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Rajaei, Ali; Fattaheian-Dehkordi, Sajjad; Fotuhi-Firuzabad, Mahmud; Lehtonen, Matti
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Transactive Energy Management Framework for Active Distribution Systems

Ali Rajaei
Sharif University of
Technology
Tehran, Iran
alirajaei95@gmail.com

Sajjad Fattaheian-Dehkordi
Aalto University
Sharif University of
Technology
sajjad.fattaheian@gmail.com

Mahmud Fotuhi-Firuzabad
Sharif University of
Technology
Tehran, Iran
fotuhi@sharif.edu

Matti Lehtonen
Aalto University
Espoo, Finland
matti.lehtonen@aalto.fi

Abstract—Distribution networks are undergoing a fundamental transition due to the expansion of flexible resources as well as renewable energy sources in the system. In this regard, multi-agent structures are developed in modern distribution systems to facilitate the independent operation of local resources. Nevertheless, the non-coordinated operation of independent agents could result in a deviation between the real-time power purchased from transmission network and the day-ahead scheduling. Consequently, this paper aims to provide a novel framework that enables the decentralized management of multi-agent distribution systems, while coordinating the real-time power request and the day-ahead scheduling. In this regard, the alternating direction method of multipliers (ADMM) is taken into account to facilitate the decentralized operation of the multi-agent systems. Furthermore, transactive control signals are employed to exploit the real-time operational scheduling of independent agents in order to minimize the deviation of real-time power exchange and the day-ahead scheduling. Finally, the developed methodology is implemented on the IEEE 37-bus test system in order to analyze the effectiveness of the proposed approach for the operational management of multi-agent distribution systems.

Index Terms—Transactive Energy, multi-agent system, distribution system, ADMM, resource scheduling, energy management, flexible resources.

I. INTRODUCTION

With the advent of new smart grid technologies as well as the increasing penetration of distributed energy resources (DERs), electric power distribution systems are undergoing a fundamental transition from passive conventional systems into active modern multi-agent systems [1]. In these systems, each agent of the system would independently operate its local resources while providing operational flexibility services for the system utilities. In this respect, new management techniques should be employed by system operators in order to coordinate the operation of independent agents with the aim of improving the security and flexibility of the system.

In recent years, the concept of transactive energy (TE) has been introduced as a promising solution to provide the dynamic supply-demand balance in multi-agent systems in a reliable and efficient manner [2-4]. TE facilitates the participation of independent prosumers in local electricity markets using a set of economic-based mechanisms and value-driven signals [5]. Authors in [2] have proposed a TE framework for the distribution system operator to act as a mediator between

distribution system and transmission system. However, the proposed framework overlooks an accurate modeling of power flow as well as the distributed nature of modern distribution systems with multi-agent structures. In [6], a TE scheme is developed to facilitate negotiations among microgrids to optimize their power exchanges. Moreover, a day-ahead operational management framework is devised in [7]; which utilizes distribution locational marginal price (DLMP) as a TE control signal. Note that the devised framework in [7] considers linearized AC-OPF and strives to deal with the uncertainty of renewable energy sources (RESs). Furthermore, authors in [8] have reviewed several approaches to integrate small-scale DERs into distribution networks based on the TE concept. In [9], a peer-to-peer energy trading framework is proposed taking into account the technical constraints of the distribution network. In particular, the impact of peer-to-peer transactions on the network is estimated based on the sensitivity coefficients.

The above discussed operational management frameworks rely on a central entity to coordinate the operation of independent agents, which could raise privacy issues, communication complexity, and scalability problems in modern power systems [10]. In this regard, distributed algorithms such as the alternating direction method of multipliers (ADMM) have been utilized in recent works to conduct the operational management of power systems in a distributed manner. In this context, an ADMM-based algorithm is proposed in [11] to solve the optimal power flow (OPF) problem in a distributed fashion. Moreover, an ADMM-based operational optimization is developed in [10] by utilizing the TE concept in order to facilitate bilateral energy transactions between distribution system's agents. The authors in [12] have employed stochastic programming to cope with the intermittency and uncertainty associated with RESs. However, the central operator of the system is considered as the responsible party for generating the stochastic scenarios of RESs. Furthermore, ADMM concept is employed in [13] for the distributed energy management of multi-agent distribution systems, while robust optimization technique is taken into account in local optimization models to address the uncertainty of local resources.

