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Dynamic Operating Envelope-Based Local Energy Market for Prosumers with Electric Vehicles

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***Abstract*—This paper presents a new framework for the management of prosumers with electric vehicles (EVs) and photovoltaic (PV) systems in a local energy market (LEM) using the dynamic operating envelope (DOE) that secures the network operation for prosumers' trading and allows prosumers to manage EVs charge/discharge with PV systems. Prosumers can configure the charge/discharge status of their EVs depending on mobility and determine their net import/export power which will be used to establish DOEs. The proposed framework incorporates a bidding strategy to enable prosumers to participate in the LEM within DOE limits, and peer-to-peer (P2P) energy trading is developed to offer economic benefits to prosumers. The framework's performance is evaluated with a 100% penetration level of EVs and PV systems on the IEEE 55-node low-voltage European test system. The simulation results demonstrate that DOEs can facilitate prosumers in managing their imports/exports for trading without violating voltage and congestion limits. The proposed framework efficiently manages EV charging/discharging with PV systems and enables prosumers to make optimal bids within DOEs, thereby benefiting from P2P trading in the LEM.**

***Index Terms*—Dynamic operating envelope (DOE), electric vehicle (EV), EVs charging/discharging, local energy market (LEM), peer-to-peer (P2P) trading, photovoltaic (PV) systems.**

I. Introduction

A. Background and Motivations

With the advances in technology and the rapid adoption of distributed energy resources (DERs) and electric vehicles (EVs), the number of customers with DERs (commonly known as prosumers) in distribution networks is rapidly growing. Coordinated integration of EVs and photovoltaic (PV) systems can provide benefits to both prosumers and network operators [1]. Prosumers' EVs can be charged from their rooftop PV generations cost-free, and they can trade their excess generations from EVs discharge and PV systems in a local energy market (LEM) to earn profits from the LEM [2]. Their regulated integration to the distribution networks can also provide diverse services to the networks such as voltage and congestion management [3], [4]. Typically, EVs charging/discharging mainly occurs during the time between 5:00 pm and 8:00 am, although a few EVs may be available during the daytime due to their usage patterns. In contrast, PV system generation occurs during the daytime, and the amount of EV charging from PV system generation is relatively low. Depending on the EV's mobility and owner's preferences, EV discharging may also be allowed to trade in the LEM. Therefore, without appropriate management, the integration of prosumers with EVs and PV systems into residential distribution networks can introduce various operational problems. These problems include voltage violation, congestion problems, phase imbalances in the networks, and energy imbalance and price fluctuations in the LEM [5].

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B. Related Works

The existing studies in the literature have proposed various techniques to manage prosumers considering network and market constraints as control decisions [1]-[18], [23]-[26], [31]-[29].

1) Coordination frameworks: A model predictive voltage control method is proposed in [6] to enhance the power quality of EV charging stations with battery storage systems by estimating EV charging loads and PV generations. In [3], a coordinated EV management system is presented to mitigate grid overloading and voltage issues by implementing vehicle-to-grid (V2G) resource optimization and minimizing costs for the customers. Rabiee *et al.* [7] have developed a management framework to integrate more EVs and PV systems in power networks considering transmission and distribution level constraints by optimally using their assets and flexibility. In [8], an approach for regulating voltages in low-voltage (LV) distribution networks integrated with EV charging stations is developed by utilizing PV and energy storage systems. A decentralized voltage control method is proposed in [9] to coordinate EV charging and PV, which utilizes the active and reactive power of PV inverters. In [10], a customer-centric optimal scheduling algorithm is developed for PV and battery energy storage integrated EV charging stations by minimizing the operational cost of customers and balancing their supply and demand. Coordination between home and grid energy management systems is proposed in [11], in which voltage fluctuation of EV charging stations is reduced by managing EVs charge/discharge with PV systems. These research works mainly focus on EVs with PV coordination and scheduling management in the power networks. However, the above studies neither consider market-based management for prosumers nor explicitly deal with network issues.

2) Price-based management frameworks: Price-based management frameworks have been studied for prosumers equipped with EVs and PV systems to provide benefits to the prosumers and solve specific network issues [2], [12]-[16]. In [12], a pricing mechanism with an optimal operation for PV farms and EV charging stations is presented to provide profit to the investor and EV owners by utilizing PV power. To reduce PV curtailment, an EV charging management is presented in [13] using an auction mechanism that mitigates the over-voltage problem in low-voltage distribution networks. A distributed approach for the day-ahead market clearing in a vehicle-grid integrated framework has been developed in [5] considering EVs' uncertainty based on their capacity measurement. Huang *et al.* [14] have presented a market mechanism by regulating distribution locational marginal price (DLMP) for congestion management in distribution networks, where the penetration of PV systems, heat pumps, and EVs with V2G have been considered. A transactive framework for EV charging management is proposed for commercial buildings with on-site PV generation that considers uncertainties of PV and EVs [15]. A pricing strategy is proposed in [16] to schedule EV charging with PV systems based on the transformer capacity limit by reducing EV charging costs and maximizing distribution system operator (DSO) profit. Asrari *et al.* [2] propose a market framework for congestion management in distribution networks integrated with distributed generations (DGs) and EVs, where EVs are considered as flexible loads and EV aggregators collaborate for adjusting their prices.

3) Network-aware management frameworks: Network-aware management frameworks have been developed recently that facilitate prosumers' participation in the LEM without violating network operating conditions. In [17], a LEM-based EV coordination framework is presented by considering network constraints and EV preferences. Affolabi *et al.* [18] developed a network-constrained transactive control for EV charging stations with on-site PV that provides energy scheduling and trading with maximum payoffs of charging stations. A transactive coordination framework is developed in [19] for EV charge/discharge to control voltage in distribution networks by using voltage sensitivity coefficients that incentivize EV owners to provide charge flexibility. In [4], a coordination framework for aggregated EVs is presented, in which line congestion and voltage in distribution networks are managed by considering EVs' charge/discharge flexibility. The above studies could explicitly manage the network issues with the participation of prosumers in the LEM. Nonetheless, these frameworks rely on the direct involvement of the DSO, where the DSO directly participate in managing market prices and assets of prosumers in the LEM.

4) Dynamic operating envelopes (DOE)-based frameworks: DSOs can employ alternative indirect approaches to maintain the integrity of the networks with high DER penetration. One of these solutions, which is being trialed by network operators in Australia (e.g., [20], [21],) is the concept of operating envelopes that limit the imports/exports of prosumers to ensure network integrity. In [20], the operating envelope is defined as "a principled allocation of the available hosting capacity to the individuals or aggregate DER or connection points within a segment of a distribution network in each time interval". The DSO is responsible for determining DOEs for prosumers based on network constraints to limit their expected imports/exports for trading in the LEM. This framework does not require the DSO to manage market prices and prosumers' assets. Instead, prosumers manage their assets individually within their assigned DOEs to trade in the LEM using their own management systems. This helps to preserve the privacy of prosumers' data while improving the system's economic efficiency. DOEs can be calculated using near real-time data from prosumers for each time interval. DOEs can unlock a number of benefits for prosumers and distribution systems by managing energy imports/exports of prosumers from/to the network and improving network efficiency with greater interoperability [22]. To facilitate prosumers to take part in the LEM, incorporating the DOE can enhance both network and market efficiencies. Moreover, prosumers equipped with EVs and PV systems can be managed in a decentralized way in the LEM to trade energy with their peers respecting their preferences and desires so that they can profit from the tradings and at the same time the integrity of the network is preserved.

The concept of DOE, as a method for ensuring network integrity, has been employed by some recent studies. A framework is presented in [23], in which DOE is used for prosumers equipped with PV and battery storage systems. Attarha *et al.* [1] have proposed a price-elastic bidding approach for aggregated prosumers having PV and battery storage systems through interaction between the DSO and aggregator, where the DSO calculates the DOE to resolve network problems and to shape the aggregator bids. Scott *et al.* [24] have developed a coordination approach for DER (PV and batteries) considering network constraints using distributed optimal power flow (OPF). An OPF-based operating envelopes is proposed in [25] to facilitate residential solar PV and battery storage systems, by exploiting controllable network assets. A framework for the coordination of prosumers using DOEs is presented in [26], in which prosumers are able to control their PV and battery storage system according to their assigned DOE. A collaboration between aggregators and the DSO is proposed in [27] to generate energy and frequency control ancillary service bids that ensures network security by using DOEs.

5) DOE and LEM: Along with solving the network issues as discussed above, the DOE can be used to configure prosumers' bids for their trades in the LEM by limiting their imports/exports and securing network operations. Prosumers can participate in the LEM to trade energy with their peers in a decentralized fashion within the DOEs without the explicit engagement of the DSO in price settlement. Peer-to-peer (P2P) trading is such kind of technique that allows prosumers to trade in the LEM at their preferred prices and reduce their energy costs by having access to less expensive energy. It also enables DER owners to increase their bilateral trading and meet up the energy demand locally [28]. Aznavi *et al.* [29] proposed a P2P trading framework between a business company of PV generations and an EV charging station through a dynamic pricing mechanism considering EV owners' profit. A P2P market model is presented in [30] that incorporates energy and uncertainty trading utilizing flexible demand of EVs to absorb

TABLE I: Comparison between this paper and the state of the art in terms of incorporating network constraints, EV charge-discharge flexibility, and P2P trading into the framework.

References	Network Constraints	EV Charge -Discharge	P2P Trading
[15]	×	✓	×
[29]	×	✓	✓
[24]	Directly	×	×
[2],[3],[5],[10]-[14],[16]-[18]	Directly	✓	×
[30]	Directly	✓	✓
[4], [19]	Indirectly/SA	✓	×
[31], [32]	Indirectly/SA	×	✓
[1], [23], [25]-[27]	Indirectly/DOE	×	×
This Paper	Indirectly/DOE	✓	✓

PV generations. A P2P trading method is developed in [31] by using an iterative peer matching and negotiation process for prosumers in presence of PV, storage and flexible loads considering network losses. A network-aware decentralized P2P trading is developed in [32] that ensures energy transactions without violation of network constraints. In this work, prosumers are blocked from participating in P2P trading for a specific time-slot if their expected exports/imports are found to have an adverse impact on network operation. Although it is an effective mechanism to maintain network integrity, prosumers may get demotivated if they get blocked repeatedly due to their physical location in the connected network. Moreover, EV management is not considered which can also be used for P2P contracts.

