A Peer-to-Peer Market-Based Control Strategy for a Smart Residential Community with Behind-the-Meter Distributed Energy Resources

Preprint

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National Renewable Energy Laboratory

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A Peer-to-Peer Market-Based Control Strategy for a Smart Residential Community with Behind-the-Meter Distributed Energy Resources

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***Abstract*—This paper presents a distributed peer-to-peer market control strategy to manage and to enable resource sharing of behind-the-meter distributed energy resources in a residential community. In the proposed strategy, each consumer or prosumer determines the flexibility of their point of connection to the power network such that the obtained flexibility is network-feasible. Based on the feasible flexibility, the consumers and the prosumers trade power among each other at each time instance to fulfil their preferred load requirements while maximizing their payoffs and helping to regulate node voltages inside the community. Because the problem to be solved is non-convex, a distributed particle swarm optimization algorithm is used to coordinate the consumers/prosumers in a fully autonomous manner without any centralized or hierarchical coordination. Numerical simulations performed on a community of 48 homes demonstrate the efficacy of the proposed approach.**

Keywords*— *Behind-the-meter, distributed control, distributed energy resource, flexibility, peer-to-peer market.

I. Introduction

The power system landscape is changing rapidly with the ever-increasing integration of numerous distributed energy resources (DERs), mainly in medium- to low-voltage networks. The increased adoption of distribution-level, customer-owned DERs provides opportunities for the power system in terms of network voltage regulation while also enabling geographically close prosumers (customers who are able to supply power) and consumers (customers who are only able to draw power) to exchange resources for optimal local utilization and reduction in their energy costs [1].

For consumers and prosumers, however, exchanging power with the distribution grid, or, exchanging power with other neighboring customers (peers), at fixed prices and pre-determined power levels is suboptimal; therefore, strategies are needed in which the customers can individually decide and come to an agreement on the per unit price of electricity along with the amount of electricity they would like to exchange with other neighboring customers.

To improve local resource sharing while benefiting both consumers and prosumers, multiple peer-to-peer (P2P) models have been developed in the power system literature, borrowing the concept from computer science in which computers act as peers providing resources [2]. Overall, resource trading in distribution systems can be divided into three methods: 1) leader-follower, where one agent sets price or other signals, and the rest of the agents follow, as in [3]–[4]; 2) aggregator-based, where an aggregator enables the market and handles the optimization [5]–[6]; and 3) resource sharing using P2P markets [7]–[8].

Most existing studies, however, ignore the network aspect when designing P2P strategies and are usually implemented using a centralized or hierarchical controller. There have been some very recent studies [9]-[10] that develop P2P strategies while also considering network constraints. However, in these studies, the P2P transactions that are done in the first stage, need to be verified and corrected by a hierarchical controller, such as the distribution system operator, in the second stage for any network limit violations. Further, some studies that propose distributed P2P solutions, such as [11], do not consider network constraints. Therefore, in this paper, we propose a fully distributed P2P trading strategy considering node voltage feasibility without the need for any coordination with the system operator. The main contributions of this paper are as follows:

1) A P2P market model while maintaining node voltage feasibility is proposed for a smart community of homes based on equitable benefits to the consumers and prosumers.

2) A fully distributed implementation of the P2P market strategy is proposed based on a distributed version of particle swarm optimization to handle the non-convexity of the problem.

The rest of this paper is organized as follows. Section II discusses the aspects of system modeling, Section III presents the optimization model for P2P trading, Section IV presents the distributed P2P trading framework, Section V presents the simulations results, and Section VI provides concluding remarks.

