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RESEARCH ARTICLE

Modeling a Local Electricity Market for Transactive Energy Trading of Multi-Aggregators

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ABSTRACT The present article aims at modeling a day-ahead local electricity market (DA LEM) for transactive energy trading at the distribution level. In this regard, a wide range of distributed energy resources (DERs) in the form of multiple aggregators (AGs) participates in the DA LEM in order to trade energy with the distribution system operator (DSO), the operator of the market. On the other hand, the DSO, as the owner of the system, has the responsibility to procure the required energy of its customers with respect to the technical constraints of the distribution network. To settle the designed local market, a Stackelberg game-based approach is exploited in this research work. In the raised Stackelberg scheme, the leader of the game, the DSO, seeks to maximize its expected profit, while followers of the game, DER AGs, tend to minimize their operating costs. Ultimately, to evaluate the proposed framework, a typical case study is implemented on a modified IEEE-33 bus test system.

INDEX TERMS DER aggregator, distribution system operator, local electricity market, Stackelberg game, transactive energy trading.

NOMENCLATURE

Acronyms:

AG	Aggregator
BS	Battery Storage
DA	Day-Ahead
DER	Distributed Energy Resource
DG	Dispatchable Generator
DSO	Distribution System Operator
LEM	Local Electricity Market
PV	Photovoltaic System
WT	Wind Turbine
WEM	Wholesale Electricity Market

Sets and Indices:

$b \in B$	Set of BSs
$i \in I$	Set of DGs
m	Index in modeling the DGs' minimum up / down time
$n \in N$	Set of AGs
$l \in L$	Set of Loads
$t \in T$	Set of Hours
$v \in V$	Set of PVs
$w \in W$	Set of WTs
α, β	Set of Buses
Λ	Set of Lines
$\Omega_{\times}$	Set of $\times$ connected to set of buses
$\Xi^{n^{th} Follower}$	Set of nth follower's decision variables
Ξ^{Leader}	Set of leader's decision variables

Parameters:

a_{DSO}^{DG}, b_{DSO}^{DG}	Linear cost coefficients of DSO's DGs
$b_{\alpha\beta}$, $g_{\alpha\beta}$	Susceptance / conductance of line $\alpha\beta$
c_{AG}^{DG}	Marginal generation cost of AGs' DGs

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dt_{DSO}^{DG}, ut_{DSO}^{DG}	Parameters in modeling the DGs' minimum down / up time
$E_{AG}^{BS,ini}$	Initial energy stored in AGs' BSs
$E_{AG}^{BS,max}$, $E_{AG}^{BS,min}$	Maximum / minimum energy stored in AGs' BSs
mdt_{DSO}^{DG}, mut_{DSO}^{DG}	Minimum down / up time of DSO's DGs
$P_{AG}^{BS,ch,max}$, $P_{AG}^{BS,ch,min}$	Maximum / minimum charge power of AGs' BSs
$P_{AG}^{BS,dch,max}$, $P_{AG}^{BS,dch,min}$	Maximum / minimum discharge power of AGs' BSs
$P_{AG}^{DG,ini}$	Initial generation power of AGs' DGs
$P_{AG}^{DG,max}$, $P_{AG}^{DG,min}$	Maximum / minimum generation power of AGs' DGs
$P_{DSO}^{DG,max}$, $P_{DSO}^{DG,min}$	Maximum / minimum generation power of DSO's DGs
$P_{DSO}^{Load,F}$	Forecasted demand of DSO
$P_{exch}^{LEM,DA,max}$	Maximum exchange power in DA LEM
$P_{AG}^{PV,F}$, $P_{DSO}^{PV,F}$	Forecasted generation power of AGs / DSO's PVs
$P_{AG}^{WT,F}$, $P_{DSO}^{WT,F}$	Forecasted generation power of AGs / DSO's WTs
$P_{\alpha\beta}^{max}$	Maximum capacity of line $\alpha\beta$
RD_{AG}^{DG}, RU_{AG}^{DG}	Ramp down / up rate of AGs' DGs
sdc_{DSO}^{DG}, suc_{DSO}^{DG}	Shut down / start up price of DSO's DGs
V_{nom}	Nominal voltage
λ^{Cus}	Price of DSO's sold energy to customers
$\lambda^{LEM,DA,max}$	Maximum amount of energy price in DA LEM
$\lambda^{WEM,DA}$	Energy price in DA WEM
$\eta_{AG}^{BS,ch}$, $\eta_{AG}^{BS,dch}$	Charge / discharge efficiency of AGs' BSs
ε	Maximum voltage variation

Variables:

E_{AG}^{BS}	Energy stored in AGs' BSs
$P_{AG}^{BS,ch}$	Charge power of AGs' BSs
$P_{AG}^{BS,dch}$	Discharge power of AGs' BSs
P_{AG}^{DG}	Generation power of AGs' DGs
P_{DSO}^{DG}	Generation power of DSO's DGs
$P_{exch}^{LEM,DA}$	Exchange power in DA LEM
$P_{exch}^{WEM,DA}$	Exchange power in DA WEM
SDC_{DSO}^{DG}	Shut down cost of DSO's DGs
SUC_{DSO}^{DG}	Start up cost of DSO's DGs
V	Voltage magnitude
ΔV	Voltage deviation
$\lambda^{LEM,DA}$	Energy price in DA LEM
λ, μ	Dual variables
θ	Voltage angle

Binary Variable:

U_{DSO}^{DG}	Binary variable for operation of DSO's DGs
Z	Binary variable in Big-M method

I. INTRODUCTION

Over the past few years, the high penetration of real DERs, including generation units, as well as virtual DERs, including storage units and demand response programs, aligned with the growing development of smart technologies, has led to the transformation of centralized electricity systems into decentralized and smart networks [1]. These trends have challenged the conventional methods of supplying and selling electricity. That is because, for the effective integration of DERs and benefit from their provided advantages, the implementation of new control and operational layers at the distribution level is highly required. Recently, various solutions have been raised to implement these layers and exploit these emerging resources. One of the most important and practical ways is to create a new platform called the local electricity market (LEM) [2]. In different references, several definitions have been provided for LEMs. For instance, in [3], the LEM is considered as a marketplace for the energy exchange between producers and consumers at variable prices. In [4], the LEM is based on a local community in which a variety of prosumers, producers, and consumers are engaged to serve more sustainable energy on involved members. In [5], the LEM is taken into account as a market platform for exchanging locally produced electricity between residential agents within a community. Finally, in [6], the LEM is interpreted as transactive energy management based on market rules and regulations. Transactive Energy is a framework that enables the integration of the individual preferences and resource characteristics of prosumers in the energy management program [7]. The entire mentioned definitions for the LEM contain two common features: engagement of customers as well as the localization of the market [8]. Engagement of customers indicates that customers are active players in the LEM decision-making process. Furthermore, localization of the market emphasizes on both the position of customers in the formation of the LEM and the transactive energy exchange at the distribution level.

In general, the development of LEMs presents numerous advantages to different stakeholders [9]. In this regard, the LEM participants are able to consume their generated energy and share their excess with the DSO or with other customers on a local platform. Hence, customers strengthen their position as effective and active players in the LEM. Moreover, local energy trading not only reduces voltage fluctuations and losses in transmission and distribution lines but also increases the stability and reliability of the whole power system. On the other hand, through the integration and coordination of small-scale DERs in the LEM framework, a variety of services including energy sales to different markets as well as voltage and frequency control of distribution networks can be provided. To achieve these goals, designing a proper model for the LEM is very essential. Nonetheless, since the LEM needs to address conflicting objectives, the procedure of designing an efficient framework for these types of markets is a challenging matter [10]. Accordingly, several studies have been carried out in the most recent years in order to model the LEM. In the following, some of these research works are highlighted:

For coordination of the DSO with multiple microgrids, a local market-based platform has been provided in [11]. In this framework, the DSO attempts to promote its profit, whereas microgrid owners try to diminish their operating costs. This research has proposed a game-based approach to settle the considered LEM. For the optimal operation of distribution networks, a DA LEM has been modeled in [12], in which various prosumers, producers, and consumers are administered at the local level by participating in the market. The designed LEM is cleared by the DSO with the aim of social welfare maximization and satisfying the technical constraints of the system. In [13], a LEM has been provided for allowing small players, including microgrids, to participate in fully transactive energy systems. In this context, a two-stage stochastic programming method has been exploited to solve the market transactions within this framework. To organize a variety of real and virtual DERs at the distribution level, a DA LEM has been provided in [14]. To this end, an energy services company, as the operator of the LEM, manages the entire participants in a coordinated manner to maximize its expected profit. A feeder-based market has been proposed in [15] for energy trading at the local level. In this market, the distribution system is divided into several LEMs with a limited number of players, and in each market, producers and consumers exchange power in a way to maximize their social welfare. In this study, the feeder-based market is settled in two-step and by utilizing the primal-dual decomposition method. In [16], an architecture of the LEM has been suggested for peer-to-peer energy exchange between a group of prosumers equipped with various DERs in a transactive environment. In this study, a heuristic-based algorithm has been utilized to minimize the electricity bill of market participants. A LEM has been modeled in [17], in which the DSO and several microgrids are able to interact with one another in this platform. This study has implemented a game-based method to not only set the power trading in the LEM but also evaluate its impact on the wholesale market.