The studies discussed above have considered different strategies to manage prosumers without/with EVs, PV systems, energy tradings (e.g., P2P trading) and the DOE. Table I provides a summary of the features of the relevant existing papers reviewed above, highlighting the differences between this paper and others in terms of incorporating network constraints, EV charge-discharge flexibility, and P2P trading into the framework. Regarding the incorporation of network constraints, most of the reviewed works include them in the market clearing problem either directly or indirectly through sensitivity analysis (SA) and DOE.

C. Contributions and Organization of the Paper

Recently, DOE has been used as an emerging concept in some papers and trial projects (e.g., [1], [23], [25]-[27]) to ensure network operation within its operational constraints by indirectly incorporating constraints into the market clearing problem. However, existing works primarily focus on addressing solar PV and voltage regulation challenges in DER-rich networks and do not consider EV charge-discharge management or P2P energy trading. Some of the reviewed works consider EVs as flexible resources and incorporate EV charge-discharge flexibility into the energy management framework. Additionally, P2P trading has been considered in some of these papers (e.g., [30], [31], [32]). However, to the best of the authors' knowledge, a comprehensive framework for the network-secure management of prosumers with EVs and PV systems incorporating P2P trading in the LEMs is not presented yet. To this end, this paper proposes DOE-based management of prosumers in presence of EVs and PV systems in the LEM. The framework is developed to manage prosumers for their participation in the LEM and to benefit them via P2P trading by respecting the network constraints and the prosumers' preferences effectively. The key contributions and features of the proposed framework are as follows:

- A new framework for prosumers' energy management in the LEM based on the DOE is proposed that allows prosumers to manage EVs charge/discharge with PV systems through their participation in the LEM, by taking into account the network constraints.
- An algorithm is developed to compute the import/export DOEs for three-phase unbalanced LV distribution networks to secure network operations by managing prosumers' energy imports/exports.
- A bidding strategy for prosumers is proposed that facilitates their participation in the LEM within the assigned DOEs.
- A P2P energy trading mechanism is proposed for prosumers with EVs and PV systems by developing a mismatching minimization algorithm that provides economic benefits to the prosumers.

The performance evaluation of the proposed framework in a simple toy model (a 5-node LV distribution feeder) and in a complex three-phase unbalanced 55-node LV distribution network verifies its effectiveness and feasibility. In particular, the following results can be highlighted:

- The proposed DOE-based LEM framework enables secure network operation for consumers trading in the LEM using assigned DOEs. The presented DOE calculation algorithm is computationally efficient and can be implemented for near real-time market clearing.
- Prosumers can manage their energy consumption by coordinating the charge-discharge of their EVs with their PV systems and generate bids for trading in the LEM within their assigned DOEs.
- The proposed P2P energy trading provides increased profit to prosumers with respect to the business-as-usual (BAU) such that prosumers are able to reduce their energy costs and generate higher profits by participating in the proposed framework. The proposed method demonstrates superior performance compared to both the fixed limit method (FLM) and the network-constrained method (NCM) with respect to the BAU in terms of generating more increased profit for prosumers.

The rest of this paper is organized as follows. Section II presents the overview of the proposed framework followed by system model description in Section III. The DOE computation algorithm is described in Section IV. Section V demonstrates the proposed DOE-based LEM for prosumers that includes the energy management of prosumers in V-A, the prosumers bidding strategy in V-B and the P2P trading mechanism in V-C. Section VI provides the case studies including results and analysis of the technical and economic performance of the proposed framework. Finally, conclusions are summarized in Section VII.

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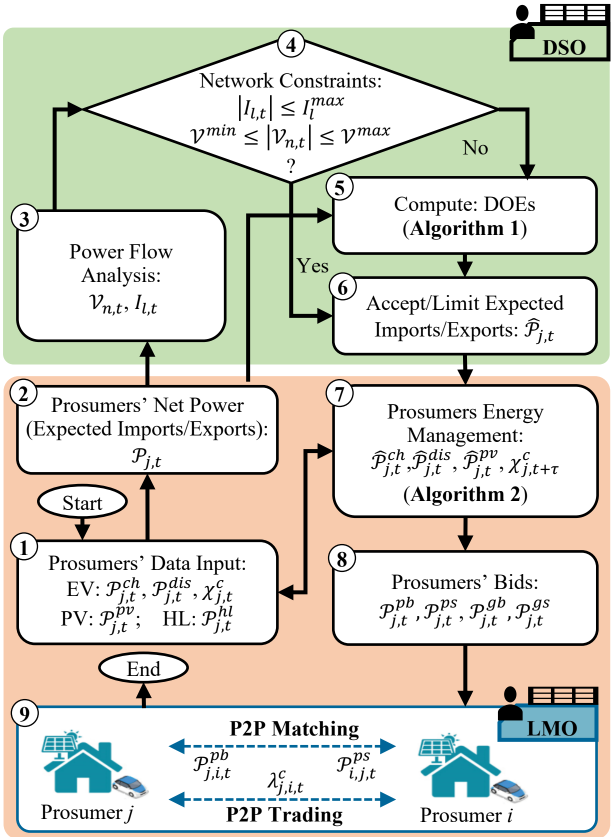

Fig. 1: The proposed framework of DOE-based prosumers management in the LEM.

II. Overview of the Proposed Framework

The framework comprises an algorithm that enables the DSO to compute DOEs for both imports and exports of prosumers on three-phase unbalanced distribution networks. In the framework, a prosumer bidding strategy is introduced where prosumers obtain their bids within the assigned DOEs for taking part in the LEM. Furthermore, a P2P energy trading mechanism is proposed that facilitates prosumers for P2P trading in the LEM and provides economic benefits to the prosumers. Overall, the proposed framework ensures the integrity of the distribution network ensuring that voltage and line congestion constraints are not violated. At the same time, it maximizes prosumers' welfare by taking into account their preferences and priorities. An overview of the proposed framework is represented in Fig. 1.

The proposed framework is developed in two layers with several steps. In the lower layer, prosumers who are equipped with EVs, PV systems and household loads (HLs), manage their energy resources (Step 1) along with the outputs from the prosumers' energy management in the previous time-slot and obtain their expected net demands (imports) and net generations (exports), and send them to the DSO to obtain the DOEs (Step 2). In the upper layer, the DSO monitors network constraints and manages prosumers' expected energy imports/exports by calculating DOEs. Firstly, the DSO runs a power flow analysis (Step 3), considering the expected imports/exports of prosumers located at different nodes, to check for any constraint violations (Step 4). The DSO accepts the expected imports/exports for prosumers' trading if no violations occur. Otherwise, it performs an optimization process to compute DOEs for prosumers to avoid the violation of network constraints (Steps 5 and 6). In the lower layer, prosumers then execute their energy management algorithm to update EVs' charging/discharging based on the assigned DOEs (Step 7). The updates are used to obtain prosumers' expected power for the next time-slot so that the DOE computation and energy management can be accomplished by valuing the prosumers' preferences. It is noteworthy to mention that EVs' involvement in the proposed framework is to provide network and economic services, while also fulfilling the desires of EV owners in terms of achieving their desired SOC for driving during departure times. As such, the energy management algorithm is executed to manage prosumers' power consumption by coordinating EVs' charge-discharge cycles, while simultaneously ensuring the satisfaction of EV owners' SOC preferences. Prosumers also generate trading bids upon receiving the DOEs in each time-slot to participate in P2P trading (Step 8). Finally, a P2P trading process is executed by a local market operator (LMO) through a matching mechanism to obtain the P2P clearing prices and the quantities of the trading energy with the peers (Step 9). The details are explained in Sections III-V.

III. System Model

Consider a distribution network with a set of $n \in \mathcal{N} \triangleq \{1, ..., n, ..., N\}$ nodes, connected through distribution lines denoted by a set of $l \in \mathcal{L} \triangleq \{1, ..., l, ..., L\}$. A set of $j \in \mathcal{J} \triangleq \{1, ..., j, ..., J\}$ prosumers are connected to different nodes. Each prosumer can be equipped with any of these assets; an EV, a PV system and HLs. At each time $t \Rightarrow t \in \mathcal{T} \triangleq \{1, ..., t, ..., T\}$, prosumer j acts as a consumer or a producer depending on the net power $\mathcal{P}_{j,t}$ of prosumer as in (1). Therefore, the set of prosumers as consumers can be defined as $\mathcal{J}_t^c := j \in \mathcal{J} : \mathcal{P}_{j,t} > 0$ and as producers can be defined as $\mathcal{J}_t^p := j \in \mathcal{J} : \mathcal{P}_{j,t} \leq 0$, where $\mathcal{J}_t^c \cup \mathcal{J}_t^p = \mathcal{J}$, $\mathcal{J}_t^c \cap \mathcal{J}_t^p = \emptyset$.

$$\mathcal{P}_{j,t} = \mathcal{P}_{j,t}^d + \mathcal{P}_{j,t}^g \quad ; \forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{1}$$

where (1) presents the net power $\mathcal{P}_{j,t}$ which is the sum of total demand $\mathcal{P}_{j,t}^d (> 0)$ and total generation $\mathcal{P}_{j,t}^g (\leq 0)$ of prosumer j at time t. The total demand $\mathcal{P}_{j,t}^d$ and total generation $\mathcal{P}_{j,t}^g$ of prosumer j are computed by (2) and (3), respectively

$$\mathcal{P}_{j,t}^d = \mathcal{P}_{j,t}^{ch} + \mathcal{P}_{j,t}^{hl} \quad ; \forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{2}$$

$$\mathcal{P}_{j,t}^g = \mathcal{P}_{j,t}^{dis} + \mathcal{P}_{j,t}^{pv} \quad ; \forall j \in \mathcal{J}, \forall t \in \mathcal{T}. \tag{3}$$