II. System Modelling

A. Network Model

In this section, $j \in N$ is used to index multiphase buses in the considered smart community. We assume that the community has a single point of common coupling (PCC), indexed as bus 0, with the upstream distribution grid. The set of homes are denoted as $N^+ := N \backslash \{0\}$; and let a, b, c denote the three phases; and let Φ_j denote the set of phases of bus j. Denote by $v := \left[v_h^\phi, \phi \in \Phi_h, h \in N^+\right]$, $p := [p_h^\phi, \phi \in \Phi_h, h \in N^+]$, $q := [q_h^\phi, \phi \in \Phi_h, h \in N^+]$ the vectors of the squared voltage magnitudes and of the active and reactive power consumptions, respectively, at each phase of bus h. An unbalanced power flow model [12] for the multiphase community network is used as shown in (1a), where vector $\tilde{v}_0 := [v_0^\phi]$ contains the squared voltages at different phases of the PCC bus. The elements of the matrices R and X are defined in (1b)-(1d) ($a = 0, b = 1, c = 2$ represent the three phases):

$$v = Rp + Xq + \tilde{v}_0 \quad (1a)$$

$$\partial_{p_k^\phi} v_j^\psi = -2Re\left\{\overline{Z}_{jk}^{\psi\phi} e^{-\frac{i2\pi(\psi-\phi)}{3}}\right\} \quad (1b)$$

$$\partial_{q_k^\phi} v_j^\psi = +2Im\left\{\overline{Z}_{jk}^{\psi\phi} e^{-\frac{i2\ (\psi-\phi)}{3}}\right\} \quad (1c)$$

$$Z_{jk}^{\psi\phi} := \sum_{(\xi,\zeta)\in E_j \cap E_k} z_{\xi\zeta}^{\psi\phi} \quad (1d)$$

where $\bar{\cdot}$ denotes the complex conjugate, and z impedances.

B. Customer Model

In this paper, we assume every customer has a home energy management system (HEMS) to manage behind-the-meter DERs, such as rooftop photovoltaics, battery energy storage systems, electric water heaters, and heating, ventilating and air-conditioning appliances. In this section, i is used to index homes and t to index time slots over the horizon H, i.e., $\{t, t+1 \ldots, t+H-1\}$ at which power is dispatched. The numerical models for individual DERs in each home are adopted from [13], and after summation of such DER powers, the net active/reactive power of home i at time t, denoted as $\tilde{p}_{hi}^t$ and $\tilde{q}_{hi}^t$, are obtained.

At time t, given the forecasts and aggregated active/reactive power of the uncontrollable loads for the horizon H, every HEMS i (controlling home i) evaluates the trajectories of the upper bound $(\hat{p}_i^t, \hat{q}_i^t)$ and the lower bound $(\check{p}_i^t, \check{q}_i^t)$. These two trajectories combined inform the maximum available flexibility of home i. Additionally, the nominal or preferred trajectories $\tilde{p}_i^t$ and $\tilde{q}_i^t$ are determined to maximize revenue and to fulfill the comfort requirements of home i. All three trajectories (upper, lower, nominal) are solved using the optimization problem developed in [14, Section III-D] and are omitted in this paper for brevity. Essentially, this optimization problem maximizes the active/reactive power flexibility of each home while penalizing deviations of indoor air and hot water temperatures from their user-preferred values, along with minimizing the cost to purchase power from the grid. It is assumed that the rate at which the customers are compensated for feeding into the grid is equal to a factor *f* of the time-of-use (TOU) rate c_p^t.

C. Utility of Consumers and Prosumers

Each customer at node *i* can be categorized as a consumer or a prosumer for each time step, *t*, depending on the flexibility band evaluated by the HEMS, *i*. In traditional peer-to-grid interactions, each customer buys or sells power to the distribution grid at the TOU and the feed-in rates, respectively. With P2P trading, however, the consumers can save on their energy costs, and the prosumers can earn a higher revenue by determining the optimal trading prices and trading powers with each other along with power to be bought/sold from/to the distribution grid for each time step, *t*.

For each time step, *t*, a customer, *i* is categorized as a consumer if $\check{p}_i^t > 0$, whereas a customer is categorized as a prosumer if $\check{p}_i^t < 0$; therefore, let us denote N_c^t as the set of consumers and N_p^t as the set of prosumers at time *t*.