A two-step LEM has been designed in [18] for peer-to-peer energy and uncertainty trading among PV owners and consumers with flexible demands. The clearing mechanism of the considered market is based on the unilateral auction with the aim of maximizing the production and flexibility capacities of PVs and consumers, respectively. A LEM has been presented in [19] for transactive energy trading among several microgrids and the DSO at the distribution level. In this market, the DSO tends to reduce its operating costs, while each microgrid owner tries to increase its expected profit. Hence, to clear the LEM, a game-based method has been used in this study. To provide an appropriate marketplace for microgrids' interaction with one another, a DA LEM has been designed in [20]. For clearing the considered market, a bi-level programming approach has been utilized, in which the operating cost of each microgrid is minimized at the upper level, and the social welfare of the entire players is maximized at the lower level. A distributed optimization approach has been exploited in [21] for clearing a grid-connected DA LEM while preserving the privacy of the entire market participants. The purpose of this study is to reduce the cost of energy procurement in the presence of the distribution network's technical constraints. A LEM has been suggested in [22] to support peer-to-peer energy exchange among multiple prosumers in a transactive framework. In this article, the impact of peer-to-peer trading on the technical constraints of the distribution system, including voltage fluctuations, power losses, etc., has been investigated. A DA LEM has been designed in [23] to manage peer-to-peer transactions among different kinds of prosumers integrated within a local community. The modeled market is settled from a central operator's point of view by a centralized method in order to minimize the total operating costs of the community.

To get the maximum benefit from the high penetration of electric vehicles at distribution systems, a DA LEM has been exploited in [24]. In this regard, the market, which is cleared by a centralized method, seeks to determine the optimal power transaction among prosumers equipped with DERs and electric vehicles. The objective function of the LEM operator is to minimize the operating cost of the community. To enable peer-to-peer local energy sharing and trading among multiple consumers in a community, a bi-level programming approach has been suggested in [25]. Accordingly, the community, which is the owner of several flexible units, seeks to maximize its profit at the upper level of the problem, while consumers attempt to minimize their utility bills at the lower level. A market-based framework that handles the energy trading between the DSO and several microgrids at the local distribution level has been proposed in [26]. To this end, a two-level approach has been employed, in which, at the first level, the DSO sets the energy exchange price in a way to increase its earnings from the trading. At the second level, each microgrid operator is responsible for solving the optimal power flow problem to decrease both the generation cost as well as power loss of the system. Different types of auction-based algorithms for clearing LEMs have been compared with one another in [27]. The primary objective of this study is to satisfy the willingness to pay and preference of the market participants. A potential LEM has been modeled in [28] to facilitate the high deployment of DERs owned by residential customers at the distribution level. The LEM operator, as a central entity, minimizes the cost of importing power and maximizes the income from exporting power to the upstream grid in the presence of distribution network constraints. In the end, a local market-based platform has been provided in [29] for the interaction among the DSO and different types of AGs at the distribution level. In this study, to settle this interaction, a bi-level programming method has been executed.

Analyzing the above articles demonstrates that, normally, the LEM modeling has been implemented from a central operator's perspective, and independent financial identity has not been considered for the market participants. Indeed, the entire stakeholders are required to share all their information with the operator as passive players in the LEM. Thus, these works have not been able to raise practical solutions for establishing a competitive environment among the existing participants. On the other hand, the proposed models in these works have not provided a suitable platform for the coordination and cooperation of decentralized DERs and getting fully advantages from their provided services. Therefore, these works have not been able to properly assess the technical and operational constraints of the distribution system and manage the DSO's challenges in the presence of a wide range of DERs. Since the presented paper is conducted to handle the mentioned gaps, its primary contributions are as follows:

1. Integration of decentralized DERs in the multi-AG platform for the transactive energy trading with the DSO at the local level and dealing with technical challenges of the distribution system in the presence of an extensive amount of DERs.
2. Modeling a DA LEM and utilizing a Stackelberg game-based approach to consider the selfish behavior of independent financial entities with distinguished objective functions in this market.

Table 1 clarifies the novelties and contributions of this article by comparing it with the reviewed research works.

TABLE 1. Taxonomy of the previous studies.

# Ref.	Competitive environment in the LEM	Technical constraints of the distribution system	Integration of decentralized DERs
[11]	✓	×	×
[12]	×	✓	×
[13]	×	×	×
[14]	×	×	×
[15]	×	×	✓
[16]	×	×	×
[17]	✓	✓	×
[18]	×	×	×
[19]	✓	✓	×
[20]	✓	×	×
[21]	×	✓	×
[22]	×	✓	×
[23]	×	×	×
[24]	×	×	×
[25]	✓	×	×
[26]	✓	✓	×
[27]	×	×	×
[28]	×	✓	×
This Paper	✓	✓	✓

II. METHODOLOGY

As previously mentioned, the key goal of this article is modeling a DA LEM to facilitate the participation of various small and medium-sized DERs in the energy management program of the DSO. To this end, it is assumed that different types of decentralized DERs are integrated into the multi-AG platform to trade energy with the DSO in the local marketplace as autonomous financial entities. On the contrary, the DSO, as the owner of the system, has the responsibility to procure the needed energy of its customers from the LEM and wholesale electricity market (WEM) as well as its local generation resources with respect to the technical constraints of the distribution network. Owing to the existence of independent players with distinguished objective functions in the modeled LEM, a Stackelberg game-theoretic method is utilized in this paper to settle the market [30]. The general scheme of the proposed framework is illustrated in Figure 1. While the DER AGs might be able to participate in other markets as well, their participation in the proposed LEM will be more beneficial for these players and the DSO. The reason is that since integrated DERs within the AGs are located at the distribution networks, these entities are required to utilize the DSO's infrastructure for their energy trading in different markets. However, the extensive presence of these resources and their independent energy exchange with other markets endanger power quality indices of distribution systems and cause voltage fluctuations, high power losses, etc. Accordingly, by exploiting the presented local market-based framework, not only the DER AGs can sell their energy to the DSO by considering their financial interests, but also the technical constraints of the distribution network are well satisfied.

In the raised Stackelberg scheme, the leader of the game, the DSO, seeks to maximize its expected profit, while followers of the game, DER AGs, tend to minimize their daily operating costs. In this procedure, LEM energy price signals, as well as market players' bids/offers, act as linking variables between the leader and followers. Accordingly, the DSO sends the energy price signal to the AGs at the local level. Based on the signal, AGs submit their offers/bids to the LEM operator. Afterward, the DSO optimizes its objective function and evaluates its expected benefit based on AGs' received offers/bids. For the sake of clarification, non-linking and linking decision variables of the leader and followers are stated in Figure 1 as well.

In the following of this section, objective functions and also technical constraints of players are mathematically formulated.

A. PROBLEM FORMULATION OF THE LEADER–DSO

The DSO, as the leader of the game, has the responsibility to provide its demand by taking part in the existing markets, the LEM and WEM, as well as utilizing its local dispatchable and non-dispatchable units. Hence, the objective function of the DSO is to promote its expected profit, which is defined as the difference between income and expenditure. The considered objective function is formulated mathematically in Eq (1).

$$\begin{aligned} &O.F_{Leader} \\ &= \mathrm{Max} \sum_{t \in T} \Bigg\{ \sum_{l \in L} P_{DSO}^{Load,F}(l,t)\,\lambda^{Cus}(t) \\ &\quad - P_{exch}^{WEM,DA}(t)\,\lambda^{WEM,DA}(t) \\ &\quad - \sum_{n \in N} P_{exch}^{LEM,DA}(n,t)\,\lambda^{LEM,DA}(t) \\ &\quad - \left(\begin{array}{l} \sum_{i \in I} a_{DSO}^{DG}(i)\,P_{DSO}^{DG}(i,t) + b_{DSO}^{DG}(i)\,U_{DSO}^{DG}(i,t) \\ + \mathrm{SUC}_{DSO}^{DG}(i,t) + \mathrm{SDC}_{DSO}^{DG}(i,t) \end{array} \right) \Bigg] \Bigg\}, \end{aligned} \tag{1}$$

The first term of Eq (1) is related to the DSO's revenue from selling energy to its customers. The second and third terms are related to the DSO's costs from participating in the WEM and interacting with DER AGs in the LEM platform, respectively. Finally, the last term is associated with the operating costs of the DSO's DGs.