EVs charge power $\mathcal{P}_{j,t}^{ch}$ and discharge power $\mathcal{P}_{j,t}^{dis}$ are constrained by (4) and (5), respectively

$$0 \leq \mathcal{P}_{j,t}^{ch} \leq P_j^{evm} \mathcal{A}_{j,t}^{ev} (\mathcal{A}_{j,t}^{ev} + 1)/2 \, ; \forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{4}$$

$$-P_j^{evm} \mathcal{A}_{j,t}^{ev} (\mathcal{A}_{j,t}^{ev} - 1)/2 \leq \mathcal{P}_{j,t}^{dis} \leq 0 \, ; \forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{5}$$

where P_j^{evm} is the maximum EV charger rating. An integer variable $\mathcal{A}_{j,t}^{ev}$ is used to state EV's charge (buy)/discharge (sell) condition at each t which is defined as $\mathcal{A}^{ev}_{j,t} = \{1, -1, 0\}$. $\mathcal{A}^{ev}_{j,t} = 1$ means EV is in charging mode, $\mathcal{A}^{ev}_{j,t} = -1$ donates EV discharging mode; and $\mathcal{A}^{ev}_{j,t} = 0$ means EV is in idle mode. EVs are allowed to charge/discharge within constraints (4) and (5). EVs charge and discharge are configured by setting EVs' state variable $\mathcal{A}^{ev}_{j,t}$ depending on the mobility pattern of EVs according to (6) as,

$$\mathcal{A}^{ev}_{j,t} := \begin{cases} -1 \quad ;\text{if} \begin{cases} \chi^{c}_{j,t} > X^{min}_{j}, \\ \tau^{av}_{j,t} > \tau^{re}_{j,t}, \\ \Lambda^{lem}_{j,t}, \Lambda^{fit}_{t} \geq \Lambda^{dm}_{j}, \end{cases} \\ 1 \quad ;\text{else if} \quad \chi^{c}_{j,t} < X^{d}_{j} < X^{max}_{j}, \\ 0 \quad ;\text{otherwise} \quad ;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \end{cases} \tag{6}$$

where in (6), $\chi^{c}_{j,t}$, X^{min}_{j}, X^{max}_{j} and X^{d}_{j} are the current state-of-charge (SOC), the minimum SOC, the maximum SOC and the desired SOC of jth EV; $\tau^{av}_{j,t}$ and $\tau^{re}_{j,t}$ are the available time and the remaining time to reach X^{d}_{j} that are computed by (7); and $\Lambda^{lem}_{j,t}$, Λ^{fit}_{t} and Λ^{dm}_{j} are the local market prices, the feed-in-tariff prices and the EV discharge price margin, respectively. Equation (8) depicts that EVs can start charging/discharging at their arrival time τ^{ar}_{j} with the initial SOC X^{ini}_{j} and depart at their departure time τ^{d}_{j} with the desired SOC X^{d}_{j}. The current SOC $\chi^{c}_{j,t}$ is constrained and updated by (9) and (10), respectively

$$\tau^{av}_{j,t} = \tau^{d}_{j} - \tau^{ac}_{j,t}, \quad \tau^{re}_{j,t} = (X^{d}_{j} - \chi^{c}_{j,t}) \frac{E^{evm}_{j}}{P^{evm}_{j}}, \tag{7}$$

$$\chi^{c}_{j,\tau^{ar}_{j}} = X^{ini}_{j}, \quad \chi^{c}_{j,\tau^{d}_{j}} = X^{d}_{j} \quad ;\forall j \in \mathcal{J}, \tag{8}$$

$$X^{min}_{j} \leq \chi^{c}_{j,t} \leq X^{max}_{j} \quad ;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{9}$$

$$\begin{aligned} \chi^{c}_{j,t+\tau} =& \chi^{c}_{j,t} + \frac{\tau \eta^{ch} \mathcal{P}^{ch}_{j,t} \mathcal{A}^{ev}_{j,t} (\mathcal{A}^{ev}_{j,t} + 1)}{2E^{evm}_{j}} \\ &+ \frac{\tau \mathcal{P}^{dis}_{j,t} \mathcal{A}^{ev}_{j,t} (\mathcal{A}^{ev}_{j,t} - 1)}{2\eta^{dis} E^{evm}_{j}} \quad ;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \end{aligned} \tag{10}$$

where in (7), $\tau^{ac}_{j,t}$ and E^{evm}_{j} are the action time and the maximum battery capacity of EVs, and in (10), τ is the time-slot duration; η^{ch} and η^{dis} are the EVs' charge and discharge efficiencies.

The generation of prosumer PV system, $\mathcal{P}^{pv}_{j,t}$, is constrained by (11)

$$-P^{pvm}_{j} \leq \mathcal{P}^{pv}_{j,t} \leq 0 \quad ;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{11}$$

where P^{pvm}_{j} is the peak generation of PV systems. In the proposed framework, the PV system generations are assumed as the priority power for their own HLs and EVs charging due to their negligible generation cost. The HLs $\mathcal{P}^{hl}_{j,t}$ are assumed to be fulfilled at their maximum without curtailing any load.

IV. The DOE Computation Algorithm

In the proposed framework, the DOEs are determined by the DSO to limit the expected imports/exports from prosumers in the presence of EVs and PV systems to operate the distribution network within its operational constraints. DOEs are utilized to secure the network operations considering prosumers' imports

Algorithm 1 DOE computation algorithm

Input: $\mathcal{P}_{j,t}, \mathcal{Q}_{j,t}, Q^{max}_{j}, \tau, \alpha_{n,\phi}, \mathcal{R}_{l}, \mathcal{X}_{l}, \tilde{\mathcal{V}}_{n,t}, V^{min}, V^{max}, I^{max}_{l}$, $j \in \mathcal{J}, n \in \mathcal{N}, l \in \mathcal{L}, t \in \mathcal{T}$
Output: $\widehat{\mathcal{P}}_{j,t}, \mathcal{V}_{n,t}, \mathcal{I}_{l,t}, j \in \mathcal{J}, n \in \mathcal{N}, l \in \mathcal{L}, t \in \mathcal{T}$

```
1: Obtain P_{j,t}                          ▷ Expected imports/exports of prosumers
2: Run Power Flow Analysis
3: Compute V_{n,t}, I_{l,t}                ▷ No-control network results
4: if I_{l,t} ≤ I_l^{max} and V_{n,t} ≥ V^{min} and V_{n,t} ≤ V^{max} then
5:     P̂_{j,t} ← P_{j,t}
6: else
7:     Set Constraints (13) − (20)
8:     Optimize Equation (12),
           subject to (13) − (20)
9:     Compute P̂_{j,t}                    ▷ DOEs computation
10:    Compute V_{n,t}, I_{l,t}           ▷ Controlled results with proposed framework
11: end if
```

and exports so that prosumers can participate in the LEM within assigned DOEs without any network challenges. DOEs are directly communicated to prosumers, so prosumers can manage their assets autonomously and limit the access of other agents to their information and assets. The proposed framework incorporates an algorithm for the DSO to compute the DOEs in a three-phase unbalanced network considering voltage and line congestion constraints as presented in Algorithm 1, in which the execution is represented through DOEs $\widehat{\mathcal{P}}_{j,t}$, node voltages $\mathcal{V}_{n,t}$, and line currents $\mathcal{I}_{l,t}$. In the DOE Computation algorithm, the DSO accepts imports/exports of prosumers if their expected imports/exports satisfy the network constraints through the power flow analysis. Otherwise, the imports/exports are limited by means of the proposed Algorithm 1 which is presented below.

Algorithm 1 comprises an objective function as in (12), that is formulated to minimize the absolute difference between expected imports/exports $\mathcal{P}_{j,t}$ and assigned DOEs $\widehat{\mathcal{P}}_{j,t}$ subject to (13)-(20).

$$\begin{aligned} \min_{\widehat{\mathcal{P}}_{j,t}, \mathcal{V}_{n,t}, \mathcal{I}_{l,t}} \sum_{j \in \mathcal{J}} \left| \mathcal{P}_{j,t} - \widehat{\mathcal{P}}_{j,t} \right| \\ ;\forall n \in \mathcal{N}, \forall l \in \mathcal{L}, \forall t \in \mathcal{T}, \end{aligned} \tag{12}$$

subject to:

$$0 \leq \widehat{\mathcal{P}}_{j,t} \leq \mathcal{P}_{j,t}, \text{ if } \mathcal{P}_{j,t} > 0 \quad ;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{13}$$

$$\mathcal{P}_{j,t} \leq \widehat{\mathcal{P}}_{j,t} \leq 0, \text{ if } \mathcal{P}_{j,t} \leq 0 \quad ;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{14}$$

$$\begin{aligned} [\mathcal{I}_{n,t}] = \left[\frac{\widehat{\mathcal{P}}_{j,t} + \mathbf{j}\mathcal{Q}_{j,t}}{\tilde{\mathcal{V}}_{n,t} \big(cos(\alpha_{n,\phi}) + \mathbf{j} sin(\alpha_{n,\phi}) \big)} \right]^{*} \\ ;\forall n \in \mathcal{N}, \forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \phi \in \Phi, \end{aligned} \tag{15}$$

$$\begin{aligned} [\mathcal{I}_{l,t}] = [\mathcal{I}_{n,t}] + \sum_{k \in \mathcal{K}} [\mathcal{I}_{k,t}] \\ ;\forall l \in \mathcal{L}, \forall n \in \mathcal{N}, \forall k \in \mathcal{K}, \forall t \in \mathcal{T}, \end{aligned} \tag{16}$$

$$\begin{aligned} [\mathcal{V}_{n,t}] = [\mathcal{V}_{n-1,t}] - [\mathcal{R}_{l} + \mathbf{j}\mathcal{X}_{l}] \, [\mathcal{I}_{l,t}] \\ ;\forall n \in \mathcal{N}, \forall l \in \mathcal{L}, \forall t \in \mathcal{T}, \end{aligned} \tag{17}$$

$$V^{min} \leq |\mathcal{V}_{n,t}| \leq V^{max} \quad ;\forall n \in \mathcal{N}, \forall t \in \mathcal{T}, \tag{18}$$

$$0 \leq |\mathcal{I}_{l,t}| \leq I^{max}_{l} \quad ;\forall l \in \mathcal{L}, \forall t \in \mathcal{T}, \tag{19}$$

$$0 \leq \left| \mathcal{Q}^{pv}_{j,t} \right| \leq Q^{max}_{j} \; ;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}. \tag{20}$$

