computational time compared to only AC PF execution. For instance, 3.18 sec, 3.03 sec, 2.89 sec, and 2.88 sec are required to run the DOE at 9:30 am, 12:00 pm, 12:30 pm, and 1:30 pm, respectively, and the total computation times of the proposed P2P method during these periods are 4.42 sec, 4.34 sec, 4.29 sec, and 4.06 sec, respectively. With regard to the number of iterations, $2-4$ iterations are required to converge the AC PF throughout the considered day. However, the number of iterations for convergence varies between 26 and 31 if AC OPF is performed. These values are depicted in Fig. 8b.

V. Conclusion

A network-aware P2P trading mechanism for a constrained LV distribution network has been proposed in this paper, in which the power exchange and subsequent financial benefits of engaging prosumers have been maximised without endangering network constraints. A DOE approach has been developed to determine the time-varying power export and import limits to maximise the local exchange of prosumers while keeping network constraints within the permissible range. A cooperative P2P trading model has then been formulated, considering the power export and import limits assigned to all participating prosumers to avoid any unsafe trading quantities. The proposed network-aware P2P coalition has been shown to be structurally stable and also beneficial for involving prosumers. Furthermore, the Shapley value theorem has been adopted to distribute the total network-aware P2P coalition benefit among all engaging prosumers.

Lastly, various simulation results have been demonstrated to examine the performance of our proposed P2P trading methodology in comparison with other existing mechanisms. It has been observed from the simulation results that the designed network-aware P2P trading model can permit prosumers to exchange increased amounts of power without creating an issue in the considered LV voltage network. This has also enabled prosumers to trade more power with their peers, resulting in greater financial gains. The proposed P2P trading framework can be redesigned in the future by including fairness when determining export and import limits in power networks through the DOE to improve the satisfaction level of all participating prosumers.

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