This objective function is subject to a set of constraints as follows:

$$\begin{aligned} &P_{exch}^{WEM,DA}(t) \\ &\quad = \sum_{\beta : (\alpha,\beta) \in \Lambda} \left[\begin{array}{l} V_{nom}\left(\Delta V(\alpha,t) - \Delta V(\beta,t)\right) g_{\alpha\beta} \\ -V_{nom}^{2}\left(\theta(\alpha,t) - \theta(\beta,t)\right) b_{\alpha\beta} \end{array} \right], \\ &\qquad\qquad \forall \alpha = 1, t \end{aligned} \tag{2}$$

$$\begin{aligned} &\sum_{w : (w,\alpha) \in \Omega_W} P_{DSO}^{WT,F}(w,t) + \sum_{v : (v,\alpha) \in \Omega_V} P_{DSO}^{PV,F}(v,t) \\ &\quad + \sum_{i : (i,\alpha) \in \Omega_I} P_{DSO}^{DG}(i,t) - \sum_{l : (l,\alpha) \in \Omega_L} P_{DSO}^{Load,F}(l,t) \\ &\quad + \sum_{w : (w,\alpha) \in \Omega_W}^{W} \sum_{n \in N} P_{AG}^{WT,F}(n,w,t) \\ &\quad + \sum_{v : (v,\alpha) \in \Omega_V}^{V} \sum_{n \in N} P_{AG}^{PV,F}(n,v,t) \\ &\quad + \sum_{i : (i,\alpha) \in \Omega_I}^{I} \sum_{n \in N} P_{AG}^{DG}(n,i,t) \\ &\quad + \sum_{\beta : (\beta,\alpha) \in \Omega_B}^{I} \sum_{n \in N} \left(P_{AG}^{BS,dch}(n,b,t) - P_{AG}^{BS,ch}(n,b,t) \right) \\ &\quad = \sum_{\beta : (\alpha,\beta) \in \Lambda} \left[\begin{array}{l} V_{nom}\left(\Delta V(\alpha,t) - \Delta V(\beta,t)\right) g_{\alpha\beta} \\ -V_{nom}^{2}\left(\theta(\alpha,t) - \theta(\beta,t)\right) b_{\alpha\beta} \end{array} \right], \\ &\qquad\qquad \forall\, a \neq 1, t \end{aligned} \tag{3}$$

$$\begin{aligned} &-P_{\alpha\beta}^{max} \\ &\quad \le \left[\begin{array}{l} V_{nom}\left(\Delta V(\alpha,t) - \Delta V(\beta,t)\right) g_{\alpha\beta} \\ -V_{nom}^{2}\left(\theta(\alpha,t) - \theta(\beta,t)\right) b_{\alpha\beta} \end{array} \right] \le P_{\alpha\beta}^{max}, \\ &\qquad\qquad \forall\, (\alpha,\beta) \in \Lambda, t \end{aligned} \tag{4}$$

$$-\varepsilon\, V_{nom} \le \Delta V(\alpha,t) \le \varepsilon\, V_{nom}, \quad \forall \alpha, t \tag{5}$$

$$V(\alpha,t) = V_{nom} + \Delta V(\alpha,t), \quad \forall \alpha, t \tag{6}$$

$$-\pi \le \theta(\alpha,t) \le \pi, \quad \forall \alpha, t \tag{7}$$

$$0 \le \lambda^{LEM,DA}(t) \le \lambda^{LEM,DA,max}, \quad \forall t \tag{8}$$

$$\begin{aligned} &P_{DSO}^{DG,min}(i)\,U_{DSO}^{DG}(i,t) \\ &\quad \le P_{DSO}^{DG}(i,t) \le P_{DSO}^{DG,max}(i)\,U_{DSO}^{DG}(i,t), \quad \forall\, i, t \end{aligned} \tag{9}$$

$$\begin{aligned} &U_{DSO}^{DG}(i,t) - U_{DSO}^{DG}(i,t-1) \\ &\quad \le U_{DSO}^{DG}\left(i, t + \mathrm{ut}_{DSO}^{DG}(i,m)\right), \quad \forall i, t \end{aligned} \tag{10}$$

$$\begin{aligned} &U_{DSO}^{DG}(i,t-1) - U_{DSO}^{DG}(i,t) \\ &\quad \le 1 - U_{DSO}^{DG}\left(i, t + \mathrm{dt}_{DSO}^{DG}(i,m)\right), \quad \forall i, t \end{aligned} \tag{11}$$

$$\begin{aligned} &\mathrm{ut}_{DSO}^{DG}(i,m) \\ &\quad = \begin{cases} m, & m \le \mathrm{mut}_{DSO}^{DG}(i) \\ 0, & m > \mathrm{mut}_{DSO}^{DG}(i), \end{cases} \quad \forall\, i \end{aligned} \tag{12}$$

$$\begin{aligned} &\mathrm{dt}_{DSO}^{DG}(i,m) \\ &\quad = \begin{cases} m, & m \le \mathrm{mdt}_{DSO}^{DG}(i) \\ 0, & m > \mathrm{mdt}_{DSO}^{DG}(i), \end{cases} \quad \forall\, i \end{aligned} \tag{13}$$

$$\begin{aligned} &\mathrm{SUC}_{DSO}^{DG}(i,t) \\ &\quad \ge \mathrm{suc}_{DSO}^{DG}(i)\left[U_{DSO}^{DG}(i,t) - U_{DSO}^{DG}(i,t-1)\right], \\ &\qquad\qquad \forall\, i, t \end{aligned} \tag{14}$$

$$\begin{aligned} &\mathrm{SDC}_{DSO}^{DG}(i,t) \\ &\quad \ge \mathrm{sdc}_{DSO}^{DG}(i)\left[U_{DSO}^{DG}(i,t-1) - U_{DSO}^{DG}(i,t)\right], \\ &\qquad\qquad \forall\, i, t \end{aligned} \tag{15}$$

Eqs (2) and (3) are related to the power balance constraints of the DSO in the slack and other buses, respectively. In this study, a linear AC power flow has been exploited, as presented in [31]. In this regard, Eq (4) limits the amount of power flow in distribution lines. Eq (5) restricts the voltage deviation of buses. The voltage magnitude of each bus is represented by Eq (6). Eq (7) illustrates the limitation of voltage angle. Furthermore, energy price in the DA LEM is a non-negative variable that is limited by Eq (8). Operational constraints of the DSO's DGs are specified by Eqs (9) to (15). Accordingly, the generation power of DGs is limited by Eq (9). Eqs (10) to (13) model the minimum up and down time limitations of these units. Finally, Eqs (14) and (15) formulate the start up and shut down costs of these sources. It should be noted that the produced power of non-dispatchable units, namely WTs and PVs, are calculated by expressions that have been presented in [32].

In the end, the leader's set of decision variables are listed as follows:

$$\Xi^{Leader} = \left\{ \begin{array}{l} P_{exch}^{WEM,DA}(t),\, \lambda^{LEM,DA}(t),\, P_{DSO}^{DG}(i,t) \\ U_{DSO}^{DG}(i,t),\, \Delta V(\alpha,t),\, V(\alpha,t),\, \theta(\alpha,t) \end{array} \right\}$$

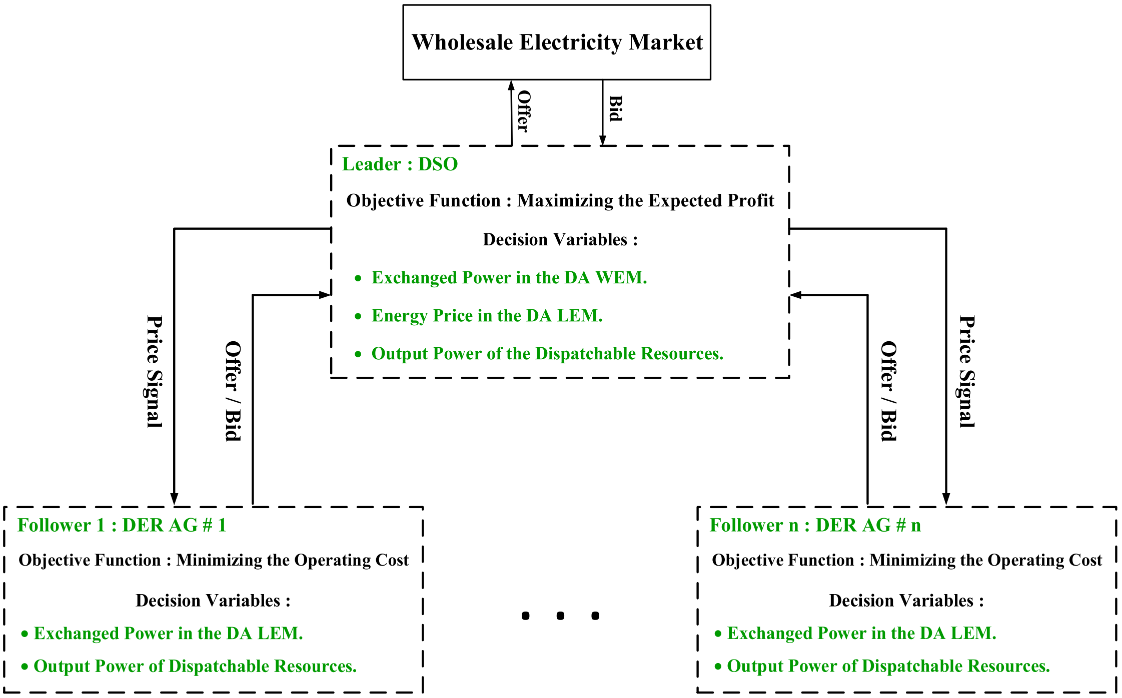

FIGURE 1. Overview of the proposed framework.

B. PROBLEM FORMULATION OF THE FOLLOWERS–DER AGS

On the other hand, each DER AG seeks to diminish its daily operating cost by integrating decentralized DERs at the distribution level and exchanging their generation as well as storage capacities with the DSO in the LEM platform. Each DER AG's objective function is mathematically formulated in Eq (16).

$$O.F^{n^{th}\ Follower} = \mathrm{Min} \sum_{t \in T} \left\{ \begin{array}{l} \sum_{i \in I} P_{AG}^{DG}(n,i,t)\, c_{AG}^{DG}(n,i) \\ -P_{exch}^{LEM,DA}(n,t)\, \lambda^{LEM,DA}(t) \end{array} \right\}, \quad (16)$$

The first and second terms of Eq (16) are related to the operating costs of the nth AG's DGs and its income from participating in the LEM, respectively.

