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Modeling Local Energy Market for Energy Management of Multi-Microgrids

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***Abstract*— The diffusion of distributed energy resources (DERs) has changed the supply-demand balance of power systems. One option to modernize the management of the electricity distribution is to operate the distribution system with interconnected micro-grids (MGs). However, the MG participation in wholesale energy and ancillary service markets creates several challenges in the interactions among the energy market managing entities. To solve these problems, local energy markets (LEMs) have been proposed, where the MGs can trade energy with each other under the management of the LEM manager (LEMM) to minimize their operation cost. In this paper, a local energy market is modeled for multi-MGs (MMGs) to minimize the operation cost of MGs individually and their social welfare in cooperation with each other. In such model, the optimal scheduling of the DERs in each MG is done through the market clearing process. To investigate the effectiveness of the proposed approach, the local energy market is applied to a distribution network with three MGs.**

***Index Terms*—Multi-microgrids, local energy market, distributed energy resources, distribution system operator.**

NOMENCLATURE

Acronyms

Disco	Distribution Company
DSO	Distribution System Operator
DER	Distributed Energy Resources
DG	Distributed Generation
IL	Interruptible Load
LEM/LEMM	Local Energy Market / LEM Manager
MG/MMG	Micro-grid / Multi-MG
MGA/MGM	MG Aggregator / MG Manager
TSO	Transmission System Operator
WEM/WEMM	Wholesale Energy Market / WEM Manager

Indices and Sets

t/T	Index/number of time period
j/J	Index/number of MGs

Parameters

C_j^{DG}	Operation cost of DGs ($/MWh)
C_j^{IL}	Cost of MGs load interruption ($/MWh)
$P_{j,t}^{\mathrm{Demand}}$	MGs load consumption (MW)
$P_j^{\mathrm{DG,max}}$	Maximum power produced by DGs (MW)
$P_j^{\mathrm{IL,max}}$	Maximum amount of load interruption (MW)
π_t^{WEM}	Wholesale energy market price ($/MWh)

Variables

$Cost_j$	Total operation cost of each MG ($)
$Cost_{\mathrm{LEM}}$	Total cost of LEM ($)
$C_{j,t}^{\mathrm{MG\_LEM}}$	MGs' bid/offer to the LEM ($/MWh)
$P_{j,t}^{\mathrm{DG}}$	DGs output power (MW)
$P_{j,t}^{\mathrm{IL}}$	The amount of MGs load interruption (MW)
$b_{j,t}^{\mathrm{MG\_LEM}}$	MGs offers/bids ($/MWh)
P_t^{WEM}	Power exchange between LEM and WEM (MW)
$P_{j,t}^{\mathrm{MG\_LEM}}$	Power trading of each MG with LEM (MWh)
λ_t^{LEM}	LEM clearing price ($/MWh)

I. INTRODUCTION

The decision making framework in the future electrical distribution networks could change from centralized decisions into decentralized ones in the presence of distributed energy resources (DERs) and microgrids (MGs) [1]. The MGs are independent entities which integrate DERs to meet the local demand in an optimal way [2]. The MGs attempt to follow optimal strategies to trade energy with the wholesale energy market (WEM). Emerging new players in the WEM (e.g., MGs, DER aggregators, etc.) create different problems for the operation and management of the transmission and distribution systems [3, 4]. A solution studied for solving these problems is to establish local energy markets (LEMs) where the MGs trade energy with each other [5]. The trend towards LEM development, linked to the evolution of MGs, is progressively becoming evident [6]. The aim of this paper is modeling the energy management problem of multi-MGs (MMGs) connected to a distribution network.

A. Literature review and contributions

A hierarchical decision making framework is proposed in [7, 8] to model the operation problem of distribution networks in the presence of MGs. In this framework, the decision-making of the distribution company (Disco) and of the MG managers (MGMs) are modeled as the upper-level and lower-level problems, respectively, in a bi-level approach. The Disco sends the price signals to the MGs, regarding which the MGMs schedule the DERs and decide on optimal power trading with the Disco. Then, the Disco receives the power trading signals from the MGMs, updates the price signals and resends them to the MGMs. This iterative process is continued until the convergence condition (in which the difference of objective function at two successive iterations is lower than a user-defined threshold) is satisfied. In such models, the Disco participates in the wholesale energy and ancillary service markets with optimal cooperation with the MGMs. Some solutions with a LEM defined for MGs consider the local energy communities role in balancing generation and demand at a local level [9]. In [10], the local users can trade power in a single MG without interacting with the utility grid. In [11], a two-stage model is proposed for optimizing design and operations of community MGs.