Despite various studies which have been conducted on coordinated energy management of multi-agent distribution systems; to the best of authors' knowledge, employing TE in a

fully distributed manner to enable coordinated operation of independent agents with bulk power system has not yet been fully investigated in previously proposed frameworks. Motivated by the aforementioned points, this paper aims to develop a distributed TE-based market framework to optimally manage multi-agent distribution systems considering the real-time operational condition of the system. In this respect, TE signals are derived based on the electricity prices at day-ahead and real-time markets, as well as the real-time operational condition of the distribution grid. Moreover, the ADMM algorithm is taken into account to provide a distributed operational management framework which addresses scalability and privacy concerns. Based on the above discussions, distribution system operator (DSO) as the mediator entity between distribution and transmission systems strives to coordinate the operation of independent agents taking into account the TE concept. Consequently, in the proposed scheme, agents would independently optimize the operation of their local resources considering the TE signals which represent the price of energy exchange with the distribution grid.

The rest of this paper is structured as follows. In Section II, the system modeling, the proposed TE management framework, the ADMM-based coordination scheme, and the proposed TE control signal are provided. Section III presents the numerical results of implementing the proposed TE management framework on the modified IEEE 37-bus system, while Section IV concludes the paper.

II. METHODOLOGY

A. System Modeling

Figure 1 represents the model of a distribution system with multi-agent structure which is considered in the proposed scheme for energy management in this paper. As can be traced, each node of the system could encompass several DERs which are independently operated by agents at that node. Moreover, the resources at each node receive a TE control signal that is associated with the energy price at the respective node. In this regard, the coordinator entity at each node would calculate the TE control signal at the respective node and announce it to the independent agents of that node. It is noteworthy that various DERs including flexible load demands, conventional distributed generation (CDG) units, energy storage systems (ESSs), and photovoltaic (PV) units are considered in this study.

B. The Proposed Transactive Operational Framework for Multi-Agent Distribution Systems

As mentioned, the proposed scheme aims to provide a TE market framework to coordinate the operation of independent

agents in the system. In this respect, the DSO acts as a mediator between the wholesale electricity market in the transmission system and independent agents in the distribution system. In this respect, the DSO bids in the day-ahead wholesale electricity market to supply the customers based on the forecasted operational data. However, due to independent operation of agents and the uncertainty of local resources, a control signal should be employed to efficiently coordinate the operation of agents considering the day-ahead and real-time electricity prices. In this regard, during the day, the TE signals for each time interval are calculated based on the cleared electricity price from the day-ahead market and are announced to the agents. In other words, due to the operational uncertainties in the real-time operation of the agents, the real-time determined power exchange with the transmission system may deviate from the scheduled power exchange according to the submitted bid. In this regard, the DSO could adjust the TE signals to fully exploit the operational flexibility of local resources in order to provide the dynamic supply-demand balance at the minimum cost. It is noteworthy that the DSO could alter the TE signal at the substation node to the limit that reaches the price of real-time balancing market of transmission system; if the supply-demand balance is not yet provided, the DSO has to compensate the deviation from the real-time balancing market.

Based on the proposed scheme, the agents would independently schedule their generation/consumption according to the TE signal and the real-time operational conditions of the system. Therefore, the power injection of each node of the network is determined by its respective coordinator entity based on the announced generation/consumption of respective agents of that node. Furthermore, an ADMM-based OPF problem would be conducted, which determines the operational condition of the network, as well as the power exchange between the distribution and transmission network. It is noteworthy that the ADMM-based OPF problem is solved by communicating non-critical information among adjacent nodes and solving sub-problems at each node in an iterative manner. The step-wise flowchart of the proposed algorithm for distributed TE management of multi-agent distribution systems is presented in Fig. 2.

C. Distributed Operational Management of the Distribution Network

1) Optimal Power Flow

The operational management of the distribution grid could be modeled as an OPF problem. In this regard, it is assumed that the distribution grid is composed of a set of nodes shown by N and a set of lines represented by Ω . Moreover, the common coupling point of distribution and transmission network is considered as node 0; while, the remaining nodes $i \in N \setminus \{0\}$ are considered to have a unique parent node shown by A_i and a set of child nodes represented by C_i . In this respect, the unique line that connects node i and A_i is denoted by line i . Finally, the OPF problem for a radial distribution network considering the SOCP relaxation [13-15] is modeled as follows:

Fig. 1 The model of a distribution system with multi-agent structure.