This objective function is also subject to a set of constraints as follows:

$$\sum_{w \in W} P_{AG}^{WT,F}(n,w,t) + \sum_{v \in V} P_{AG}^{PV,F}(n,v,t) + \sum_{i \in I} P_{AG}^{DG}(n,i,t) + \sum_{b \in B} \left(P_{AG}^{BS,dch}(n,b,t) - P_{AG}^{BS,ch}(n,b,t) \right) = P_{exch}^{LEM,DA}(n,t), \quad \lambda_1(n,t), \quad \forall n,t \quad (17)$$

$$-P_{exch}^{LEM,DA,max}(n) \le P_{exch}^{LEM,DA}(n,t) \le P_{exch}^{LEM,DA,max}(n), \quad \mu_1(n,t), \mu_2(n,t), \quad \forall n,t \quad (18)$$

$$P_{AG}^{DG,min}(n,i) \le P_{AG}^{DG}(n,i,t) \le P_{AG}^{DG,max}(n,i), \quad \mu_3(n,i,t), \mu_4(n,i,t) \quad \forall n,i,t \quad (19)$$

$$P_{AG}^{DG}(n,i,t) - P_{AG}^{DG}(n,i,t-1) \le \mathrm{RU}_{AG}^{DG}(n,i), \quad \mu_5(n,i,t), \quad \forall n,i,t>1 \quad (20)$$

$$P_{AG}^{DG}(n,i,t) - P_{AG}^{DG,ini}(n,i) \le \mathrm{RU}_{AG}^{DG}(n,i), \quad \mu_6(n,i,t), \quad \forall n,i,t=1 \quad (21)$$

$$P_{AG}^{DG}(n,i,t-1) - P_{AG}^{DG}(n,i,t) \le \mathrm{RD}_{AG}^{DG}(n,i), \quad \mu_7(n,i,t), \quad \forall n,i,t>1 \quad (22)$$

$$P_{AG}^{DG,ini}(n,i) - P_{AG}^{DG}(n,i,t) \le \mathrm{RD}_{AG}^{DG}(n,i), \quad \mu_8(n,i,t), \quad \forall n,i,t=1 \quad (23)$$

$$P_{AG}^{BS,dch,min}(n,b) \le P_{AG}^{BS,dch}(n,b,t) \le P_{AG}^{BS,dch,max}(n,b), \quad \mu_9(n,b,t), \mu_{10}(n,b,t), \quad \forall n,b,t \quad (24)$$

$$P_{AG}^{BS,ch,min}(n,b) \le P_{AG}^{BS,ch}(n,b,t) \le P_{AG}^{BS,ch,max}(n,b), \quad \mu_{11}(n,b,t), \mu_{12}(n,b,t), \quad \forall n,b,t \quad (25)$$

$$E_{AG}^{BS}(n,b,t) = E_{AG}^{BS}(n,b,t-1) + P_{AG}^{BS,ch}(n,b,t)\, \eta_{AG}^{BS,ch}(n,b) - P_{AG}^{BS,dch}(n,b,t,s) / \eta_{AG}^{BS,dch}(n,b), \quad \lambda_2(n,b,t), \quad \forall n,b,t>1 \quad (26)$$

$$E_{AG}^{BS}(n,b,t) = E_{AG}^{BS,ini}(n,b) + P_{AG}^{BS,ch}(n,b,t)\, \eta_{AG}^{BS,ch}(n,b) - P_{AG}^{BS,dch}(n,b,t,s) / \eta_{AG}^{BS,dch}(n,b), \quad \lambda_3(n,b,t), \quad \forall n,b,t=1 \quad (27)$$

$$E_{AG}^{BS,min}(n,b) \le E_{AG}^{BS}(n,b,t) \le E_{AG}^{BS,max}(n,b), \quad \mu_{13}(n,b,t), \mu_{14}(n,b,t), \quad \forall n,b,t \quad (28)$$

Eq (17) is related to the power balance constraint of the nth AG. Eq (18) confines the exchange power of the AG in the DA LEM. Eqs (19) to (23) are associated with DGs' operational constraints and their power limitations. Accordingly, the generation power of the AG's DGs is limited by Eq (19). Moreover, Eqs (20) and (21) limit the maximum increase, and Eqs (22) and (23) limit the maximum decrease in the output power of DGs. Ultimately, mathematical and technical requirements of the AG's BSs are demonstrated in Eqs (24) to (28). In this regard, BSs' discharge and charge power limitations are stated in Eqs (24) and (25), respectively. Also, energy stored in BSs and their related limitations are illustrated in Eqs (26) and (27) as well as Eq (28), respectively.

In the end, the nth follower's set of decision variables are listed as follows:

$$\Xi^{n^{th}Follower} = \left\{ \begin{array}{l} P_{exch}^{LEM,DA}(n,t), P_{AG}^{DG}(n,i,t), P_{AG}^{BS,dch}(n,b,t) \\ P_{AG}^{BS,ch}(n,b,t), E_{AG}^{BS}(n,b,t), \lambda, \mu \end{array} \right\}$$

C. SOLVING THE PROPOSED STACKELBERG GAME-BASED FRAMEWORK

Since problems of followers, DER AGs, are linear, continuous, and thus convex, the considered one-leader-multi-follower game-based model could be reformulated to a single-level model by replacing the followers' problem with their Karush-Kuhn-Tucker (KKT) conditions [33]. In this context, KKT conditions, including the stationary, complementary slackness, and dual feasibility, are illustrated in Eqs (29) to (48).

$$\begin{aligned} \frac{\partial \mathrm{LF}}{\partial P_{exch}^{LEM,DA}(n,t)} &= -\lambda^{LEM,DA}(t) + \lambda_1(n,t) \\ &\quad + \mu_1(n,t) - \mu_2(n,t) = 0, \quad \forall n,t \end{aligned} \tag{29}$$

$$\begin{aligned} \frac{\partial \mathrm{LF}}{\partial P_{AG}^{DG}(n,i,t)} &= c_{AG}^{DG}(n,i) - \lambda_1(n,t) + \mu_3(n,t) - \mu_4(n,t) \\ &\quad + \mu_5(n,t)|_{t>1} - \mu_5(n,t+1) + \mu_6(n,t)|_{t=1} \\ &\quad - \mu_7(n,t)|_{t>1} + \mu_7(n,t+1) - \mu_8(n,t)|_{t=1} = 0, \\ &\quad \forall n,i,t \end{aligned} \tag{30}$$

$$\begin{aligned} \frac{\partial \mathrm{LF}}{\partial P_{AG}^{BS,dch}(n,b,t)} &= -\lambda_1(n,t) + \mu_9(n,b,t) - \mu_{10}(n,b,t) \\ &\quad - \left. \lambda_2(n,b,t)/\eta_{AG}^{BS,dch}(n,b) \right|_{t>1} \\ &\quad - \left. \lambda_3(n,b,t)/\eta_{AG}^{BS,dch}(n,b) \right|_{t=1} = 0, \quad \forall n,b,t \end{aligned} \tag{31}$$

$$\begin{aligned} \frac{\partial \mathrm{LF}}{\partial P_{AG}^{BS,ch}(n,b,t)} &= \lambda_1(n,t) + \mu_{11}(n,b,t) - \mu_{12}(n,b,t) \\ &\quad + \left. \lambda_2(n,b,t)\,\eta_{AG}^{BS,dch}(n,b) \right|_{t>1} \\ &\quad + \left. \lambda_3(n,b,t)\,\eta_{AG}^{BS,dch}(n,b) \right|_{t=1} = 0, \quad \forall n,b,t \end{aligned} \tag{32}$$

$$\begin{aligned} \frac{\partial \mathrm{LF}}{\partial E_{AG}^{BS}(n,b,t)} &= -\lambda_2(n,b,t)|_{t>1} \\ &\quad + \lambda_2(n,b,t+1) - \lambda_3(n,b,t)|_{t=1} \\ &\quad + \mu_{13}(n,b,t) - \mu_{14}(n,b,t) = 0, \quad \forall n,b,t \end{aligned} \tag{33}$$

$$0 \le P_{exch}^{LEM,DA,max}(n) - P_{exch}^{LEM,DA}(n,t) \perp \mu_1(n,t) \ge 0, \quad \forall n,t \tag{34}$$

$$0 \le P_{exch}^{LEM,DA}(n,t) + P_{exch}^{LEM,DA,max}(n) \perp \mu_2(n,t) \ge 0, \quad \forall n,t \tag{35}$$

$$0 \le P_{AG}^{DG,max}(n,i) - P_{AG}^{DG}(n,i,t) \perp \mu_3(n,i,t) \ge 0, \quad \forall n,i,t \tag{36}$$

$$0 \le P_{AG}^{DG}(n,i,t) - P_{AG}^{DG,min}(n,i) \perp \mu_4(n,i,t) \ge 0, \quad \forall n,i,t \tag{37}$$

$$\begin{aligned} 0 \le \mathrm{RU}_{AG}^{DG}(n,i) &- P_{AG}^{DG}(n,i,t) \\ &+ P_{AG}^{DG}(n,i,t-1) \perp \mu_5(n,i,t) \ge 0, \\ &\forall n,i,t>1 \end{aligned} \tag{38}$$