Constraints (13) and (14) limit import power and export power of prosumers, respectively, that must not exceed the expected ones $\mathcal{P}_{j,t}$. The import/export current of prosumer j at node n and phase ϕ is obtained by (15), where ϕ is a set of phases of the distribution network defined as $\phi \in \Phi = \{a, b, c\}$, $\tilde{\mathcal{V}}_{n,t}$ is the nominal voltage and $\alpha_{n,\phi}$ is the phasor voltage angle at phase ϕ. Using (16), the line current $\mathcal{I}_{l,t}$, that flows on line section l between upstream node $(n-1)$ and node n, is computed. Here, k is a set of lines connected downstream to n defined as $k \in \mathcal{K} \triangleq \{1, ..., k, ..., K\}$. The node voltage $\mathcal{V}_{n,t}$ is calculated by (17), where $\mathcal{V}_{n-1,t}$ is the upstream node voltage at node $(n-1)$, and $\mathcal{R}_l$ and $\mathcal{X}_l$ are the resistance and reactance matrices of the network. The voltage and line congestion constraints are presented as in (18) and (19), respectively. The total reactive power $\mathcal{Q}^{pv}_{j,t}$ of PV system generation is constrained by the maximum value Q^{max}_j as in (20). All parameters and variables are represented in per unit (p.u.). By implementing Algorithm 1, the DOEs can be computed by the DSO and sent to prosumers so that they can update their power imports/exports using Algorithm 2 in Section V-A with EVs charging/discharging management and determine prosumers' bids for trading in the LEM.

V. Proposed DOE-based LEM for Prosumers

In the proposed framework, each prosumer models its energy resources for the expected import/export power as presented in Section III and sends them to the DSO to get acceptance/limits (DOEs) so that prosumers' participation in the LEM does not violate the network constraints. This section explains the energy management of prosumers by using the assigned DOEs, a bidding strategy of prosumers in the LEM, and the P2P trading mechanism.

A. Prosumers Energy Management

The energy management of prosumers is illustrated in Algorithm 2 by taking into account the DOEs. According to Algorithm 2, prosumers calculate their expected imports/exports ($\mathcal{P}_{j,t}$) by computing the charge/discharge power ($\mathcal{P}^{ch}_{j,t}/\mathcal{P}^{dis}_{j,t}$) and the SOC ($\chi^c_{j,t}$) of EVs as described in Section III, and send the expected imports/exports to the DSO to receive the DOEs (Algorithm 1). In the proposed framework, the generated power of PV system is prioritized for HL and EV charging due to cost-free generation and usage. Therefore, in Algorithm 2, first EVs charge/discharge power and then PV power (in case) are updated within the assigned DOEs by $\mathcal{P}^{ad}_{j,t}$ as in (21)

$$\mathcal{P}^{ad}_{j,t} = \mathcal{P}_{j,t} - \widehat{\mathcal{P}}_{j,t} \; ; \forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{21}$$

where $\mathcal{P}^{ad}_{j,t}$ is the amount to be adjusted from EVs and PV system power to get their updated energy profiles. An integer variable $\mathcal{B}^{ad}_{j,t}$ is used to manage prosumer j's power update for imports/exports at t which is defined as in (22)

$$\mathcal{B}^{ad}_{j,t} := \begin{cases} 1; \text{if} \begin{cases} 0 \le \mathcal{P}^{ad}_{j,t} \le \mathcal{P}^{ch}_{j,t} \text{ (EV charge update)}, \\ 0 \le \mathcal{P}^{ch}_{j,t} \le \mathcal{P}^{ad}_{j,t} \text{ (EV dis/charge update)}, \end{cases} \\ -1; \text{if} \begin{cases} \mathcal{P}^{dis}_{j,t} \le \mathcal{P}^{ad}_{j,t} \le 0 \text{ (EV discharge update)}, \\ \mathcal{P}^{ad}_{j,t} \le \mathcal{P}^{dis}_{j,t} \le 0 \text{ (EV dis/charge, PV update)}, \end{cases} \\ 0; \text{ (No update)} \; ; \forall j \in \mathcal{J}, \forall t \in \mathcal{T}. \end{cases} \tag{22}$$

Algorithm 2 Prosumers energy management algorithm

Input: $P^{evm}_j, \mathcal{P}^{pv}_{j,t}, \mathcal{P}^{hl}_{j,t}, \tau^{ar}_j, \tau^d_j, X^{ini}_j, X^d_j, X^{min}_j, X^{max}_j, \Lambda^{lem}_{j,t}, \Lambda^{fit}_t, \Lambda^{dm}_j, E^{evm}_j, \eta^{ch}, \eta^{dis}, \tau, j \in \mathcal{J}, t \in \mathcal{T}$
Output: $\widehat{\mathcal{P}}^{ch}_{j,t}, \widehat{\mathcal{P}}^{dis}_{j,t}, \widehat{\mathcal{P}}^{pv}_{j,t}, \chi^c_{j,t}, j \in \mathcal{J}, t \in \mathcal{T}$

for $t \in \mathcal{T}$ **do**
  for $j \in \mathcal{J}$ **do**
    $\chi^c_{j,t} \leftarrow X^{ini}_j$ when $t = \tau^{ar}_j$
    Compute τ^{av}_j, τ^{re}_j using (7)
    Compute $\mathcal{A}^{ev}_{j,t}$ using (6)
    $\mathcal{P}^{ch}_{j,t} \leftarrow P^{evm}_j, \mathcal{P}^{dis}_{j,t} \leftarrow -P^{evm}_j$ using (4) and (5)
    Compute $\mathcal{P}_{j,t}$ using (1),(2) and (3)
  end for
  Go to Algorithm 1 ▷ DOEs computation algorithm
  Compute $\widehat{\mathcal{P}}_{j,t}$ for assigned DOEs
  for $j \in \mathcal{J}$ **do**
    Compute $\mathcal{P}^{ad}_{j,t}, \mathcal{B}^{ad}_{j,t}$ using (21), (22)
    if $\mathcal{A}^{ev}_{j,t} == 1$ **then**
      if $\mathcal{B}^{ad}_{j,t} == 1$ **then**
        if $\mathcal{P}^{ad}_{j,t} \le \mathcal{P}^{ch}_{j,t}$ **then**
          $\widehat{\mathcal{P}}^{ch}_{j,t} \leftarrow \mathcal{P}^{ch}_{j,t}\mathcal{A}^{ev}_{j,t} - \mathcal{P}^{ad}_{j,t}\mathcal{B}^{ad}_{j,t}$ using (23)
        else
          $\widehat{\mathcal{P}}^{ch}_{j,t} \leftarrow 0, \; \mathcal{A}^{ev}_{j,t} \leftarrow -1$
          $\widehat{\mathcal{P}}^{dis}_{j,t} \leftarrow (\mathcal{P}^{ad}_{j,t}\mathcal{B}^{ad}_{j,t} - \mathcal{P}^{ch}_{j,t})\mathcal{A}^{ev}_{j,t}$ using (24)
        end if
      else if $\mathcal{B}^{ad}_{j,t} == -1$ **then**
        $\widehat{\mathcal{P}}^{ch}_{j,t} \leftarrow \mathcal{P}^{ch}_{j,t}, \quad \widehat{\mathcal{P}}^{pv}_{j,t} \leftarrow \mathcal{P}^{pv}_{j,t} + \mathcal{P}^{ad}_{j,t}\mathcal{B}^{ad}_{j,t}$ using (27)
      else
        $\widehat{\mathcal{P}}^{ch}_{j,t} \leftarrow \mathcal{P}^{ch}_{j,t}, \quad \widehat{\mathcal{P}}^{pv}_{j,t} \leftarrow \mathcal{P}^{pv}_{j,t}$
      end if
    else if $\mathcal{A}^{ev}_{j,t} == -1$ **then**
      if $\mathcal{B}^{ad}_{j,t} == -1$ **then**
        if $\mathcal{P}^{ad}_{j,t} \ge \mathcal{P}^{dis}_{j,t}$ **then**
          $\widehat{\mathcal{P}}^{dis}_{j,t} \leftarrow \mathcal{P}^{ad}_{j,t}\mathcal{B}^{ad}_{j,t} - \mathcal{P}^{dis}_{j,t}\mathcal{A}^{ev}_{j,t}$ using (25)
        else
          $\widehat{\mathcal{P}}^{dis}_{j,t} \leftarrow 0, \; \mathcal{A}^{ev}_{j,t} \leftarrow 1$
          $\widehat{\mathcal{P}}^{ch}_{j,t} \leftarrow (\mathcal{P}^{dis}_{j,t} + \mathcal{P}^{ad}_{j,t}\mathcal{B}^{ad}_{j,t})\mathcal{A}^{ev}_{j,t}$ using (26)
        end if
      else
        $\widehat{\mathcal{P}}^{dis}_{j,t} \leftarrow \mathcal{P}^{dis}_{j,t}, \quad \widehat{\mathcal{P}}^{pv}_{j,t} \leftarrow \mathcal{P}^{pv}_{j,t}$
      end if
    else
      $\widehat{\mathcal{P}}^{ch}_{j,t} \leftarrow 0, \quad \widehat{\mathcal{P}}^{dis}_{j,t} \leftarrow 0$
      if $\mathcal{B}^{ad}_{j,t} == -1$ **then**
        $\widehat{\mathcal{P}}^{pv}_{j,t} \leftarrow \mathcal{P}^{pv}_{j,t} + \mathcal{P}^{ad}_{j,t}\mathcal{B}^{ad}_{j,t}$ using (27)
      else
        $\widehat{\mathcal{P}}^{pv}_{j,t} \leftarrow \mathcal{P}^{pv}_{j,t}$
      end if
    end if
    Update $\chi^c_{j,t+\tau}$ using (10) for updated SOC of EVs
  end for
end for

TABLE II: Prosumer's energy management actions based on $\mathcal{A}^{ev}_{j,t}$ and $\mathcal{B}^{ad}_{j,t}$.