For each consumer, *i*, its utility, U_{ci}^t or the cost advantage in trading power with other prosumers is defined as follows:

$$U_{ci}^t = c_p^t p_i^t - \left\{ \sum_{j \in N_p^t} \overline{\pi}_{s,ij}^t \overline{p}_{s,ij}^t + c_p^t \left(p_i^t - \sum_{j \in N_p^t} \overline{p}_{s,ij}^t \right) \right\} \quad (2a)$$

$$\textit{subject to:} \quad f c_p^t \le \overline{\pi}_{s,ij}^t \le c_p^t \quad (2b)$$

$$\check{p}_i^t \le p_i^t \le \hat{p}_i^t \quad (2c)$$

$$0 \le \overline{p}_{s,ij}^t, \quad p_i^t \ge \sum_{j \in N_p^t} \overline{p}_{s,ij}^t \quad (2d)$$

where p_i^t is the power ultimately used by the consumer, *i*; and $\overline{\pi}_{s,ij}^t$ and $\overline{p}_{s,ij}^t$ are the optimal price and power traded with the prosumer, *j*. In (2a), the first term denotes the TOU cost of purchasing power directly from the distribution grid, whereas the rest of the terms denote the cost when trading with other prosumers as well. The constraint (2b) ensures that the trading prices are within the range of the feed-in and TOU prices; the constraint (2c) ensures power feasibility; and constraint (2d) ensures that the power requirement, p_i^t, is fulfilled first by P2P trading and only then via import from the distribution grid.

For each prosumer, *i*, its utility, U_{pi}^t or the revenue advantage in trading power with other consumers, is defined as follows:

$$U_{pi}^t = -\left\{ -\sum_{j \in N_c^t} \overline{\pi}_{b,ij}^t \overline{p}_{b,ij}^t + f c_p^t \left(p_i^t + \sum_{j \in N_p^t} \overline{p}_{b,ij}^t \right) \right\} + f c_p^t p_i^t \quad (3a)$$

$$\textit{subject to:} \quad f c_p^t \le \overline{\pi}_{b,ij}^t \le c_p^t \quad (3b)$$

$$\check{p}_i^t \le p_i^t \le \hat{p}_i^t \quad (3c)$$

$$0 \le \overline{p}_{b,ij}^t, \quad p_i^t \le -\sum_{j \in N_p^t} \overline{p}_{b,ij}^t \quad (3d)$$

where p_i^t is the power ultimately sold by the prosumer, *i*; and $\overline{\pi}_{b,ij}^t$ and $\overline{p}_{b,ij}^t$ are the optimal price and power traded with the consumer, *j*. In (3a), the last term denotes the feed-in revenue of selling power directly to the distribution grid, and the rest of the terms denote the revenue when trading with other consumers as well. The constraint (3b) ensures that the trading prices are within the range of the feed-in and TOU prices; the constraint (3c) ensures power feasibility; and constraint (3d) ensures that the power to be sold, p_i^t, is first sold by P2P trading and only then via export to the distribution grid.

III. Optimization Model

As mentioned in Section I, most existing studies on P2P trading either do not use distributed control methods or do not consider the community network's voltage feasibility. Here, we present an optimization model considering the community network's voltage feasibility while enabling equitable distribution of cost savings and increased revenue among the consumers and the prosumers via P2P trading. It is assumed that there are no charges for reactive power draw; however, this too can be easily integrated if needed.