In several studies [12, 13], the MGs are aggregated by a MG aggregator (MGA) to participate in the markets. The decisions of the MGA in the markets are determined with optimal scheduling of MGs' resources. Since the MGs have various DERs and consume energy with different load profiles, the MGA can increase the MG benefits compared with the individual MG participation in the markets.

Various approaches to model the cooperation of the MGs with each other have been proposed. In [14], the discrete characteristics associated with the energy trading among the MGs are defined through formulating the collaborative operation of the MMGs. A two-stage adaptive robust optimization method is proposed with the purpose of minimizing a residential MMG operation cost under the PV uncertainty. In [15], the advantages of the cooperation in a MMG with diverse types of the DERs at the distribution network level are investigated. The total operation cost of the MMG is minimized using cooperative game theory. In [14, 15], the operation problems of the MMGs are not modeled in a LEM environment, and only the amount of power exchange among them is scheduled.

In the mentioned studies, the operation problem of the distribution networks is modeled where the Disco, the MGA, and the MGs participate in wholesale energy and ancillary service markets. As remarked in [16], there are several issues for the participation of DERs and MGs in the WEM, also regarding the cooperation between the transmission system operator (TSO) and distribution system operator (DSO).

Since the MGs with small sizes cannot behave as price-maker players in the market, they cannot affect the market prices. To solve these problems, the LEMs are proposed, where the MGs can trade power with each other. In the LEM, the MGs have the ability to minimize their total operation cost with the optimal trading power with the main grid and other MGs. A two-stage feeder-based LEM is proposed in [17], in which the energy prices are determined in each feeder regarding the social welfare of the prosumers and consumers of that feeder as the first step. According to these prices, the market is cleared among the feeders, so that the feeders with low energy prices sell energy to the ones with high energy prices. In the proposed model, both markets are cleared individually without any coordination with each other. A distribution energy management method is developed in [18], for a MMG in which the operation problem of the MGs is optimized in the internal loop considering its cooperation with the other MGs. In the external loop, the profit of all MGs are optimized via the optimal power trading with the market. In the proposed model, the LEM among MGs is not modeled.

In this paper, the LEM model is developed for the optimal energy management of the MMGs. The model illustrates that clearing such market maximizes the social welfare of all MGs that are operated individually and in cooperation with each other. The output decision variables of the model are the optimal scheduling of MG resources, the local market prices, the optimal power trading with the main grid, the optimal power trading between the MGs and LEM. Hence, the main contributions of this paper are:

- Modeling the energy management problem of several MGs in the LEM environment.
- Using a two-level framework to minimize the operation cost of MGs individually and their social welfare in cooperation with each other.

B. *Paper organization*

In the rest of this paper, section II presents the problem description. The mathematical formulation is presented in section III. Section IV reports and discusses the numerical results, and section V concludes the paper.

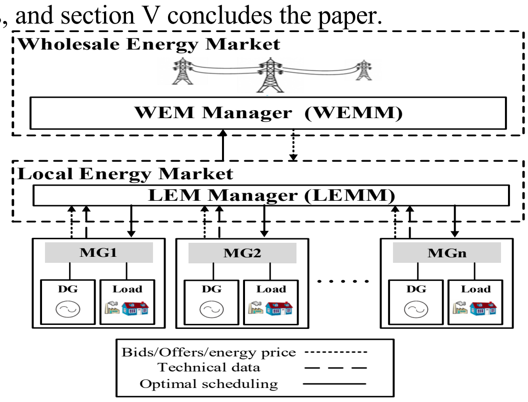

Fig. 1. Structure of the interactions among LEMM and MGs in the LEM.

II. Problem Description

In this paper, the energy management problem of several MGs is modeled in the LEM environment. In such framework, the MGs trade energy with each other in the LEM as shown in Fig. 1. The MGs contain distributed generation (DG) and interruptible loads (ILs) and can trade energy with the LEM to meet their required energy or to sell the extra energy. The LEM is managed by the LEM Manager (LEMM), a non-profit market operator which interacts with the WEM to trade energy and aims at minimizing the operation cost of the MGs. The MGs, the LEMM, and the WEM can interact with each other using the MGs bids/offers, the technical data of the MGs, and the wholesale market prices.