Fig. 2 Flowchart of the proposed distributed TE management framework.

$$\min \sum_{i \in T} LMP_i P_i^{TS} \quad (1a)$$

s.t.

$$v_{A,i,t} = v_{i,t} + 2(r_i PL_{i,t} + x_i QL_{i,t}) + \ell_{i,t} (r_i^2 + x_i^2), \quad i \in \Omega \quad (1b)$$

$$PL_{i,t} + p_{i,t} = \sum_{j \in C_i} (PL_{j,t} + r_j \ell_{j,t}), \quad i \in N \quad (1c)$$

$$QL_{i,t} + q_{i,t} = \sum_{j \in C_i} (QL_{j,t} + x_j \ell_{j,t}), \quad i \in N \quad (1d)$$

$$PL_{i,t}^2 + QL_{i,t}^2 \leq v_{i,t} \ell_{i,t}, \quad i \in \Omega \quad (1e)$$

The objective function (1a) strives to minimize the cost of purchasing power from transmission system over the scheduling horizon T . Respectively, the power purchased from transmission network is represented by P_i^{TS} ; while the price of purchased power is shown by LMP_i . Moreover, $PL_{i,t}$, $QL_{i,t}$, and $\ell_{i,t}$ denote active power flow, reactive power flow, and squared current magnitude of line i , while $v_{i,t}$, $p_{i,t}$, and $q_{i,t}$ are used to show the squared voltage magnitude, active power injection, and reactive power injection of node i , respectively. The operational constraints of SOCP-relaxed DistFlow model are represented in (1b)-(1e).

2) ADMM-based OPF of Distribution Grid

Recently, ADMM concept is employed by several research works in order to operate power systems in a distributed manner. In this regard, a consensus-based ADMM algorithm [16] is taken into account in this paper to model the distributed management of multi-agent distribution systems. Respectively, the coordinator entities would exchange operational information in the context of ADMM algorithm to distributedly solve the OPF problem in the distribution system. In this regard, the OPF problem (1) could be represented as follows:

$$\min_x \sum_{i \in N} f_i(x_i) \quad (2a)$$

$$\text{s.t. } \sum_{j \in N_i} A_{i,j} x_j = 0 \quad i \in N \quad (2b)$$

where for each $i \in N$, N_i is a set of adjacent coordinator entities, x_i presents a vector of decision variables, and $A_{i,j}$ is a constant matrix that shows operational constraints that couple local variables x_i together. It is assumed that in case of problem (1), $x_i := \{v_i, \ell_i, PL_i, QL_i, p_i, q_i\}$. In order to apply the consensus-based ADMM, the optimization model of each coordinator entity should be decoupled from its adjacent coordinator entities. Based on this objective, a set of auxiliary variables $z_{j,i}$ are defined, which represents the duplicate of x_j observed by agent i . Therefore, (2) could be reformulated as follows:

$$\min_{x,z} \sum_{i \in N} f_i(x_i) \quad (3a)$$

$$\text{s.t. } \sum_{j \in N_i} A_{i,j} z_{j,i} = 0 \quad i \in N \quad (3b)$$

$$z_{j,i} = x_j \quad i \in N, j \in N_i \quad (3c)$$

Taking into account a Lagrangian multiplier $\lambda_{i,j}$ for (3c) and a positive constant ρ , the augmented Lagrangian model could be determined as follows:

$$L_\rho(x, z, \lambda) := \sum_{i \in N} \left(f_i(x_i) + \sum_{j \in N_i} \lambda_{i,j} (x_i - z_{j,i}) + \frac{\rho}{2} \|x_i - z_{j,i}\|_2^2 \right) \quad (4)$$

In this regard, the ADMM algorithm could be conducted in a three-step process, where variables could be updated at each iteration k as follows:

$$x^{k+1} = \arg \min_x L_\rho(x, z^k, \lambda^k) \quad (5a)$$

$$z^{k+1} = \arg \min_z L_\rho(x^{k+1}, z, \lambda^k) \quad (5b)$$

$$\lambda^{k+1} = \lambda^k + \rho(x^{k+1} - z^{k+1}) \quad (5c)$$

Finally, the following criteria are defined to assure the convergence of the ADMM procedure:

$$r^k := \|x^k - z^k\| \quad (6a)$$

$$s^k := \rho \|z^k - z^{k-1}\| \quad (6b)$$

where r^k and s^k respectively show the primal and dual residuals. It is noteworthy that the complete formulation of the ADMM-based OPF is presented in [11].