For each customer at node *i*, the actual feasible flexibility might be smaller than the available flexibility because of the possibility of node voltage violations; thus, the following optimization function and constraints solve for the feasible upper $(\hat{\hat{p}}_i^t, \hat{\hat{q}}_i^t)$ and lower $(\check{\check{p}}_i^t, \check{\check{q}}_i^t)$ bounds of all homes:

$$F_{flex}^t = -\alpha_{flex} \sum_{i \in N^+} \left[\min(\hat{\hat{p}}_i^t - \check{\check{p}}_i^t) + \min(\hat{\hat{q}}_i^t - \check{\check{q}}_i^t) \right] \quad (4a)$$

$$\textit{subject to:} \quad (1a) - (1d) \; for \; \check{\check{v}}_i^t, \check{\check{p}}_i^t, \check{\check{q}}_i^t, \quad (4b)$$

$$(1a) - (1d) \; for \; \hat{\hat{v}}_i^t, \hat{\hat{p}}_i^t, \hat{\hat{q}}_i^t, \quad (4c)$$

$$\hat{\hat{p}}_i^t \ge \check{\check{p}}_i^t, \quad \hat{\hat{q}}_i^t \ge \check{\check{q}}_i^t, \quad \forall t \quad (4d)$$

$$\underline{v} \le \hat{\hat{v}}_i^t \le \overline{v}, \quad \underline{v} \le \check{\check{v}}_i^t \le \overline{v}, \quad \forall t \quad (4f)$$

where $\underline{v}$ and $\overline{v}$ are the minimum and maximum voltage limits to be enforced, and α_{flex} is a weighting factor. It is noted that the feasible ranges of individual nodes are not decoupled across time-steps and that maximizing (4a) might lead to slightly tighter feasible boundaries compared to actual flexibility available. However, in the context of this paper, we aim to determine definite boundary definitions for each time-step *t* so that those can serve as feasible power limits for the purposes of P2P trading.

Further, the P2P trading framework is modeled as a solution of the function maximizing the product of the cost advantage for consumers and the revenue advantage for prosumers. Both the feasible flexibility evaluation and the P2P trading optimization can be solved simultaneously and are represented in the following optimization model:

$$min\ F_{p2p}^t = F_{flex}^t - \prod_{i\in N_p^t, j\in N_c^t} U_{ci}^t U_{pj}^t$$

$$= -\alpha_{flex} \sum_{i\in N^+} \left[\min(\hat{p}_i^t - \check{p}_i^t) + \min(\hat{q}_i^t - \check{q}_i^t)\right] -$$

$$\prod_{i\in N_p^t, j\in N_c^t} \left\{ c_p^t p_i^t - \left[\sum_{j\in N_p^t} \bar{\pi}_{s,ij}^t \bar{p}_{s,ij}^t + c_p^t\left(p_i^t - \sum_{j\in N_p^t} \bar{p}_{s,ij}^t\right)\right]\right\} \times$$

$$\left\{-\left[-\sum_{j\in N_c^t} \bar{\pi}_{b,ij}^t \bar{p}_{b,ij}^t + fc_p^t\left(p_i^t + \sum_{j\in N_p^t} \bar{p}_{b,ij}^t\right)\right] + fc_p^t p_i^t\right\} \quad (5a)$$

$$subject\ to: \quad (1a)-(1d)\ for\ \check{v}_i^t, \check{p}_i^t, \check{q}_i^t, \hat{v}_i^t, \hat{p}_i^t, \hat{q}_i^t \quad (5b)$$

$$\hat{p}_i^t \geq \check{p}_i^t, \quad \hat{q}_i^t \geq \check{q}_i^t, \quad (5c)$$

$$\underline{v} \leq \hat{v}_i^t \leq \bar{v}, \quad \underline{v} \leq \check{v}_i^t \leq \bar{v}, \quad (5d)$$

$$fc_p^t \leq \bar{\pi}_{s,ij}^t \leq c_p^t \quad (5e)$$

$$\check{p}_i^t \leq p_i^t \leq \hat{p}_i^t \quad (5f)$$

$$0 \leq \bar{p}_{s,ij}^t, \quad p_i^t \geq \sum_{j\in N_p^t} \bar{p}_{s,ij}^t \quad (5g)$$