$\mathcal{A}^{ev}_{j,t}$	$\mathcal{B}^{ad}_{j,t}$	Action
1	1	Update $\widehat{\mathcal{P}}^{ch}_{j,t}$; if $\widehat{\mathcal{P}}^{ad}_{j,t} \le \widehat{\mathcal{P}}^{ch}_{j,t}$ $\widehat{\mathcal{P}}^{ch}_{j,t} = 0$, Update $\widehat{\mathcal{P}}^{dis}_{j,t}$; otherwise
-1	-1	Update $\widehat{\mathcal{P}}^{dis}_{j,t}$; if $\widehat{\mathcal{P}}^{ad}_{j,t} \ge \widehat{\mathcal{P}}^{dis}_{j,t}$ $\widehat{\mathcal{P}}^{dis}_{j,t} = 0$, Update $\widehat{\mathcal{P}}^{ch}_{j,t}$; otherwise
1/0	-1 0	Update $\widehat{\mathcal{P}}^{pv}_{j,t}$ No update

Let $\widehat{\mathcal{P}}^{ch}_{j,t}, \widehat{\mathcal{P}}^{dis}_{j,t}$ and $\widehat{\mathcal{P}}^{pv}_{j,t}$ be the updates of EVs-charge, EVs-discharge and PV system power, respectively. The proposed energy management Algorithm 2 is implemented by using the status of $\mathcal{A}^{ev}_{j,t}$ and $\mathcal{B}^{ad}_{j,t}$ to compute $\widehat{\mathcal{P}}^{ch}_{j,t}$, $\widehat{\mathcal{P}}^{dis}_{j,t}$ and $\widehat{\mathcal{P}}^{pv}_{j,t}$. Table II presents the combination of the status of $\mathcal{A}^{ev}_{j,t}$ and $\mathcal{B}^{ad}_{j,t}$ for EV charge-discharge and PV system power updates for prosumers' energy management within the assigned DOE. According to the status and condition as shown in Table II, if the values of both $\mathcal{A}^{ev}_{j,t}$ and $\mathcal{B}^{ad}_{j,t}$ are 1, EV charge and discharge are updated as in (23) and (24), respectively.

$$\widehat{\mathcal{P}}^{ch}_{j,t} = \mathcal{P}^{ch}_{j,t}\mathcal{A}^{ev}_{j,t} - \mathcal{P}^{ad}_{j,t}\mathcal{B}^{ad}_{j,t}\,;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{23}$$

$$\widehat{\mathcal{P}}^{dis}_{j,t} = (\mathcal{P}^{ad}_{j,t}\mathcal{B}^{ad}_{j,t} - \mathcal{P}^{ch}_{j,t})\mathcal{A}^{ev}_{j,t}\,;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}. \tag{24}$$

On the contrary, if the values of both $\mathcal{A}^{ev}_{j,t}$ and $\mathcal{B}^{ad}_{j,t}$ are -1, EV discharge and charge are updated as in (25) and (26), respectively.

$$\widehat{\mathcal{P}}^{dis}_{j,t} = \mathcal{P}^{ad}_{j,t}\mathcal{B}^{ad}_{j,t} - \mathcal{P}^{dis}_{j,t}\mathcal{A}^{ev}_{j,t}\,;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{25}$$

$$\widehat{\mathcal{P}}^{ch}_{j,t} = (\mathcal{P}^{dis}_{j,t} + \mathcal{P}^{ad}_{j,t}\mathcal{B}^{ad}_{j,t})\mathcal{A}^{ev}_{j,t}\,;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}. \tag{26}$$

Otherwise, for other combinations of $\mathcal{A}^{ev}_{j,t}$ and $\mathcal{B}^{ad}_{j,t}$ as referred to Table II, EV charge, discharge, and PV system export remain unchanged. PV system export is updated as in (27) if the value of $\mathcal{B}^{ad}_{j,t}$ is -1 in other combinations.

$$\widehat{\mathcal{P}}^{pv}_{j,t} = \mathcal{P}^{pv}_{j,t} + \mathcal{P}^{ad}_{j,t}\mathcal{B}^{ad}_{j,t}\,;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}. \tag{27}$$

Based on EVs charge/discharge power updates $\widehat{\mathcal{P}}^{ch}_{j,t}$ and $\widehat{\mathcal{P}}^{dis}_{j,t}$, the SOC values $\chi^{c}_{j,t+\tau}$ of EVs are updated as in (10) until the SOC values reach the desired SOC levels X^d_j before departure. With the SOC updates prosumers can estimate the expected EVs charge/discharge power to calculate the net imports/exports for the DSO in each τ so that the DOEs can be determined for prosumers accordingly.

B. Prosumers Bidding Strategy

Prosumers can decide on their participation in the P2P trading or trading with the upstream grid by generating their bids for buying/selling energy within DOEs. Each prosumer decides on the trading bids and submits them to the LEM in each τ by the proposed bidding strategy. In this case, the objective of prosumer is to minimize the total trading cost as,

$$\begin{aligned} min \sum_{j\in\mathcal{J}} \Big(&\mathcal{P}^{pb}_{j,t}\cdot\Lambda^{lem}_{j,t} + \mathcal{P}^{gb}_{j,t}\cdot\Lambda^{tou}_{j,t} + \mathcal{P}^{ps}_{j,t}\cdot\Lambda^{lem}_{j,t} \\ &+ \mathcal{P}^{gs}_{j,t}\cdot\Lambda^{fit}_{t}\Big)\tau\,;\mathcal{P}^{ps}_{j,t}, \mathcal{P}^{gs}_{j,t} \le 0,\ \forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \end{aligned} \tag{28}$$

subject to: (29) – (35),

where the first and second terms in (28) refer to the total cost of buying energy from the peers and the upstream grid, respectively and the third and fourth terms define the total profit of selling energy to the peers and the upstream grid in the LEM, respectively. Here, $\mathcal{P}^{pb}_{j,t}/\mathcal{P}^{ps}_{j,t}$ and $\mathcal{P}^{gb}_{j,t}/\mathcal{P}^{gs}_{j,t}$ are buying/selling quantities of prosumer j with the peers and the upstream grid in each τ, respectively; and $\Lambda^{tou}_{j,t}$ are the time-of-use (ToU) buying prices with the upstream grid.

Prosumers are allowed to trade in the LEM within the assigned DOEs $\widehat{\mathcal{P}}_{j,t}$ confirming the network-constrained operation. The sum of the buying energy of prosumer j at time t with the peers and the upstream grid should be equal to or less than the DOE limits $\widehat{\mathcal{P}}_{j,t}(>0)$, and the sum of the selling energy with the peers and the upstream grid should be equal to or greater than the DOE limits $\widehat{\mathcal{P}}_{j,t}(\le 0)$ as in (29) and (30), respectively.

$$\mathcal{P}^{pb}_{j,t} + \mathcal{P}^{gb}_{j,t} \le \widehat{\mathcal{P}}_{j,t},\ \text{if}\ \widehat{\mathcal{P}}_{j,t} > 0\,;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{29}$$

$$\mathcal{P}^{ps}_{j,t} + \mathcal{P}^{gs}_{j,t} \ge \widehat{\mathcal{P}}_{j,t},\ \text{if}\ \widehat{\mathcal{P}}_{j,t} \le 0\,;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}. \tag{30}$$

The total P2P buying quantity $\mathcal{P}^{pb}_{j,t}(>0)$ for each prosumer in each τ is constrained by (31), which is not greater than $\widehat{\mathcal{P}}_{j,t}(>0)$, and the total P2P selling quantity $\mathcal{P}^{ps}_{j,t}(<0)$ for each prosumer in each τ is limited by $\widehat{\mathcal{P}}_{j,t}(\le 0)$ as in (32).

$$0 \le \mathcal{P}^{pb}_{j,t} \le \widehat{\mathcal{P}}_{j,t},\ \text{if}\ \widehat{\mathcal{P}}_{j,t} > 0\,;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{31}$$

$$\widehat{\mathcal{P}}_{j,t} \le \mathcal{P}^{ps}_{j,t} \le 0,\ \text{if}\ \widehat{\mathcal{P}}_{j,t} \le 0;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}. \tag{32}$$

On the other hand, constraints (33) and (34) limit the buying quantity $\mathcal{P}^{gb}_{j,t}$ and the selling quantity $\mathcal{P}^{gs}_{j,t}$ in each τ with the upstream grid, respectively. It is assumed that if no P2P trade occurs, the trade with the grid should be equal to the DOE but it is less than the DOE when there is a P2P trade.

$$0 \le \mathcal{P}^{gb}_{j,t} \le \widehat{\mathcal{P}}_{j,t},\ \text{if}\ \widehat{\mathcal{P}}_{j,t} > 0 \quad ;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}, \tag{33}$$

$$\widehat{\mathcal{P}}_{j,t} \le \mathcal{P}^{gs}_{j,t} \le 0,\ \text{if}\ \widehat{\mathcal{P}}_{j,t} \le 0 \quad ;\forall j \in \mathcal{J}, \forall t \in \mathcal{T}. \tag{34}$$

Constraint (35) defines the power balance of the total buying and the total selling of the P2P trading in each τ so that the remaining amounts of imports/exports of prosumers within $\widehat{\mathcal{P}}_{j,t}$ can be traded with the upstream grid in the LEM.

$$\sum_{j\in\mathcal{J}} \mathcal{P}^{pb}_{j,t} + \sum_{j\in\mathcal{J}} \mathcal{P}^{ps}_{j,t} = 0 \quad ;\mathcal{P}^{ps}_{j,t} \le 0, \forall t \in \mathcal{T}. \tag{35}$$