$$\begin{aligned} 0 \le \mathrm{RU}_{AG}^{DG}(n,i) &- P_{AG}^{DG}(n,i,t) \\ &+ P_{AG}^{DG,ini}(n,i) \perp \mu_6(n,i,t) \ge 0, \\ &\forall n,i,t=1 \end{aligned} \tag{39}$$

$$\begin{aligned} 0 \le \mathrm{RD}_{AG}^{DG}(n,i) &- P_{AG}^{DG}(n,i,t-1) \\ &+ P_{AG}^{DG}(n,i,t) \perp \mu_7(n,i,t) \ge 0, \\ &\forall n,i,t>1 \end{aligned} \tag{40}$$

$$\begin{aligned} 0 \le \mathrm{RD}_{AG}^{DG}(n,i) &- P_{AG}^{DG,ini}(n,i) \\ &+ P_{AG}^{DG}(n,i,t) \perp \mu_8(n,i,t) \ge 0, \\ &\forall n,i,t=1 \end{aligned} \tag{41}$$

$$\begin{aligned} 0 \le P_{AG}^{BS,dch,max}(n,b) &- P_{AG}^{BS,dch}(n,b,t) \\ &\perp \mu_9(n,b,t) \ge 0, \quad \forall n,b,t \end{aligned} \tag{42}$$

$$\begin{aligned} 0 \le P_{AG}^{BS,dch}(n,b,t) &- P_{AG}^{BS,dch,min}(n,b) \\ &\perp \mu_{10}(n,b,t) \ge 0, \quad \forall n,b,t \end{aligned} \tag{43}$$

$$\begin{aligned} 0 \le P_{AG}^{BS,ch,max}(n,b) &- P_{AG}^{BS,ch}(n,b,t) \\ &\perp \mu_{11}(n,b,t) \ge 0, \quad \forall n,b,t \end{aligned} \tag{44}$$

$$\begin{aligned} 0 \le P_{AG}^{BS,ch}(n,b,t) &- P_{AG}^{BS,ch,min}(n,b) \\ &\perp \mu_{12}(n,b,t) \ge 0, \quad \forall n,b,t \end{aligned} \tag{45}$$

$$0 \le E_{AG}^{BS,max}(n,b) - E_{AG}^{BS}(n,b,t) \perp \mu_{13}(n,b,t) \ge 0, \quad \forall n,b,t \tag{46}$$

$$0 \le E_{AG}^{BS}(n,b,t) - E_{AG}^{BS,min}(n,b) \perp \mu_{14}(n,b,t) \ge 0, \quad \forall n,b,t \tag{47}$$

$$\lambda, \quad \textit{Unrestricted} \tag{48}$$

Nonetheless, the final single-level model of the problem is non-linear due to the presence of some sources of nonlinearities, i.e., complementary slackness in Eqs (34) to (47) as well as $P_{exch}^{LEM,DA}(n,t)\,\lambda^{LEM,DA}(t)$ in Eq (1). For linearization of these expressions, the Big-M methodology and strong duality theorem (SDT) are utilized in this article [34]. Eq (49) demonstrates the generic formulation of the Big-M method. The important point in utilizing this method is selecting a proper value for "M" as a sufficiently large parameter. That is because, too small "M" leaves the optimal solution out of the feasible space, while too large "M" may lead to computational inefficiencies in the solution of the obtained model. Furthermore, the dual problem of Eq (16) that leads to deriving the linear form of $P_{exch}^{LEM,DA}(n,t)\,\lambda^{LEM,DA}(t)$ is stated in Eq (50).

$$0 \le \psi \perp \upsilon \ge 0 \rightarrow \begin{cases} \psi \le MZ \\ \upsilon \le M(1-Z) \end{cases} \tag{49}$$

$$\begin{aligned}
&\sum_{t\in T}\left\{\begin{array}{l} \sum\limits_{i\in I} P_{AG}^{DG}(n,i,t)\,c_{AG}^{DG}(n,i) \\ -P_{exch}^{LEM,DA}(n,t)\,\lambda^{LEM,DA}(t) \end{array}\right\} \\
&= \sum_{t\in T}\left\{ -\lambda_1(n,t)\left(\begin{array}{l} \sum\limits_{w\in W} P_{AG}^{WT,F}(n,w,t) \\ +\sum\limits_{v\in V} P_{AG}^{PV,F}(n,v,t) \end{array}\right)\right. \\
&\quad -\mu_1(n,t)\,P_{exch}^{LEM,DA,max}(n) \\
&\quad -\mu_2(n,t)\,P_{exch}^{LEM,DA,max}(n) + \sum_{i\in I} \\
&\quad \times\left(\begin{array}{l} -\mu_3(n,i,t)\,P_{AG}^{DG,max}(n,i) \\ +\mu_4(n,i,t)\,P_{AG}^{DG,min}(n,i) \\ -\mu_5(n,i,t)\,\mathrm{RU}_{AG}^{DG}(n,i)\big|_{t>1} \\ -\mu_6(n,i,t)\left[\mathrm{RU}_{AG}^{DG}(n,i)+P_{AG}^{DG,ini}(n,i)\right]\Big|_{t=1} \\ -\mu_7(n,i,t)\,\mathrm{RD}_{AG}^{DG}(n,i)\big|_{t>1} \\ -\mu_8(n,i,t)\left[\mathrm{RD}_{AG}^{DG}(n,i)-P_{AG}^{DG,ini}(n,i)\right]\Big|_{t=1} \end{array}\right) \\
&\quad \left. +\sum_{b\in B}\left(\begin{array}{l} -\mu_9(n,b,t)\,P_{AG}^{BS,dch,max}(n,b) \\ +\mu_{10}(n,b,t)\,P_{AG}^{BS,dch,min}(n,b) \\ -\mu_{11}(n,b,t)\,P_{AG}^{BS,ch,max}(n,b) \\ +\mu_{12}(n,b,t)\,P_{AG}^{BS,ch,min}(n,b) \\ -\mu_{13}(n,b,t)\,E_{AG}^{BS,max}(n,b) \\ +\mu_{14}(n,b,t)\,E_{AG}^{BS,min}(n,b) \\ +\lambda_3(n,b,t)\,E_{AG}^{BS,ini}(n,b)\Big|_{t=1} \end{array}\right)\right\}, \\
&\qquad \forall n,t
\end{aligned} \tag{50}$$

As a point of interest, if the feasibility of the resulting single-level model is not obtained momentarily due to the violation of the distribution network's operational constraints, as well as technical constraints of the existing resources, the DSO as the operator and monitor of the system is potentially able to relax some constraints if the electricity supply reliability and quality can still be maintained at the feasible and allowable level.

III. SIMULATION RESULTS AND DISCUSSION

In this part of the article, the proposed LEM model for enabling the possibility of transactive energy exchange between the DSO and DER AGs is implemented and evaluated on a modified IEEE-33 bus test system, depicted in Figure 2.

As shown in Figure 2, the DSO has two DGs, one WT and one PV, which have been located at buses 3, 8, 13, and 22, respectively. In addition, it is presumed that two DER AGs trade energy with the DSO at the distribution level. DER AG 1 contains five DGs, three WTs, and two PVs without any BS. These resources have been located at buses 2, 8, 13, 18, 23, 5, 18, 25, 10, and 15, respectively. DER AG 2 contains three DGs, three PVs, and three BSs without any WT. These resources have been located at buses 19, 27, 33, 29, 31, 33, 22, 29, and 31, respectively.

The output power of all these units is depicted in Figure 3. Note that both wind speed and solar irradiation profiles have been assumed to be the same for these DERs in the distribution system. On the other hand, the input data and technical specifications of these resources are summarized in Tables 2, 3, and 4.

It is worth noteworthy that since the primary purpose of this study is not to size and cite the available DERs at the distribution level, it has been assumed that the entire resources already exist in the network, and it is only attempted to evaluate their operating status.

On the other hand, the peak demand of the DSO's customers in each bus is reported in Table 5.

The per-unit forecasted demand profile of the DSO is shown in Figure 4. Notably, in this research work, a forecasting technique or model has not been utilized, and it has been presumed that the demand profile is a forecasted value obtained from historical data.

Moreover, the DSO's price of sold energy to its customers is a three-tariff price, which includes 30 €/MWh, 55 €/MWh, and 45 €/MWh in off-peak, peak, and mid-peak hours, respectively. Finally, it is assumed that the DSO's maximum amount of exchange power with the upstream grid, WEM, is 10 MW.

Before presenting the output results, the list of assumptions that have been made in the simulation process is summarized as follows:

1. The entire DERs are assumed to be already located in the distribution system.
2. The wind speed and solar irradiation profiles are assumed to be the same for all DERs in the distribution system.
3. The forecasted demand profile is assumed to be obtained from historical data.
4. The price of sold energy to customers is assumed to be a three-tariff price.
5. The maximum amount of exchange power with the upstream grid is assumed to be 10 MW.

The optimal participation of the DSO in both WEM and LEM, as well as WEM forecasted price and LEM clearing price, have been displayed in Figure 5. Notably, the DSO's purchased power is shown by positive bars, and its sold power is shown by negative bars.