D. The Proposed Transactive Control Signal

In the proposed framework, each independent agent receives the TE signal from the coordinator entity at the respective node as the price of energy exchange at that node. Respectively, the agent would schedule its local resources based on the received TE signal. In this regard, a novel approach is devised in this paper in order to determine the TE signals within the ADMM algorithm conducted by coordinator entities. In particular, the concept of DLMP is taken into account to determine the TE signal at each node of the network. Furthermore, the LMP is assumed as a base value for exchanging energy at node 0, and the TE signals for the remaining nodes are determined by their coordinator entity in the context of the ADMM algorithm. In this respect, besides the information exchanges in the standard ADMM algorithm, coordinator agents would exchange the information of their respective TE signal in the developed approach. It is noteworthy that the price of energy at node i is proportional to the price of energy at its parent node and the

cost of power loss in the connecting line, which could be represented as follows:

$$\psi_{i,t}^{TE} = \psi_{A_i,t}^{TE} \left(1 + \frac{\partial Loss_{i,t}}{\partial PL_{i,t}} \right), i \in N \setminus \{0\} \quad (7)$$

where $\psi_{i,t}^{TE}$ represents the TE signal at node i , and $\partial Loss_{i,t} / \partial PL_{i,t}$ shows the additional loss in the line i due to a marginal power increase in node i . In this regard, the active power loss in line i could be calculated as below:

$$Loss_{i,t} = \frac{r_i (PL_{i,t}^2 + QL_{i,t}^2)}{v_{i,t}}, i \in \Omega \quad (8)$$

As a result, a marginal increase in power flow PL_i would result in the additional active power losses as below:

$$\Delta Loss_{i,t} \Big|_{PL_{i,t} \rightarrow PL_{i,t} + \Delta PL_{i,t}} = \frac{2r_i \cdot PL_{i,t} \cdot \Delta PL_{i,t}}{v_{i,t}}, i \in \Omega \quad (9)$$

In this regard, by re-arranging (9) and then substituting it in (7), the TE signal associated with the node i could be derived as below:

$$\psi_{i,t}^{TE} = \psi_{A_i,t}^{TE} \left(1 + \frac{2r_i \cdot PL_{i,t}}{v_{i,t}} \right), i \in N \setminus \{0\} \quad (10)$$

As a result, the proposed framework enables coordinator entities to determine the TE signals based on the operational variables which are calculated during the ADMM process. Note that in the proposed framework, the DSO would update the TE signals at the substation node (i.e. $\psi_{i=0,t}^{TE}$) based on the deviation of the real-time power exchange from the scheduled value in the day-ahead market as follows:

$$\psi_{i,t}^{TE} = \psi_{i,t}^{TE,old} \cdot \alpha \cdot (P_t^{TS,RT} - P_t^{TS,Sch}), i \in N \setminus \{0\} \quad (11)$$

where $\psi_{i,t}^{TE,old}$ represent the TE signal at the last iteration, while $P_t^{TS,RT}$ and $P_t^{TS,Sch}$ respectively show the real-time and the day-ahead amount of power purchased from transmission system. Furthermore, α is a coefficient determined by the DSO to update TE signals at each iteration.

E. Operational Scheduling of Independent Agents

As mentioned earlier, each agent of the system would independently optimize the scheduling of its resources taking into account the received TE signal from the respective coordinator entity. In this respect, the operational optimization conducted by each agent connected to node $i \in N$ could be modeled as follows:

$$\min \sum_{i \in T} \psi_{i,t}^{TE} \cdot p_{i,t}^{ex} + \sum_{i \in T} g_i(p_{i,t}^{ex}) \quad (12a)$$

s.t.

$$\text{The Operational constraints of local resources.} \quad (12b)$$

where $p_{i,t}^{ex}$ indicates the amount of power exchange between the agent and the distribution grid; whereas g_i is the cost function of the agent based on its local resources.

It is noteworthy that the detailed formulation of operational constraints of the local DERs (i.e., flexible load demands, CDG units, ESSs, and PV units) which are considered in this study are presented in [13].