C. P2P Trading Mechanism

The proposed framework incorporates a P2P trading mechanism to facilitate prosumers to trade with their peers. In the proposed P2P trading mechanism, prosumers independently make an optimal decision to buy/sell energy from/to their peers. Moreover, prosumers are able to generate trading amounts and prices optimally for the P2P trading. Let the P2P trading be considered for buying (selling) energy $\mathcal{P}^{pb}_{j,i,t}(\mathcal{P}^{ps}_{j,i,t})$ by prosumer $j \in \mathcal{J}$ from (to) prosumer $i \in \mathcal{J}|i \ne j$. The single P2P buying energy $\mathcal{P}^{pb}_{j,i,t}$ is limited by $\mathcal{P}^{pb}_{j,t}$ and the single P2P selling energy $\mathcal{P}^{ps}_{j,i,t}$ is constrained by $\mathcal{P}^{ps}_{j,t}$ as in (36) and (37), respectively, where $\mathcal{P}^{pb}_{j,t}/\mathcal{P}^{ps}_{j,t}$ is the buying/selling quantity bid of prosumer j at a time t as in Section V-B. Prosumer j can only trade energy with prosumer i at time t as stated in (36) and (37), where $\mathcal{C}_{j,i,t}$ is a binary variable to represent the P2P trading status such that $\mathcal{C}_{j,i,t} = 1$ if prosumer j buys energy from prosumer i.

$$0 \le \mathcal{P}^{pb}_{j,i,t} \le \mathcal{P}^{pb}_{j,t}\mathcal{C}_{j,i,t}\,;\forall (j,i) \in \mathcal{J}|j \ne i, \forall t \in \mathcal{T}, \tag{36}$$

$$\mathcal{P}^{ps}_{j,t}(1-\mathcal{C}_{j,i,t}) \le \mathcal{P}^{ps}_{j,i,t} \le 0\,;\forall (j,i) \in \mathcal{J}|j \ne i, \forall t \in \mathcal{T}. \tag{37}$$

Equation (38) refers to the energy matching constraint of prosumers' buying and selling in each P2P trade at time t, which implies that the amount of buying energy by prosumer

j from prosumer i should be equal to the amount of selling energy by prosumer i to prosumer j at time t.

$$\mathcal{P}^{pb}_{j,i,t}+\mathcal{P}^{ps}_{i,j,t}=0;\mathcal{P}^{ps}_{i,j,t}\leq 0,\forall(j,i)\in\mathcal{J}|i\neq j,\forall t\in\mathcal{T}. \quad (38)$$

To determine the individual P2P trading bids ($\mathcal{P}^{pb}_{j,i,t}$ and $\mathcal{P}^{ps}_{i,j,t}$) and the P2P trading prices $\lambda^{c}_{j,i,t}$ of prosumers (j and i), the optimal decision making problem is devised by the LMO that minimizes the mismatches between individual P2P trades as,

$$\begin{aligned} min\sum_{j\in\mathcal{J}}\sum_{i\in\mathcal{J}|i\neq j}&\Big(\big(\mathcal{P}^{pb}_{j,i,t}\cdot\Lambda^{pb}_{j,t}+\mathcal{P}^{ps}_{i,j,t}\cdot\Lambda^{ps}_{i,t}\big)\\ &-\lambda^{c}_{j,i,t}\big(\mathcal{P}^{pb}_{j,i,t}+\mathcal{P}^{ps}_{i,j,t}\big)\Big)\tau \qquad (39)\\ &;\mathcal{P}^{ps}_{i,j,t}\leq 0,\ \forall(j,i)\in\mathcal{J}|j\neq i,\forall t\in\mathcal{T},\\ \text{subject to:}\quad &(36)-(38), \end{aligned}$$

where $\Lambda^{pb}_{j,t}$ and $\Lambda^{ps}_{i,t}$ are the prices for P2P trading between prosumer j and prosumer i at time t. The objective function (39) yields P2P trading bids ($\mathcal{P}^{pb}_{j,i,t}$ and $\mathcal{P}^{ps}_{i,j,t}$) and a P2P trading price $\lambda^{c}_{j,i,t}$ of the optimal solution using Karush–Kuhn–Tucker (KKT) conditions, and constraints (36)-(38) are relaxed by Lagrange multiplier $\lambda^{c}_{j,i,t}$ for attaining lower-extremes of (39). The first and second terms in (39) define the total cost of P2P buying energy by j from i and the total revenue of P2P selling energy by i to j. In (39), the third term presents the product of Lagrange multiplier $\lambda^{c}_{j,i,t}$ and the equilibrium quantity of P2P buying and selling energy, where the energy equilibrium constraint (38) corresponds to the Lagrange multiplier $\lambda^{c}_{j,i,t}$ in (39).

VI. Case Studies

A. Test Systems

The proposed framework is implemented for Case I on a simple toy network model and Case II on an unbalanced three-phase residential distribution network, where a single-phase EV, a PV system and household loads are considered in each house. Each house is connected to each node of different phases of the network.

1) Case I: For this case study, Consider a typical 5-node LV distribution test feeder [33] as a simple toy model, as shown in Fig. 2, to explain the proposed P2P trading framework. The network is analyzed for the DOE calculation and the P2P trading at a given time t. The network data of the distribution feeder is presented in Fig. 2. A single-phase EV, a PV system and an HL are considered in each node for a prosumer. The nodes 1-5 have $\mathcal{P}^{hl}_{j,t}=\{2.25,3.65,2.40,2.45,2.57\}$ kW HL loads with 0.95 power factor, a 5 kWp PV system having a 3.71 kW local generation ($\mathcal{P}^{pv}_{j,t}$) each and a Tesla Model 3 EV of 55 kWh capacity and 6.6 kW rating ($\mathcal{P}^{ch}_{j,t}/\mathcal{P}^{dis}_{j,t}$) with EVs' states $\mathcal{A}^{ev}_{j,t}=\{1,1,1,-1,-1\}$ at a given time t, respectively. The electricity prices for ToU $\Lambda^{tou}_{i,t}$, FiT $\Lambda^{fit}_{i,t}$ and local market $\Lambda^{lem}_{i,t}$ are used as in [34].

2) Case II: In this case study, the IEEE European 55-node LV test system [35] is considered as a residential distribution network to implement the proposed framework. As depicted in Fig. 3, Phase a (a_1-a_{21}), Phase b (b_1-b_{19}) and Phase c (c_1-c_{15}) are colored purple, green and red, respectively. Each circle represents one house, having one PV, EV and HL on one node

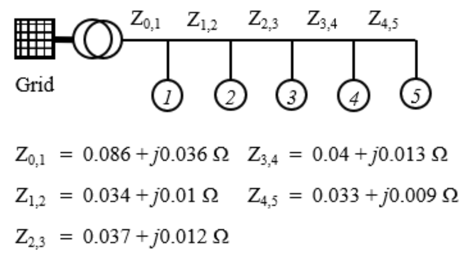

Fig. 2: A typical 5-node LV distribution feeder.

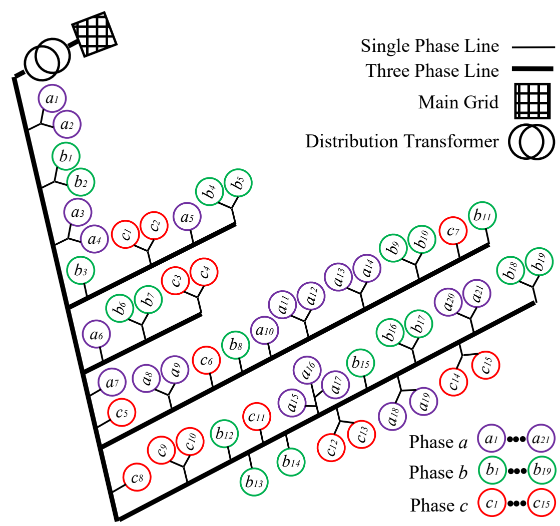

Fig. 3: LV residential distribution test network.

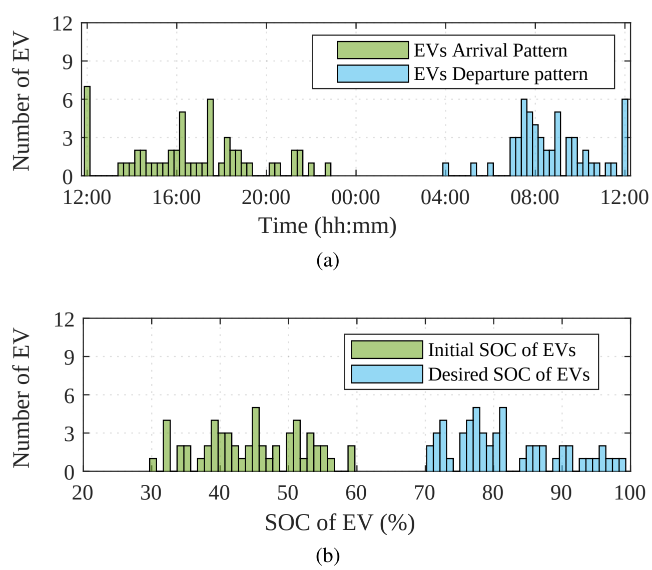

Fig. 4: Mobility data of EVs: (a) arrival and departure pattern, and (b) initial and desired SOC.

TABLE III: Results of 5-node LV distribution feeder.