$$fc_p^t \leq \bar{\pi}_{b,ij}^t \leq c_p^t \quad (5h)$$

$$\check{p}_i^t \leq p_i^t \leq \hat{p}_i^t \quad (5i)$$

$$0 \leq \bar{p}_{b,ij}^t, \quad p_i^t \leq -\sum_{j\in N_p^t} \bar{p}_{b,ij}^t \quad (5j)$$

$$\bar{\pi}_{b,ij}^t = \bar{\pi}_{s,ji}^t, \quad \bar{p}_{b,ij}^t = \bar{p}_{s,ji}^t \quad (5k)$$

The control variables in this problem are $\boldsymbol{c_{i,t}} := \left[\check{\bar{p}}_i^t, \check{\bar{q}}_i^t, \hat{\bar{p}}_i^t, \hat{\bar{q}}_i^t, \ddot{\pi}_{s,ij}^t, \ddot{\pi}_{b,ij}^t, \ddot{p}_{s,ij}^t, \ddot{p}_{b,ij}^t, p_i^t, q_i^t\right]$. Because this is a non-convex problem due to the presence of bilinear terms in (5a), we present in Section-IV a distributed particle swarm optimization-based algorithm [12], [13] to solve the P2P trading problem (5a)–(5l).

IV. Distributed Trading Framework

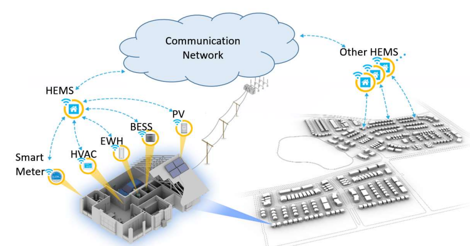

Fig. 1. Framework schematic for P2P trading among HEMS.

To solve the problem (5a)–(5l) using a distributed P2P trading framework, it is first assumed that all the HEMS at the customer nodes can communicate and exchange some information with their immediate neighboring HEMS using a communication network protocol, as shown in Fig. 1. Essentially, in the proposed distributed trading framework, each HEMS agent needs to ascertain some estimate of the global states of the community to be able to solve the P2P trading problem without any coordination from a higher-level controller. These global states basically encapsulate the coupling variables in the problem (5a)–(5l), and the HEMS agents use discrete consensus to get those estimates. The consensus formulation is briefly described next, after which the global state estimation and the distributed algorithm are discussed.

A. Consensus Overview

This paper employs discrete consensus, in which each agent communicates and exchanges information only with its neighboring agents; therefore, a doubly stochastic communication matrix, $\mathfrak{D} = [d_{k,l}]$, is adopted [17], which is presented in (6). An agent, k, updates its estimate $\xi_k[z] \in \mathbb{R}$ for iteration z based on (7), and all N^+ agents reach consensus if $|\xi_k - \xi_l| \leq \mu, \forall\, k, l = (1 \dots N), k \neq l$, where $0 < \mu \ll 1$:

$$d_{k,l} = \begin{cases} \dfrac{2}{n_k + n_l + 1}, & l \in N_k \\ 1 - \sum_{l\in N_k} \dfrac{2}{n_k + n_l + 1}, & l = k \\ 0, & otherwise \end{cases} \quad (6)$$

$$\xi_k[z+1] = \sum_{l=1}^{N} d_{k,l}\xi_l[z] \quad (7)$$

After consensus, all agents converge to the same estimate:

$$\xi_k[\infty] = (1/N^+) * \sum_{k=1}^{N^+} \xi_k[0], \forall\, k = (1 \dots N^+) \quad (8)$$

The matrix, $\mathfrak{D}$, is representative of the communication topology of the agents and is a square matrix of size equal to the number of agents. Further, each element *(k,i)* of the matrix, $\mathfrak{D}$, represents either a connection or a disconnection between the agents *i* and *k*. A sparse $\mathfrak{D}$ means that the agents are not well connected, and the algorithm's convergence will be delayed; on the other hand, a dense $\mathfrak{D}$ means that the agents are very well connected, and the algorithm's convergence will be faster.