Based on Figure 5, in the peak of the DA WEM price, i.e., hours 12 to 13 and 21 to 22, the DSO has supplied its excess

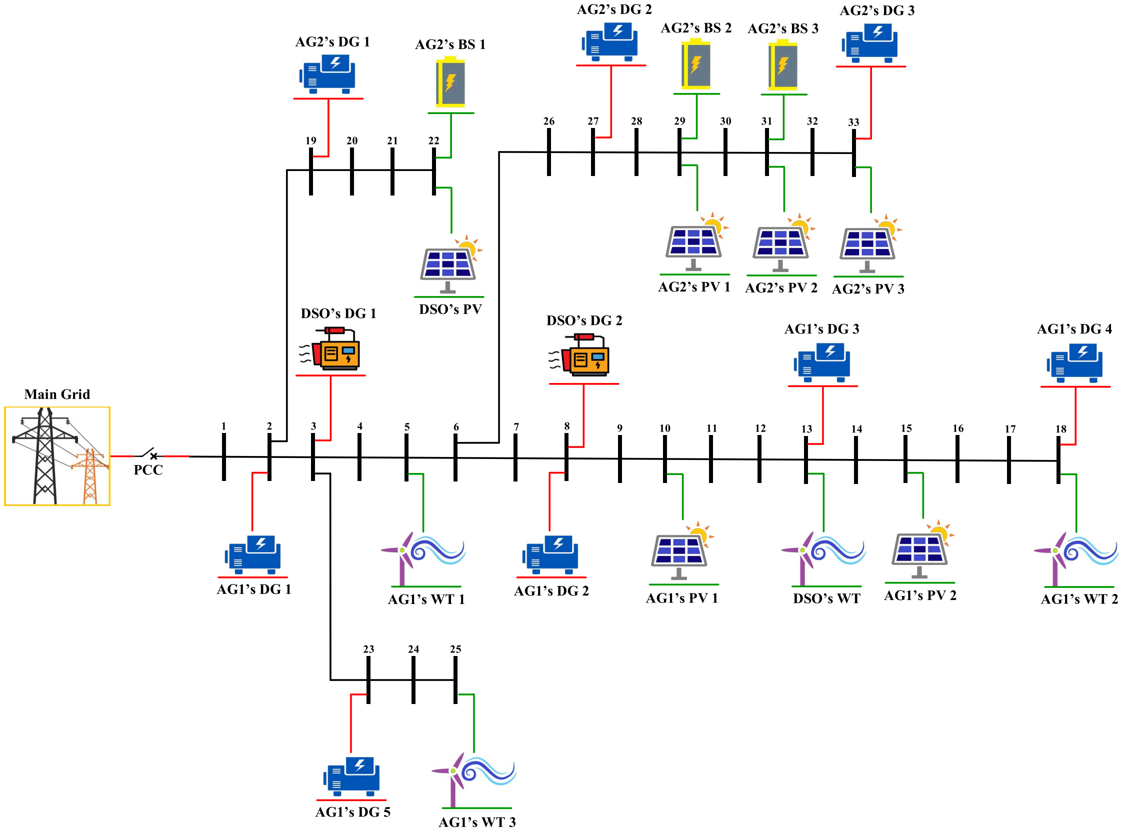

FIGURE 2. Single-line diagram of the modified IEEE-33 bus test system.

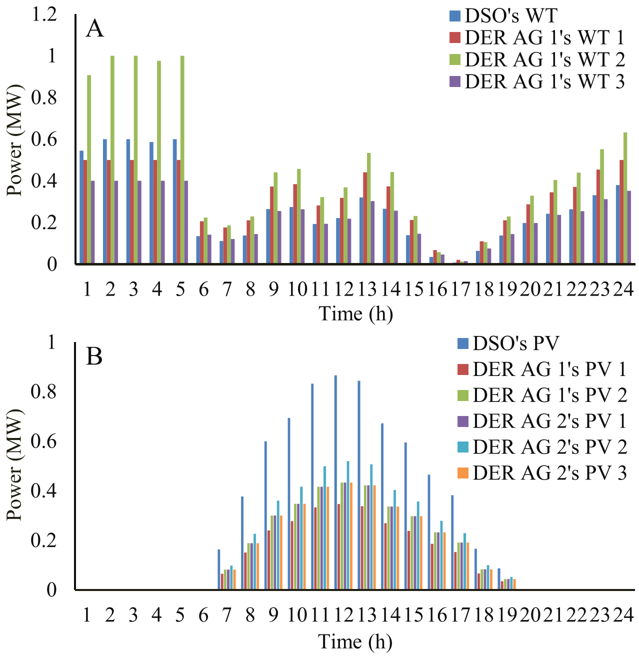

FIGURE 3. Output power of non-dispatchable DERs. (A) WTs. (B) PVs.

TABLE 2. Technical specifications of system's dispatchable units.

DSO					
# Unit	$P_{DSO}^{DG,min}$ (MW)	$P_{DSO}^{DG,max}$ (MW)	a_{DSO}^{DG} (€/MWh)	b_{DSO}^{DG} (€)	$sdc_{DSO}^{DG}, suc_{DSO}^{DG}$ (€)
1	0.16	1.6	12.5	25.0	15.0
2	0.12	1.2	25.0	30.0	10.0

DER AG 1				
# Unit	$P_{AG}^{DG,min}$ (MW)	$P_{AG}^{DG,max}$ (MW)	c_{AG}^{DG} (€/MWh)	$RD_{AG}^{DG}, RU_{AG}^{DG}$ (MW/h)
1	0	1.0	25.0	0.5
2	0	2.8	44.5	1.4
3	0	2.4	38.5	1.2
4	0	1.0	22.5	0.5
5	0	4.2	51.5	2.1

DER AG 2				
# Unit	$P_{AG}^{DG,min}$ (MW)	$P_{AG}^{DG,max}$ (MW)	c_{AG}^{DG} (€/MWh)	$RD_{AG}^{DG}, RU_{AG}^{DG}$ (MW/h)
1	0	0.5	20.0	0.3
2	0	1.2	32.0	0.6
3	0	1.0	28.5	0.5

power to the market. This power has been procured from the DA LEM as well as the DSO-own local DERs. In other words, at these hours, the WEM price is at the maximum value, and it is higher than the operating costs of the DSO's DGs as well as the LEM clearing prices. Hence, the DSO has exploited its DGs at full capacity and purchased the maximum amount of energy from the LEM to not only meet the system's demand

TABLE 3. Technical specifications of system's non-dispatchable units [35].

# Unit	$P_{DSO}^{WT,R}$ (MW)	$V_{DSO}^{WT,R}$ (m/s)	$V_{DSO}^{WT,CI}$ (m/s)	$V_{DSO}^{WT,CO}$ (m/s)	$P_{DSO}^{PV,R}$ (MW)
DSO					
1	0.6	14.0	4.0	20.0	1.0
DER AG 1					
# Unit	$P_{AG}^{WT,R}$ (MW)	$V_{AG}^{WT,R}$ (m/s)	$V_{AG}^{WT,CI}$ (m/s)	$V_{AG}^{WT,CO}$ (m/s)	$P_{AG}^{PV,R}$ (MW)
1	0.5	12.5	3.0	22.0	0.4
2	1.0	14.0	4.0	25.0	0.5
3	0.4	13.0	3.0	22.0	–
DER AG 2					
# Unit	$P_{AG}^{WT,R}$ (MW)	$V_{AG}^{WT,R}$ (m/s)	$V_{AG}^{WT,CI}$ (m/s)	$V_{AG}^{WT,CO}$ (m/s)	$P_{AG}^{PV,R}$ (MW)
1	–	–	–	–	0.5
2	–	–	–	–	0.6
3	–	–	–	–	0.5

TABLE 4. Technical specifications of the system's battery storage units.

# Unit	$E_{AG}^{BS,max}$ (MWh)	$E_{AG}^{BS,min}$ (MWh)	$P_{AG}^{BS,ch,max}$ $P_{AG}^{BS,dch,max}$ (MW)	$P_{AG}^{BS,ch,\min}$ $P_{AG}^{BS,dch,\min}$ (MW)	$\eta_{AG}^{BS,ch}$ $\eta_{AG}^{BS,dch}$ (%)
DER AG 1					
1	–	–	–	–	–
2	–	–	–	–	–
3	–	–	–	–	–
DER AG 2					
1	4.0	0.4	2.0	0	0.98
2	4.0	0.4	2.0	0	0.98
3	4.0	0.4	2.0	0	0.98

TABLE 5. Peak load of the system.

# Bus	Demand (MW)	# Bus	Demand (MW)	# Bus	Demand (MW)	# Bus	Demand (MW)
2	0.21	10	0.71	18	0.36	26	0.95
3	0.93	11	0.20	19	0.52	27	0.83
4	0.81	12	0.89	20	0.32	28	0.56
5	0.88	13	0.86	21	0.90	29	0.57
6	0.97	14	0.49	22	0.38	30	0.74
7	0.55	15	0.59	23	0.75	31	0.13
8	0.83	16	0.31	24	0.89	32	0.70
9	0.22	17	0.82	25	0.67	33	0.53

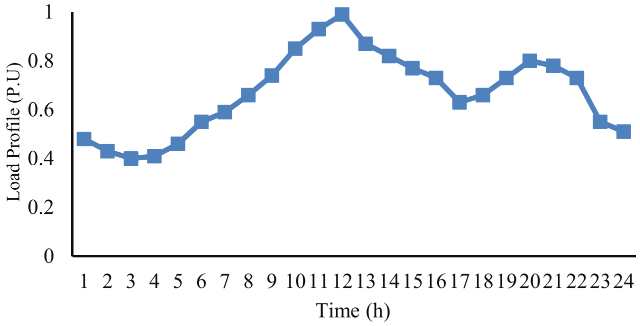

FIGURE 4. Load profile of the system.