III. NUMERICAL RESULTS

In this section, the proposed TE management framework is implemented on the modified IEEE 37-bus distribution system [17]. In this study, various DERs including flexible load demands, CDG units, ESSs, and PV units are taken into account. The operational characteristics of DERs, and LMP values are adopted from [13, 18] and presented in [19]. The topology of the 37-bus distribution network is shown in Fig. 3. Moreover, it is assumed that the buying/selling price at the real-time balancing market is 20% higher/lower than the price of the day-ahead market. It is noteworthy that the DSO updates the TE signal at the substation node $\psi_{i=0,t}^{TE}$ with $\alpha = 1\%$ steps at each TE iteration.

The proposed methodology enables the DSO to exploit the real-time operational scheduling of agents based on the scheduled power exchange in the day-ahead market as well as the energy price at the real-time market. In this respect, Fig. 4 presents the power purchased from transmission system per TE iterations in three different time slots. In this regard, the dotted lines show the scheduled value at the day-ahead market. However, as can be traced, based on the operational scheduling of the system agents, the real-time power exchange between distribution and transmission system would deviate from the scheduled value. In this respect, in order to minimize the operational cost of the system, the DSO would alter the TE signal at the substation node which would also update the TE signals at system nodes. In other words, in case the real-time power value is higher/lower than the scheduled value, the DSO would increase/decrease the TE signals in order to reduce/increase the power exchanges of agents, and minimize the gap between the real-time value and scheduled value. In this respect, Fig. 5 shows the TE signal values per TE iterations for the three time slots. Regarding the obtained results, in time slots that the real-time power value is higher/lower than the scheduled value, the $\psi_{i=0,t}^{TE}$ is increased/decreased. Note that the

DSO would continue to update the $\psi_{i=0,t}^{TE}$ values until either it reaches the price of the real-time market or the existing gap reaches a predefined threshold. It is noteworthy that the proposed scheme would eventually facilitate activating the operational flexibility service from the local resources operated by independent agents in order to minimize the deviation of real-time power exchange between the distribution and transmission system from the day-ahead scheduling. Accordingly, the proposed approach would minimize the operational cost of the system, while improving the flexibility and security of the system.

Fig. 3 The modified IEEE-37 bus test system.

As mentioned earlier, in the developed framework, coordinator entities would exchange information with their adjacent entities in order to solve the OPF problem and determine the amount of power purchased from transmission system for each TE iteration. In this respect, Fig. 6 represents the purchased power from the transmission system per ADMM iteration at three time intervals. Moreover, Fig. 7 shows the convergence results of the developed ADMM algorithm. As can be traced in this figure, the obtained result show great performance of the ADMM algorithm, as the iterative value of P_t^{TS} has successfully converged to its optimal value, while the primal and dual residuals have reached negligible values.

Fig. 4 Power purchased from transmission system per TE iterations.

Fig. 5 TE signal at the substation node per TE iterations.

Fig. 6 Power exchange between distribution and transmission system at 14:00, 18:00, 21:00 over ADMM iterations.

Fig. 7 Primal and dual residuals per ADMM iteration.

Fig. 8 The primary load profile, scheduled load profile, ESS energy profile, conventional DG output of agents connected to node 13.

As discussed earlier, the coordinator entity at each node would calculate the TE signal and announce it to the independent agents of that node. Respectively, the agents would optimally schedule their local resources based on the received TE signal. In this regard, Fig. 8 shows the power scheduling of local resources at node 13. Regarding the acquired result, the load profile of the flexible demand is shifted to time slots that the value of $\psi_{i,t}^{TE}$ is lower. Moreover, in order to maximize the profit, the power production of the CDG unit is increased in time slots that the value of $\psi_{i,t}^{TE}$ is higher. Finally, the ESS unit is charged/discharged during low/high $\psi_{i,t}^{TE}$ values.

IV. CONCLUSION

This paper strives to develop a decentralized TE management framework in order to optimize the operational management of multi-agent distribution systems, while taking into account the distributed and independent nature of the system. In this respect, transactive control signals are employed to minimize the potential deviation of the real-time power exchange between the distribution and transmission system from the day-ahead scheduling. Moreover, ADMM algorithm is deployed in the proposed framework in order to enable the distributed operation of the multi-agent system. In this regard, the developed scheme would address the privacy concerns of independent prosumers. Finally, the proposed TE management framework is applied on the IEEE 37-bus test network which demonstrates its applicability and efficiency in the decentralized operational management of multi-agent systems, while improving the flexibility and security of the system.