B. Global State Estimation and Distributed Algorithm

Because a distributed P2P trading framework is being proposed, global state estimation is required as each HEMS agent needs to ascertain the global states individually. Based on the coupling variables in the problem (5a)–(5l), we define a column-shaped local state estimate vector as follows whose estimate is maintained by each HEMS agent, *i*:

$$\chi_i^t = \left[\check{\tilde{v}}_{i1}^t, \check{\tilde{v}}_{i2}^t, \dots, \check{\tilde{v}}_{iN}^t, \hat{\tilde{v}}_{i1}^t, \hat{\tilde{v}}_{i2}^t, \dots, \hat{\tilde{v}}_{iN^+}^t, U_{i1}^t, U_{i2}^t, \dots, U_{iN^+}^t\right]^T \quad (9)$$

where $\check{\tilde{v}}_{i1}^t$ is the estimate of the state $\check{\tilde{v}}_1^t$ maintained by agent *i,* and so on. The column vector χ_i^t essentially maintains an estimate of feasible lower and upper voltages at the community nodes along with the utility estimates of the consumer and prosumer agents. Each HEMS agent *i* will communicate with other neighboring agents at discrete time steps using consensus (6)–(8) to update its local estimate vector χ_i^t to converge to the global state estimate $\tilde{\chi}^t$ in (10) (please refer to [12] for more details).

$$\tilde{\chi}^t = \left[\check{\tilde{v}}_1^t, \check{\tilde{v}}_2^t, \dots, \check{\tilde{v}}_N^t, \hat{\tilde{v}}_1^t, \hat{\tilde{v}}_2^t, \dots, \hat{\tilde{v}}_{N^+}^t, U_1^t, U_2^t, \dots, U_{N^+}^t\right]^T \quad (10)$$

The proposed distributed particle swarm algorithm employing global state estimation using discrete consensus is presented next. It is noted that in the following algorithm, φ denotes the matrix representing a linear relation between the state vector and the control variables; z is the iteration index; and p indexes the particles in the swarm. Please refer to [15] and [16] for more details on the algorithm, which has been presented here only in brevity.

Algorithm : Distributed P2P trading algorithm for a HEMS agent *i*

a : **do** for HEMS agent *i*
b : Set time step $t = 1$, convergence tolerance = δ
c : **do** for t, **Initialization**: Set $z = 0$
d : Initialize vectors $c_{i,t}$ of probable solutions

$$c_{i,t}[0] = [c_{i,t}^{1}[0] \dots c_{i,t}^{p}[0]]^{T}$$

e : **do** for element *p*

Initialize self-estimate $\tilde{\chi}_{i,t}^{p}[0]$ based on (9)

Communicate self-estimate to neighboring agents and update global estimate

$$\chi_{i,t}^{p}[0] = \sum_{j=1}^{N^{+}} d_{i,j}\, \tilde{\chi}_{j,t}^{p}[0]$$

Evaluation and Evolution: **loop** *z*

f : **do** for element *p*

g : Evaluate fitness of element *p* based on (5a)–(5l)

h : Evolve element *p* based on swarm velocity updates

Estimation update and Communication:

i : **do** for element *p*

j : Update self-estimate

$$\tilde{\chi}_{i,t}^{p}[z+1] = \chi_{i,t}^{p}[z] + N^{+}\varphi[:,i]\big(c_{i,t}^{p}[z+1] - c_{i,t}^{p}[z]\big)$$

k : Communicate self-estimate to neighboring agents and update global estimate

$$\chi_{i,t}^{p}[z+1] = \sum_{j=1}^{N^{+}} d_{i,j} * \tilde{\chi}_{j,t}^{p}[z+1]$$

Convergence check:

l : Increment *z*

m : If converged, **break**, otherwise goto Step *f*.

end

In the above algorithm, each HEMS agent runs the steps *d* to *m* for each time-step *t* of the optimization.