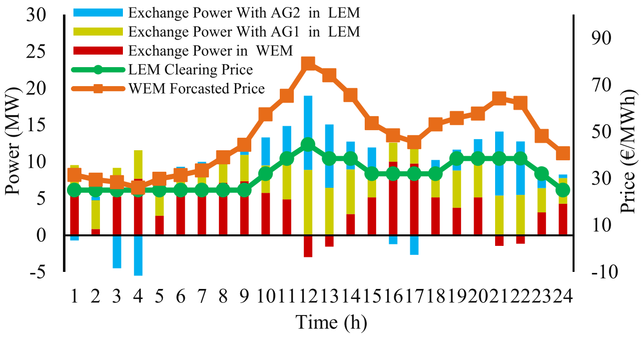

FIGURE 5. DSO's participation in both markets and market prices.

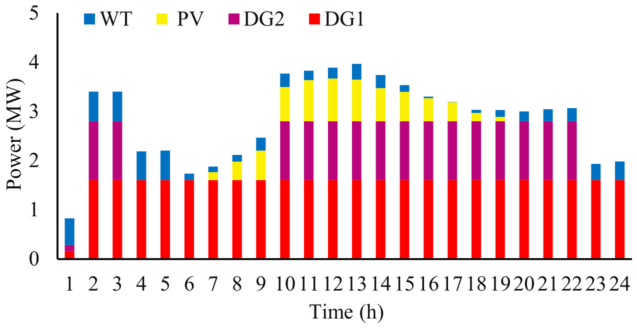

FIGURE 6. Operating points and generation profiles of the DSO's local resources.

but also sell its surplus to the WEM. Therefore, it can be inferred that the operating costs of the DSO's DGs and its costs from interacting with AGs in the LEM platform are lower than the profit made by selling energy to the WEM. On the contrary, in the off-peak of the DA WEM price, i.e., hours 3 to 4 and 16 to 17, the DSO has supplied its excess power to the DER AG 2 in the LEM platform. This power has been procured from the WEM and DER AG 1. Moreover, during the whole day, the DSO has purchased the power from AG 1 in the LEM platform. On the other hand, as shown in Figure 5, the LEM clearing price has reached its highest value in the middle hours of the day, where the DSO's demand and the WEM price are high as well. Hence, the peak of the LEM clearing price is aligned with the peak of the WEM price. Indeed, owing to the peak demand, the DSO's bids in the LEM have increased.

The optimal operating points of the DSO's DGs and the generation profile of its non-dispatchable renewable resources are illustrated in Figure 6.

According to Figure 6, the DSO's DG 1 has been exploited with the maximum capacity during the whole day. Nonetheless, the DG 2, which has a high production cost, has been

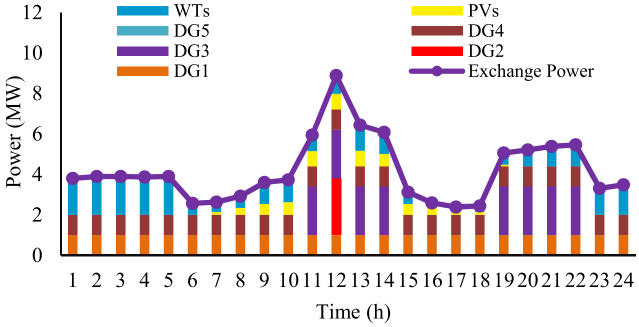

FIGURE 7. Optimal performance of the DER AG 1 in the DA LEM.

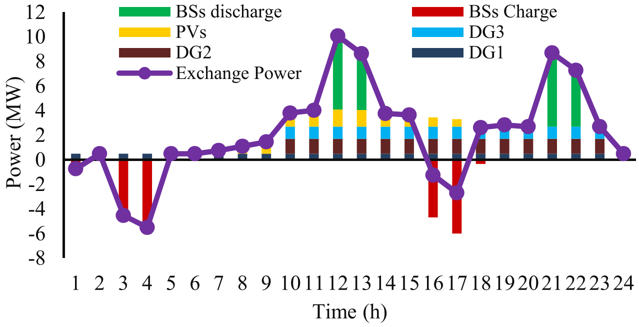

FIGURE 8. Optimal performance of the DER AG 2 in the DA LEM.

exploited only in the middle hours of the studied day. The generated power of these resources in the middle hours has been exploited by the DSO to inject energy into the WEM because their operating costs are lower than the profit made by selling this energy to the market. It can be emphasized that, since DGs' operational constraints, namely minimum up and down time, have been considered in the presented model as well, there are some limitations for turning off/turning on these units from the optimization point of view. By considering some specific constraints and costs, such as the amount of emission and its related cost, it may be better for the DSO to turn off its DGs instead of selling energy at peak hours.

On the other hand, Figures 7 and 8 represent the DER AG 1 and DER AG 2's optimal participation in the DA LEM, respectively, which has resulted from operating points as well as generation profiles of integrated DERs inside each AG.

According to Figure 7, the AG 1's DG 1 and DG 4 have been utilized with the maximum capacity during the whole day. At hours 1 to 9 and 24, the AG 1's DG 1 is the marginal producer in the LEM. The AG 1's DG 3 has been utilized in the peak of the DSO's demand and the WEM price, where the DSO's bids in the LEM have increased. At these hours, DG 3 has become the marginal producer, and the LEM clearing price has reached 38.5 €/MWh. Additionally, at hour 12, in which the DSO's demand and WEM price are at their highest value, the DER AG 1 has brought DG 2 to the service, and hence the LEM price has increased to 44.5 €/MWh. It is noteworthy that the AG 1's DG 5 has not been used over the studied day.

Based on Figure 8, the AG 2's DG 1 has been utilized with the maximum capacity during the whole day. At hours 10 to 23, the AG 2's DG 2 and DG 3 have been brought to the service and exploited with the maximum capacity. Thus, at hours 10, 15 to 18, and 23, AG 2's DG 2 has become the marginal producer, and the LEM clearing price has reached 32 €/MWh. On the other hand, DER AG 2 has charged its BSs in off-peak hours and discharged it in peak hours to sell power to the DSO via the LEM platform. It must be mentioned that some part of the BSs' charge power has been procured from the LEM, while some parts have been provided from the AG 2's own generation sources. For instance, at hour 17, for charging the AG 2's BSs, 2.7 MW power has been purchased from the LEM, and 3.3 MW power has been provided from DG 1, DG 2, DG 3, and PVs that are located at different buses.

TABLE 6. DSO's performance to supply the demand.

# T	WEM (MW)	AG 1 (MW)	AG 2 (MW)	Local DERs (MW)	Load (MW)
1	5.73	3.81	-0.72	0.82	9.64
2	0.83	3.90	0.50	3.40	8.63
3	5.25	3.90	-4.52	3.40	8.03
4	7.67	3.88	-5.50	2.19	8.24
5	2.63	3.90	0.50	2.20	9.23
6	6.23	2.58	0.50	1.73	11.04
7	6.58	2.63	0.76	1.87	11.84
8	7.11	2.93	1.10	2.11	13.25
9	7.32	3.61	1.46	2.46	14.85
10	5.75	3.73	3.81	3.77	17.06
11	4.86	5.96	4.03	3.82	18.67
12	-2.99	8.88	10.09	3.89	19.87
13	-1.57	6.44	8.63	3.96	17.46
14	2.87	6.08	3.78	3.74	16.47
15	5.15	3.12	3.65	3.53	15.45
16	10.00	2.59	-1.24	3.30	14.65
17	9.75	2.39	-2.69	3.19	12.64
18	5.15	2.44	2.63	3.03	13.25
19	3.73	5.06	2.84	3.02	14.65
20	5.15	5.21	2.70	3.00	16.06
21	-1.47	5.38	8.70	3.04	15.65
22	-1.16	5.47	7.28	3.06	14.65
23	3.09	3.32	2.70	1.93	11.04
24	4.27	3.49	0.50	1.98	10.24

To analyze the output results more accurately, the DSO's performance to supply its demand via the existing sources is reported numerically in Table 6. The second, third, and fourth columns of this table illustrate the DSO's exchanged power with the WEM, AG 1 in the LEM platform, and AG 2 in the LEM platform, respectively. Similar to Figure 5, the purchased power is shown by positive numbers, while the sold power is shown by negative numbers. The fifth column is associated with the generation power of the DSO-own DERs. Finally, the last column shows the distribution system's load in MW.

Based on Table 6, from hour 11 to hour 12, the DSO's situation has changed from purchasing energy to selling energy to the WEM, while the generation profile of its DERs, as well as its demand, are nearly the same at these hours. In this regard, the DSO has increased its purchasing powers from the DER AG 1 and DER AG 2 in the LEM by about 2.9 MW and 6.1 MW, respectively, to fulfill the network's load and

TABLE 7. Players' hourly revenue and costs.