Results	**Node 1**	**Node 2**	**Node 3**	**Node 4**	**Node 5**
Net power (kW)	5.14	6.54	5.29	-7.86	-7.74
DOE (kW)	5.14	6.54	5.29	-3.83	-7.74
P2P (kW)	0	6.54	5.03	-3.83	-7.74
Grid (kW)	5.14	0	0.26	0	0
Voltage (pu)	0.992	0.991	0.996	1.005	1.010
Increased Profit (¢)	0	7.26	5.59	4.06	8.21
	Line 1	**Line 2**	**Line 3**	**Line 4**	**Line 5**
Line Congestion(%)	50.90	11.04	54.60	100.00	66.69

connected to a bus in a particular phase, and one node or multiple nodes can be connected to the same bus in a phase. For example, houses on nodes a_{15}, a_{16} and a_{17} are connected to the same bus in Phase a of the network. The mobility data of EVs are used for 24 hour time-frame as presented in Fig. 4. It includes arrival time τ_j^{ar}, departure time τ_j^{d}, initial SOC X_j^{ini} and final SOC X_j^{d} as their preferences and desires to reflect their real mobility characteristics. EVs can take part in the LEM within the period between τ_j^{ar} and τ_j^{d}. Tesla Model 3 EV of 55 kWh capacity and 6.6 kW instantaneous power rating is assigned for an EV model with 95% charge/discharge efficiency. A PV system of 5 kW capacity and load profiles with 0.95 power factor from the IEEE LV feeder data [35] are utilized in this study. The electricity prices for ToU $\Lambda_{i,t}^{tou}$, FiT $\Lambda_{i,t}^{fit}$ and local market $\Lambda_{i,t}^{lem}$ are used as in [34]. The prices for P2P trading ($\Lambda_{j,t}^{pb}$ and $\Lambda_{i,t}^{ps}$) are assumed to be same as $\Lambda_{i,t}^{lem}$. The simulation of the proposed framework is executed with a 15 minutes duration of the time-slot τ and using a computer of Intel(R) Core(TM) i7-8700 CPU (3.20GHz) and 32.0 GB RAM. The results are analyzed at 100% penetration of EVs and PV systems into the network to evaluate the effectiveness of the proposed framework. However, the proposed framework is applicable to prosumers without/with EVs/PV systems.

B. Results and Discussions

1) Case I Results: Results for this case are presented in Table III in terms of network and economic performances through the DOE and the P2P trading execution. Table III shows that the DOE secures the network for the energy trading in the LEM and prosumers gain increased profits in the P2P trading as compared with the BAU, in which power is bought/sold at ToU/FiT price.

2) DOE Results: With implementing Algorithm 1 in the proposed framework, the DOEs ($\widehat{\mathcal{P}}_{j,t}$) are determined for prosumers to restrict their expected imports/exports ($\mathcal{P}_{j,t}$) within DOEs so that the network operates without any violations of the node voltage and line thermal constraints. Fig. 5 presents the DOEs for prosumer ($j = 27$) at a sample node a_{13} of the network, where imports/exports of the prosumer are limited from their net demands/generations ($\mathcal{P}_{j,t}$). These DOEs are applied for prosumers energy management and also to configure prosumers' bids for the P2P trading. The presented DOE calculation algorithm is computationally efficient and can be implemented for near real-time market clearing. For example, the average computation time of DOE for an IEEE European 55-node residential LV distribution network is 2.31 s. This shows that the computation time of DOE is insignificant and the DOE can be calculated for large-scale systems with short market clearing intervals.

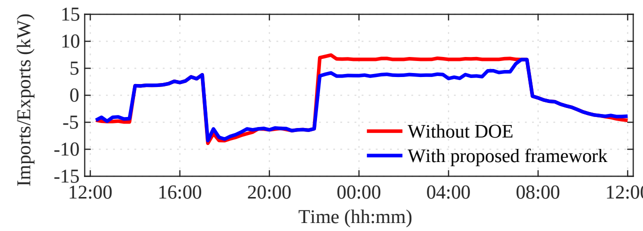

Fig. 5: Imports/exports of Prosumer ($j = 27$) at node a_{13} of the network without/with the DOE.

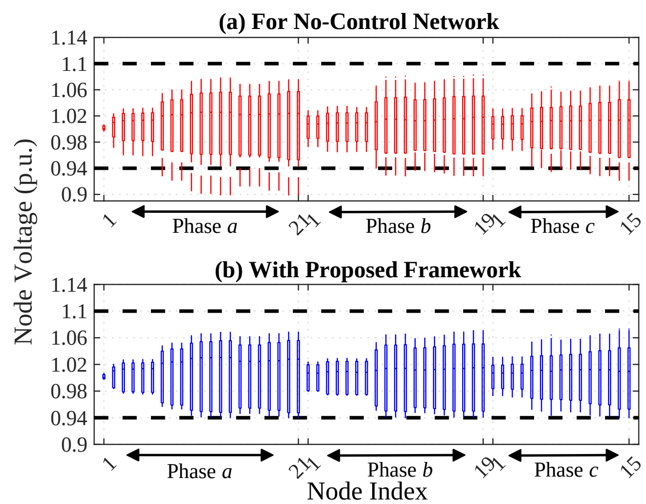

Fig. 6: Voltage variations at different nodes of the network: (a) for the no-control network model and (b) with the proposed framework.

3) Distribution Network Performance Analysis: The distribution network performance is observed in terms of node voltage ($\mathcal{V}_{n,t}$) and line congestion ($\mathcal{I}_{l,t}$). In the proposed framework, the algorithm is implemented on the test network to preserve each node voltage within the standard voltage range of 0.94 - 1.10 p.u. and line congestion within 100% level of the line capacity [35]. The network performance is analyzed in two different cases in this study: *i)* the no-control network strategy without DOEs and *ii)* the network-secure strategy with the proposed framework. The no-control network strategy does not constrain the imports/exports of prosumers by any DOEs. On the other hand, as in Algorithm 1, the network-secure strategy accepts the expected imports/exports of prosumers if there is no violation of network constraints, otherwise, it limits the imports/exports of prosumers by the DOEs. Fig. 6 shows the results of voltage variations at different nodes of the network and Fig. 7 presents line congestion results in different lines of the network for both cases. Under the no-control network strategy, a number of violations of the node voltage and line congestion in the network are identified as shown in Fig. 6(a) and Fig. 7(a), respectively. Fig. 6(b) and Fig.

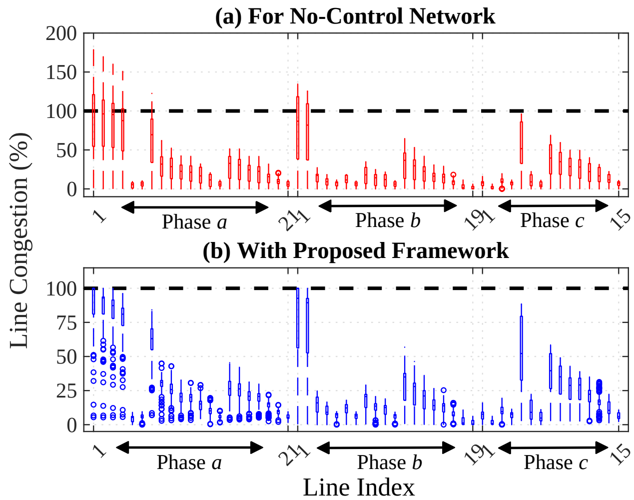

Fig. 7: Line congestion results in different lines of the network: (a) for the no-control network model and (b) with the proposed framework.

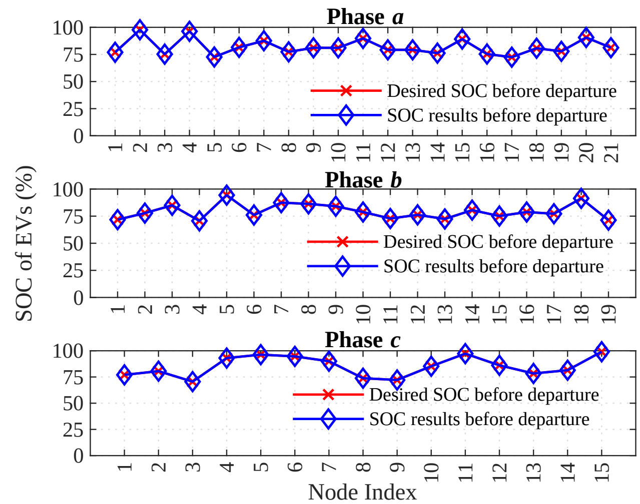

Fig. 9: SOC results of EVs before departure with the proposed framework.

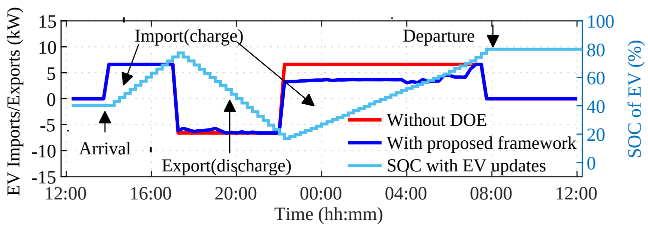

Fig. 8: EV profile of prosumer ($j = 27$) at a sample node a_{13} of the distribition network.

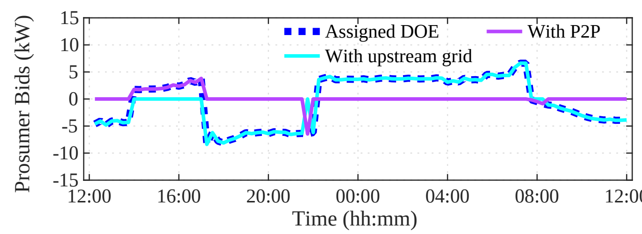

Fig. 10: Prosumer's bids of a sample prosumer ($j = 27$) within the assigned DOE.

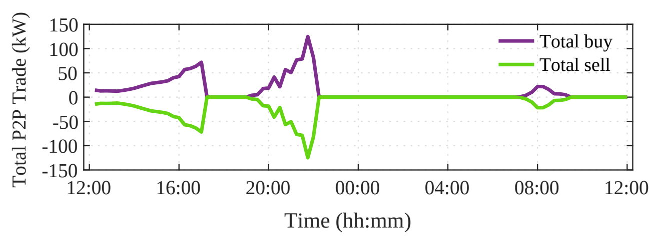

Fig. 11: P2P trade balance of total buying and total selling of prosumers.

7(b) illustrate that the proposed framework ensures a secured network operation without any violation of node voltage and line congestion in all phases of the network, respectively, to ensure the integrity of the distribution network.