V. Simulation Results

Numerical tests of the proposed distributed P2P trading strategy are performed on a smart community network of 48 homes based on an ongoing construction in Colorado, United States. Each home is assumed to host a HEMS that can communicate with neighboring HEMS to get state vector updates. The community is assumed to be connected to the distribution grid at one point, so the consumers and the prosumers can trade power with each other as well as with the distribution grid. The TOU prices are adopted from [18], the factor, *f*, for compensation for feed-in to the grid is assumed to be 0.1, and the factor α_{flex} is arbitrarily set as 1e6 (α_{flex} can be further tuned such that there is a good balance between flexibility maximization and utility maximization). The simulation is run for 96 time steps (1-day simulation of 15 min each) on a 4.0 GHz processor, and at each time step the distributed network-feasible P2P trading strategy in Algorithm 1 is executed to compute trading prices, trading powers, and grid exchange powers.

A. Convergence Analysis

To analyze the performance of the proposed distributed P2P trading strategy, we look at one time step (*t*=47) of the 96 time steps, and we evaluate the algorithm's convergence and properties of the obtained solution.

Fig. 2 shows the convergence plot of the objective function F_{p2p}^{t} in (5a), indicating good convergence properties for the proposed distributed trading algorithm in terms of required iterations, whereas Fig. 3 shows the average utility for the consumers and the prosumers being maximized as the iterations progress. Also, the convergence of the proposed distributed P2P algorithm occurs within 1 min (approx. 58s) for each time step, i.e., for each P2P transaction, which is well within the 15 min time step duration.

Further, Figs. 4 and 5 show that the HEMS agents converge to optimal trading prices and trading powers, whereas the prosumers supply all of their available power generation to the consumers within the community and do not sell any power to the distribution grid, as shown in Figs. 6 and 7.

B. Feasibility Analysis

This section presents results for the entire 96 time steps. Because the proposed strategy also considers voltage feasibility at the homes in the community, the actual

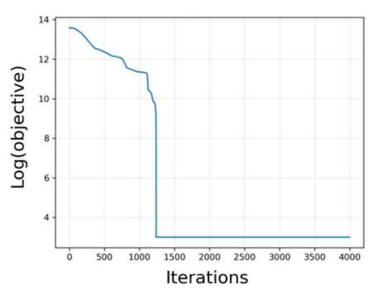

Fig. 2

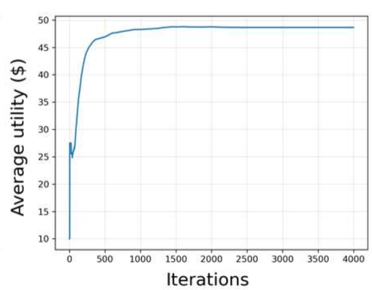

Fig. 3

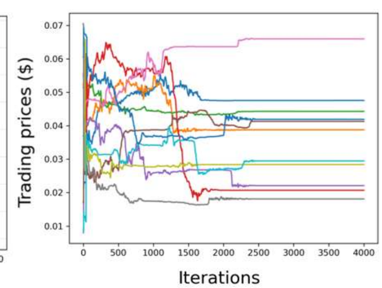

Fig. 4

Fig. 2: Plot for the objective function. Fig. 3: Plot showing average customers' utility. Fig. 4: Plots for trading price between each buyer-seller pair.