# T	DSO				DER AG 1		DER AG 2	
	Customer Revenue	WEM Revenue	LEM Revenue	Operating Costs	LEM Revenue	Operating Costs	LEM Revenue	Operating Costs
1	289.01	-180.52	-77.06	85.00	95.18	47.50	-18.11	10.00
2	258.90	-24.48	-110.00	105.00	97.50	47.50	12.50	10.00
3	240.84	-149.22	15.51	105.00	97.50	47.50	-113.01	10.00
4	246.86	-200.06	40.60	55.00	96.90	47.50	-137.50	10.00
5	276.97	-78.65	-110.00	45.00	97.50	47.50	12.50	10.00
6	331.16	-195.83	-76.78	45.00	64.28	47.50	12.50	10.00
7	355.24	-219.83	-84.77	45.00	65.75	47.50	19.02	10.00
8	397.39	-277.24	-100.66	45.00	73.08	47.50	27.58	10.00
9	816.85	-324.78	-126.71	45.00	90.21	47.50	36.50	10.00
10	938.27	-330.21	-241.25	115.00	119.31	47.50	121.93	76.90
11	1026.58	-317.61	-384.12	105.00	228.91	139.90	155.20	76.90
12	1092.81	236.52	-844.15	105.00	395.35	264.50	448.81	76.90
13	960.35	116.70	-580.22	105.00	247.8	139.90	332.42	76.90
14	905.16	-188.24	-379.31	105.00	233.96	139.90	145.35	76.90
15	849.96	-276.02	-216.86	105.00	100.00	47.50	116.86	76.90
16	805.81	-484.16	-43.24	105.00	82.88	47.50	-39.64	76.90
17	568.98	-443.60	9.50	105.00	76.54	47.50	-86.04	76.90
18	596.08	-273.53	-162.18	105.00	78.09	47.50	84.09	76.90
19	659.30	-207.89	-304.21	105.00	194.90	139.90	109.31	76.90
20	722.52	-297.06	-304.66	105.00	200.71	139.90	103.95	76.90
21	704.46	94.49	-542.24	105.00	207.29	139.90	334.95	76.90
22	659.30	72.28	-490.81	105.00	210.38	139.90	280.43	76.90
23	496.73	-148.78	-192.54	55.00	106.14	47.50	86.40	76.90
24	460.61	-174.07	-99.58	45.00	87.08	47.50	12.50	10.00

export its excess, nearly about 3 MW, to the WEM. Similarly, from hour 20 to hour 21, the DSO has been able to act as a seller at the WEM by increasing its purchasing power from the DER AG 2.

To better investigate the income and costs of the considered players, the hourly distribution of their revenue and costs are reported in Table 7. The second, third, and fourth columns are related to the DSO's income from selling energy to its customers, participating in the WEM, and exchanging energy with DER AGs in the LEM platform, respectively. The fifth column is related to the operating costs of the DSO's DGs. The sixth and seventh columns are associated with the DER AG 1's income from participating in the LEM and operating costs of its DGs, respectively. Similarly, the eighth and ninth columns are associated with the DER AG 2's income from participating in the LEM and operating costs of its DGs, respectively. Obviously, the negative revenue in this table determines the costs of entities.

As clear in Table 7, the DSO has purchased energy from the WEM at most hours of the day, and only at hours 12 to 13 as well as 21 to 22 has achieved income from selling energy to the WEM. In addition, the DSO's cost of buying energy from the LEM has reached its maximum value at the mentioned hours. Notably, at only hour 17, the DSO has received revenue from selling energy to the LEM, where the DER AG 2 has purchased a considerable amount of energy from the DSO to charge its BSs. On the other hand, both DER AGs have received the highest amount of income at 12, where the LEM clearing price is at its maximum value.

TABLE 8. Players' daily profit and exchanged energy.

Player	Exchanged Energy (MWh)		Profit (€)
	WEM	LEM	
DSO	101.90	152.20	2932.61
DER AG 1	–	100.70	1343.44
DER AG 2	–	51.50	881.91

The daily profit of the LEM's players, as well as their traded energy, are summarized and compared in Table 8. It is notable that, the total exchanged energy of both DER AGs with the LEM is equal to the DSO's exchanged energy with this market.

In the following of this section, the impact of the transmission line capacity between the upstream grid and distribution network on the LEM clearing prices is evaluated. To this end, in addition to the base case with 10 MW line capacity, simulations are executed for 8 MW and 6 MW line capacities as well. It should be pointed out that since increasing the line capacity from 10 MW had no effect on the DSO's profit and its exchanged energy with the WEM, in this study, 10 MW capacity has been selected as the base case for the line between the upstream grid and the distribution network. Figure 9 compares the LEM prices in these three cases.

As depicted in Figure 9, by decreasing the transmission line capacity, the LEM clearing prices have increased in peak hours. These prices have raised in off-peak hours, i.e., 6 to 9, as well, for 6 MW line capacity. That is because, by confining

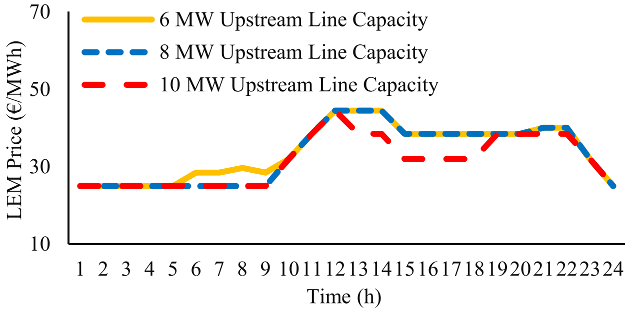

FIGURE 9. LEM clearing prices in three different cases.

TABLE 9. Players' daily profit in three different cases.

Case	Daily Profit (€)		
	DSO	DER AG 1	DER AG 2
10 MW line capacity	2932.61	1343.44	881.91
8 MW line capacity	2912.50	1504.30	997.03
6 MW line capacity	2854.57	1548.80	1012.89

the DSO's exchange power with the WEM, the DER AGs' most expensive DGs have been brought to the service and become marginal producers in the considered LEM.

Additionally, expected profits of the DSO and DER AGs in the aforementioned cases are reported and compared with one another in Table 9.

Based on Table 9, the DSO's profit has decreased by reducing the transmission line capacity between the upstream and distribution networks. On the contrary, both DER AGs' profits have increased owing to the raise in the LEM clearing prices.

Finally, to further highlight the potential advantages of the presented platform for implementing the LEM, another case study is analyzed in the following, in which electricity is traded between the DSO and DER AGs outside an organized marketplace. In this context, a bilateral contract is assumed to be made between the DSO and these entities to exchange energy at fixed prices. In this case study, three different tariffs are considered for the made bilateral contract, including:

Tariff 1 - 10 €/MWh less than the WEM price.

Tariff 2 - The WEM price.

Tariff 3 - 10 €/MWh more than the WEM price.

In Table 10, the obtained results from these three tariffs in the second case study are presented and compared with each other and with the first case study.

As shown in Table 10, when the price of the traded power between the DSO and DER AGs is less than the WEM price, the DSO has gained the highest amount of profit. In contrast, the DER AG 1's profit has been reduced remarkedly due to the decrease in the contracted price with the DSO. In the meantime, the DER AG 2 has been able to improve its situation and gain more profit owing to the existence of multiple BSs in its collation. Accordingly, the available BSs have helped the AG 2 to store its produced energy at off-peak prices and sell it to the DSO at peak prices.

TABLE 10. Comparison between case studies.

Case Study		Daily Profit (€)		
		DSO	DER AG 1	DER AG 2
Bilateral Contract	Tariff 1	3166.66	166.32	1188.34
	Tariff 2	-616.73	3094.22	1881.33
	Tariff 3	-919.24	1927.73	240.42
LEM Platform		2932.61	1343.44	881.91

When the price of the traded power between the DSO and DER AGs is equal to the WEM price, due to the high price of the WEM and the bilateral contract, the DSO has not only failed to make a profit but also incurred a cost. On the contrary, both DER AGs have gained more profit compared to the first tariff since they could sell their power at a higher price to the DSO.

When the price of the traded power between the DSO and DER AGs is more than the WEM price, the DSO has tended to procure its required demand from the WEM. Nonetheless, due to the technical constraints of the network, the DSO has had to provide some part of its needed power from the DER AGs at a higher price. Hence, this entity has faced more costs compared to the second tariff. Moreover, as a result of the DSO's unwillingness to purchase power from the DER AGs, their profits have declined as well.

The output results from two implemented case studies illustrate that in the presence of a local market-based platform for energy trading, a win-win situation can establish between the DSO and DER AGs, and these players are able to achieve their highest possible amount of profit.

IV. CONCLUSION

A DA LEM was modeled in this article to manage various types of real and virtual DERs at the distribution level. In this regard, several decentralized DERs were integrated within multi-AGs to trade their generation and storage capacities with the DSO as the operator of the LEM and the owner of the distribution system. In contrast, the DSO attempted to procure its demand through the DA LEM, DA WEM, as well as its local generation units, considering the technical constraints of the system. Since the mentioned players were independent financial entities with distinct objective functions, a Stackelberg game-theoretic method was executed in this study to settle the modeled LEM. To assess the effectiveness of the raised framework, two different case studies were conducted on a modified IEEE-33 bus test system. In the first case, the interaction between the DSO and AGs was implemented under the market-based platform, while in the second case, this interaction was executed via the bilateral contract. Simulation results demonstrated that the existence of a potential LEM establishes a win-win situation between the market participants, and these entities can gain the highest possible amount of profit. For another point, it was observed that LEM clearing price is associated with different key factors, consisting of the WEM forecasted price, marginal prices of DGs, the forecasted demand of the DSO, and the topology of the distribution system.

For future work, the authors tend to investigate the impact of insufficient energy generation in the LEM on the optimal operation and profit of the market participants, as well as the energy prices customers receive.

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