4) EVs Charge/Discharge Management: The proposed framework maximizes prosumers' welfare by managing EVs charging and discharging and fulfilling their preferences of achieving the desired SOC levels before departure as in Algorithm 2. Fig. 8 presents EV charging and discharging profile of prosumer ($j = 27$) at a sample node a_{13} of the network that illustrates the EVs coordination through their imports(charge $\widehat{\mathcal{P}}^{ch}_{j,t}$)/exports(discharge $\widehat{\mathcal{P}}^{dis}_{j,t}$) management using assigned DOEs. The SOC update ($\chi^{c}_{j,t+\tau}$) of the EV is also shown in 8, where the EV's charging and discharging are managed, and the desired SOC level (X^{d}_{j}) is achieved before departure. To evaluate the effectiveness of the proposed framework, a complete picture of the fulfilling EVs desires and a comparison with their desired SOC levels are depicted in Fig. 9 for all prosumers connected to nodes of the network. As illustrated in Fig. 9, the proposed framework performs to manage EVs charging and discharging with 100% penetration level in a PV-rich distribution network by obtaining the SOC results which are exactly equal to the desired SOC levels before departure in all cases.

5) Prosumers Bidding Analysis: According to the proposed prosumers bidding strategy, prosumers are allowed to trade in the LEM within the DOEs. Accordingly, prosumers generate prosumers' bids of buying(imports)/selling(exports) within the DOEs comprising with the trades of the P2P ($\mathcal{P}^{pb}_{j,t}/\mathcal{P}^{ps}_{j,t}$) and the upstream grid ($\mathcal{P}^{gb}_{j,t}/\mathcal{P}^{gs}_{j,t}$) in the LEM in each τ as shown in Fig. 10. Fig. 10 shows the DOEs and optimal bids for trading with the P2P and the upstream grid of a sample prosumer ($j = 27$). Results in Fig. 10 depict that the sum of the buying/selling energy with the P2P and the upstream grid is equal to the DOEs in each τ. At the same time, the proposed bidding strategy constrains prosumers' P2P trading that the total buying and the total selling must be balanced in each τ. Fig. 11 represents the P2P trade balance of total buying and

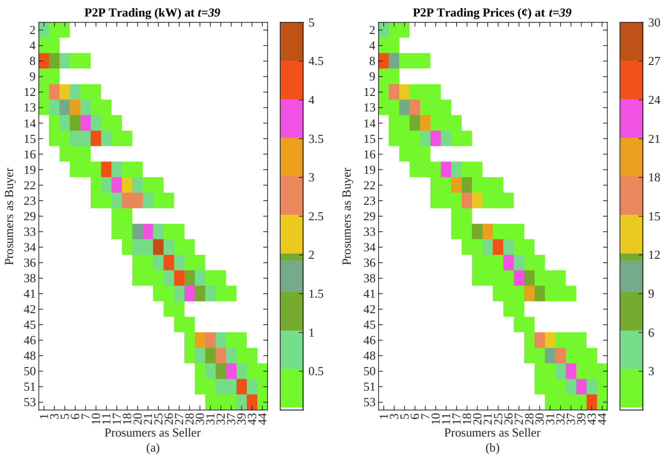

Fig. 12: Matrix of P2P trading (a) amounts (kW) and (b) prices (¢) of prosumers (buyers and sellers) at a sample time $t = 39$.

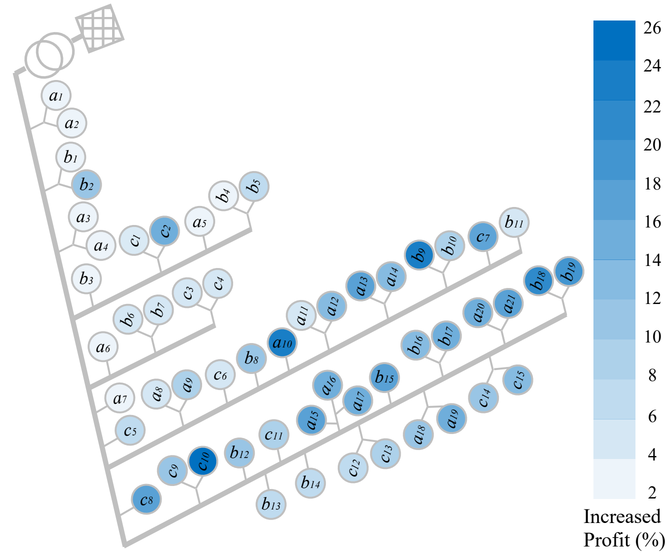

Fig. 13: Colormap of increased profit (%) in the proposed LEM compared to the BAU.

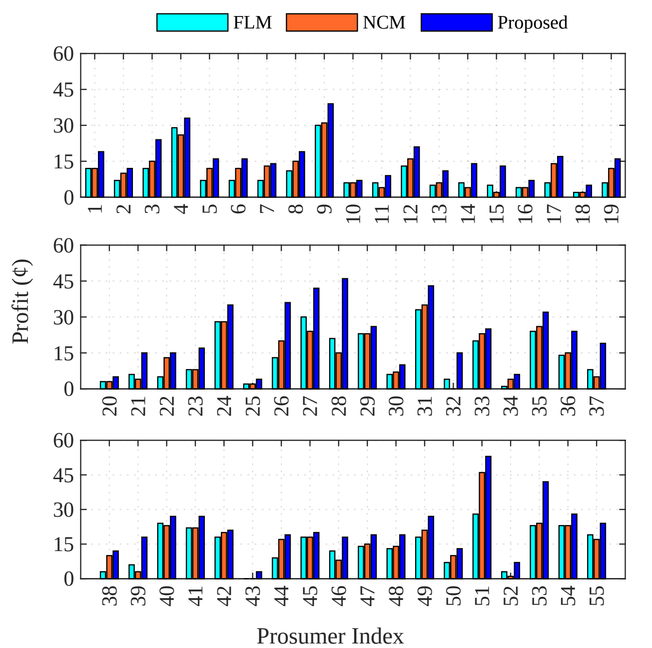

Fig. 14: Profit analysis of prosumers using different methods.

total selling of prosumers.

6) P2P Trading Analysis: As explained earlier, prosumers generate their trading bids ($\mathcal{P}^{pb}_{j,i,t}$/$\mathcal{P}^{ps}_{j,i,t}$) and prices ($\lambda^{c}_{j,i,t}$) optimally for the P2P trading coordinated by LMO in the proposed framework. Fig. 12 illustrates the P2P trading results of prosumers (buyers and sellers) at an arbitrarily-chosen sample time $t = 39$. The traded amounts (in kW) between prosumers (buyers and sellers) are represented in Fig. 12a and the prices (¢) corresponding to those tradings are shown in Fig. 12b. As is noticed in Fig. 12, each P2P trading is executed in a decentralized way, whereby a prosumer acting as a buyer purchases from another prosumer (who plays the role of a seller) at an optimal P2P trading price. Further, a buyer trades with multiple sellers simultaneously and vice versa is also true for a seller in order to meet the required energy quantity ($\mathcal{P}^{pb}_{j,t}$/$\mathcal{P}^{ps}_{j,t}$), where tradings are confined by the availability of their buying/selling amounts and constraints. Fig. 12 demonstrates that prosumers are able to manage their P2P tradings optimally by achieving their P2P trading limits and respecting both network and local market constraints.

7) Economic Performance and Comparative Analysis: In this study, an economic performance analysis is performed based on the P2P trading of prosumers, and the results are compared with the BAU, in which power is bought/sold at ToU/FiT prices. Fig 13 illustrates the increased profit in percentage (%) from the P2P energy trading in the proposed LEM compared to the BAU over the course of 24 hours. The results show that through participation in P2P trading, prosumers are able to get an increased profit with respect to the BAU. The amount of increased profit of a prosumers depends on several factors including, location of prosumer in the network, types of DERs a prosumer own, and its EV mobility pattern. Based on the system model formulation in the proposed framework, the trading of EVs' charging and discharging in the LEM takes into account their uncertain mobility, desires, and constraints, as well as the local surplus or demand. The diverse actions of EVs owned by prosumers demonstrate varying profit gains at different locations.

Moreover, a profit analysis for prosumers is conducted using three different methods: the FLM, the NCM, and the proposed method. In FLM, it is considered that prosumers are provided with a fixed limit for trading in the LEM. For this analysis, a limit of 2.25 kW is assigned that ensures no violation of network constraints [26]. The NCM is implemented by blocking prosumers to trade in the LEM for a specific time-slot if their expected exports/imports are found to be detrimental to the network operation [32]. To demonstrate the effectiveness of the proposed method, the proposed method is compared with

FLM and NCM in terms of increased profit in P2P trading with respect to the BAU over the course of 24 hours. The results of this comparative analysis are presented in Fig. 14, which show that the proposed method outperforms the other methods in terms of profit gained while trading in the LEM. Although the increased profit gained by prosumers may vary, the proposed method enables all prosumers to gain more profit compared to the FLM and NCM.

VII. Conclusion

This paper has proposed a new framework for management of prosumers equipped with EVs and PV systems based on the DOEs that facilitates prosumers to participate in the LEM without violating network constraints. In the proposed framework, the network operation is observed by the DSO with expected net imports/exports of prosumers in order to resolve any network constraints issues by using the proposed DOE computation algorithm. A DOE-enabled prosumer bidding strategy has been developed to carry out P2P energy trading among prosumers so that they can exchange energy in the LEM respecting the network constraints and receive economic benefits. The results have confirmed that the import and export power of prosumers with assigned DOEs can facilitate managing EVs charging and discharging with PV systems in the distribution network efficiently without causing voltage and line congestion problems. Further, the proposed framework has been able to obtain the prosumers' bids to trade in the LEM within the assigned DOEs, and to balance the P2P market in terms of total buy and total sell in each trading slot. Moreover, it has benefited prosumers financially through the P2P trading as compared to the BAU, FLM and NCM. Therefore, it is perceived from the evaluation and analysis of simulation results that the proposed framework is capable to maintain the network-secure operation while prosumers' preferences and desires are taken into consideration effectively.

The proposed framework can be extended by incorporating prosumer-centric features to facilitate the participation of rational prosumers. Moreover, the introduction of residential battery storage, community battery storage and their flexibility in the prosumers' energy management framework for P2P trading might increase the utilization of PV generations and improve the energy balance in the LEM. Future works can also be devoted to devising transactive coordination management for PV-installed EV charging stations with battery storage systems that might enhance network operations and reduce overall costs.

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