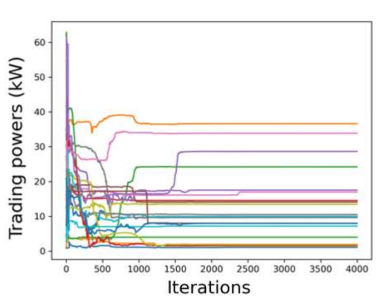

Fig. 5

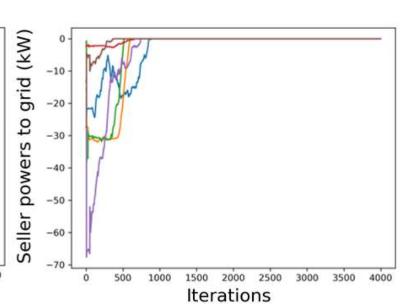

Fig. 6

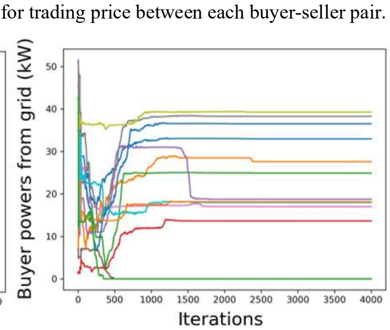

Fig. 7

Fig. 5: Plots for trading power between each buyer-seller pair. Fig. 6: Plots for all the sellers' powers to be sold to the distribution grid. Fig. 7: Plots for all the buyers' powers to be bought from the distribution grid.

flexibility at the home nodes might be smaller. This is shown in Fig. 8 for a sample home node, which presents plots showing feasible power limits provided by the HEMS, actual feasible limits evaluated by the proposed distributed strategy, along with HEMS-preferred setpoints and the actual dispatch.

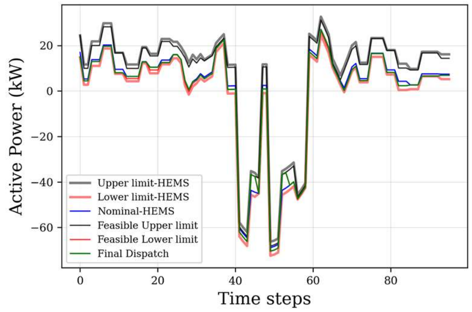

Fig. 8. Power plots for a sample home.

Further, Fig. 9 shows the home voltage bands throughout the 96 time step simulation period with and without the feasible flexibility terms, i.e., by removing F_{flex}^{t} and (5e) from (5), and it is evident from this figure that by considering feasible flexibility the proposed strategy can ensure voltage feasibility within ANSI limits of 1.05 and 0.95 p.u. in the smart community while enabling P2P trading with the consumers and the prosumers for optimal cost benefits to all the involved stakeholders. Further, it is noted that the voltages are in general closer to the maximum limit but not to the lower limit, because of the presence of regulators in the system data obtained from our utility partner, and the voltage setpoints of these regulators are such that the resulting PCC voltages for the community vary in the range 1.025 to 1.03 p.u. This is a common practice in real utility distribution systems.

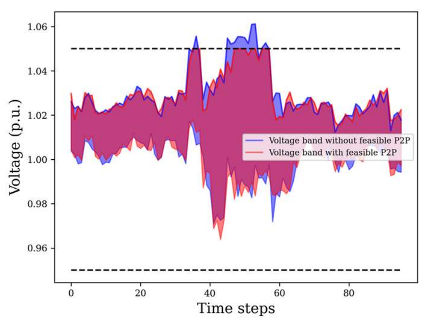

Fig. 9. Voltage time-series plots for all the home nodes.

VI. Conclusion

This paper introduced a distributed P2P trading framework to enable resource sharing of behind-the-meter DERs in a residential community, considering unbalanced power flow formulation and network voltage constraints. The proposed P2P trading strategy ensures that the distribution-level customer-owned DERs are used locally while delivering cost benefits to the consumers and the prosumers. Simulation studies performed on a 48-home smart community system showed that the proposed approach can be effectively used for optimal sharing of energy from customer-owned DERs with other consumers within the community and with the upstream distribution grid while taking full consideration of the network voltage constraints.

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