REFERENCES

- [1] S. Fattaheian-Dehkordi, M. Tavakkoli, A. Abbaspour, M. Fotuhi-Firuzabad, and M. Lehtonen, "An Incentive-based Mechanism to Alleviate Active Power Congestion in a Multi-agent Distribution System," *IEEE Transactions on Smart Grid*, 2020.
- [2] Y. K. Renani, M. Ehsan, and M. Shahidehpour, "Optimal transactive market operations with distribution system operators," *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 6692-6701, 2017.
- [3] S. Fattaheian-Dehkordi, A. Abbaspour, and M. Lehtonen, "Electric vehicles and electric storage systems participation in provision of flexible ramp service," in *Energy Storage in Energy Markets*: Academic Press, 2021.
- [4] S. Fattaheian-Dehkordi, M. Tavakkoli, A. Abbaspour, M. Fotuhi-Firuzabad, and M. Lehtonen, "Distribution Grid Flexibility-ramp Minimization using Local Resources," in *2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, 2019, pp. 1-5.
- [5] Z. Liu, Q. Wu, S. Huang, and H. Zhao, "Transactive energy: A review of state of the art and implementation," in *2017 IEEE Manchester PowerTech*, 2017, pp. 1-6: IEEE.
- [6] S. A. Janko and N. G. Johnson, "Scalable multi-agent microgrid negotiations for a transactive energy market," *Applied energy*, vol. 229, pp. 715-727, 2018.
- [7] M. N. Faqiry, L. Edmonds, H. Wu, and A. Pahwa, "Distribution locational marginal price-based transactive day-ahead market with variable renewable generation," *Applied Energy*, vol. 259, p. 114103, 2020.
- [8] J. Guerrero, D. Gebbran, S. Mhanna, A. C. Chapman, and G. Verbič, "Towards a transactive energy system for integration of distributed energy resources: Home energy management, distributed optimal power flow, and peer-to-peer energy trading," *Renewable and Sustainable Energy Reviews*, vol. 132, p. 110000, 2020.
- [9] J. Guerrero, A. C. Chapman, and G. Verbič, "Decentralized P2P energy trading under network constraints in a low-voltage network," *IEEE Transactions on Smart Grid*, vol. 10, no. 5, pp. 5163-5173, 2018.
- [10] J. Li, C. Zhang, Z. Xu, J. Wang, J. Zhao, and Y.-J. A. Zhang, "Distributed transactive energy trading framework in distribution networks," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 7215-7227, 2018.
- [11] Q. Peng and S. H. Low, "Distributed optimal power flow algorithm for radial networks, I: Balanced single phase case," *IEEE Transactions on Smart Grid*, vol. 9, no. 1, pp. 111-121, 2016.
- [12] M. Bazrafshan and N. Gatsis, "Decentralized stochastic optimal power flow in radial networks with distributed generation," *IEEE Transactions on Smart Grid*, vol. 8, no. 2, pp. 787-801, 2016.
- [13] A. Rajaei, S. Fattaheian-Dehkordi, M. Fotuhi-Firuzabad, M. Moeini-Aghtaie, and M. Lehtonen, "Developing a Distributed Robust Energy Management Framework for Active Distribution Systems," *IEEE Transactions on Sustainable Energy*, pp. 1-1, 2021.
- [14] M. Farivar and S. H. Low, "Branch flow model: Relaxations and convexification—Part I," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 2554-2564, 2013.
- [15] F. Kamrani, S. Fattaheian-Dehkordi, A. Abbaspour, M. Fotuhi-Firuzabad, and M. Lehtonen, "Flexibility-based operational management of a microgrid considering interaction with gas grid," *IET Generation, Transmission & Distribution*, 2021.
- [16] S. Boyd, N. Parikh, and E. Chu, *Distributed optimization and statistical learning via the alternating direction method of multipliers*. Now Publishers Inc, 2011.
- [17] W. H. Kersting, "Radial distribution test feeders," *IEEE Transactions on Power Systems*, vol. 6, no. 3, pp. 975-985, 1991.
- [18] Available at: <https://www.pjm.com/markets-andoperations/energy.aspx>.
- [19] Available at: https://drive.google.com/file/d/1Oou_cjSAJJ-IVRoLQC0zDB8AzWpfI9A/view?usp=sharing.