The mentioned interaction is carried out in the framework presented in Fig. 2. The proposed framework consists of two levels. In the first level, each MG solves its operation problem to minimize the total operation cost regarding the power trading and the price received from the LEM considering the constraints related to the output power of DGs and the amount of load interruption. The LEM is cleared by the LEMM with

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the objective of maximizing the social welfare using the MGs bids/offers, the WEM price, and the required technical constraints. Generally, the output signals of the first level are MGs bids/offers and the maximum and minimum amounts of power trading with the LEM. Also, the amount of power trading with MGs and the LEM prices are determined as the output signals to each MG.

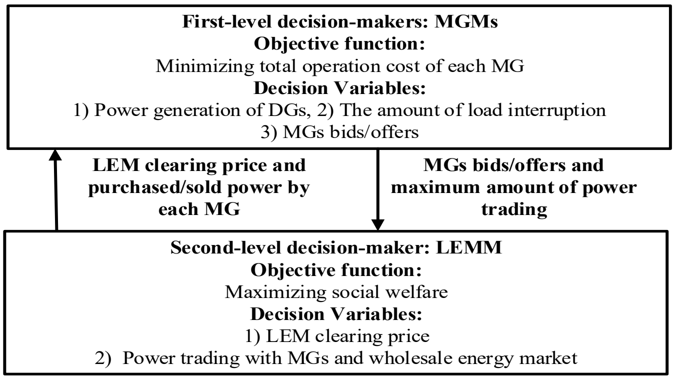


Fig. 2. Framework for the participation of MGs in LEMs.

The process of solving the LEM problem is represented in three steps according to Fig. 3. Step 1 reveals that each MG estimates its bids/offers to achieve an optimal total operation cost. In fact, the MGs optimize their problem through interaction with DGs and ILs besides considering the estimated bids/offers. Then, the maximum amount of power trading with the LEM is calculated as the technical data. In Step 2, the LEMM receives the bids/offers as well as the technical data from the MGs on the one hand, and the WEM prices on the other hand. Afterwards, the LEM is cleared with the purpose of maximizing the social welfare, taking into account the technical constraints. As a result, the LEM clearing prices, the power trading with the MGs, and power exchange with the WEM are specified as the output decisions of this step.

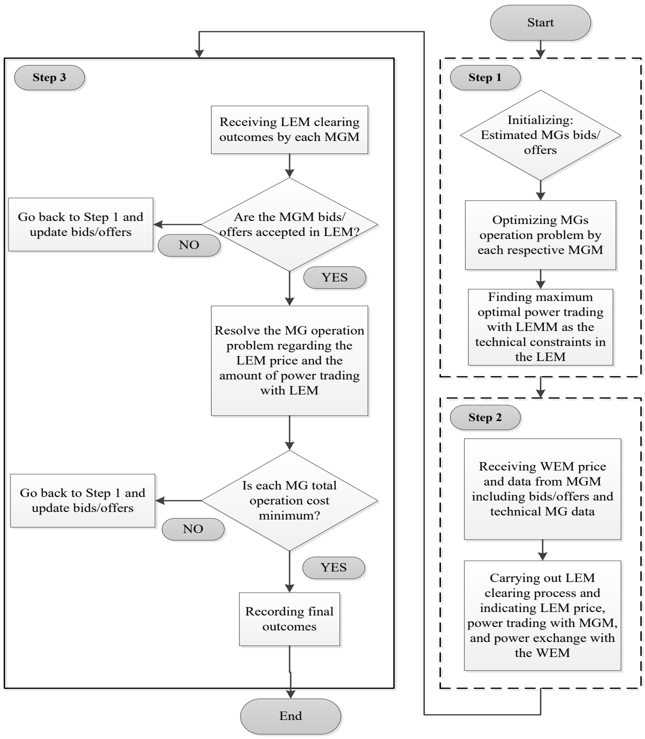


Fig. 3. Flowchart of the proposed solution process.

Finally, Step 3 is run to clear the LEM. In other words, each MG makes decisions on whether its bid/offer has been accepted in the LEM or not. If No, it comes back to Step 1 for changing the bids/offers regarding the LEM clearing price in the previous step, its DG and IL costs, and its demand-supply balance cost. Otherwise, the process continues by the MGs through solving the operation problem according to the LEM prices and the respective amount of power trading as well. Then, if the total operation cost of each MG satisfies the convergence condition (the difference of MGs' operation cost at two successive iterations is lower than a user-defined threshold), the process reaches its end, otherwise going back to Step 1 and changing the offers/bids again. This process is continued until all MGs reach the best decisions in LEM and obtain the minimum operation cost.

III. Mathematical Modeling

In this section, the proposed hierarchical framework is mathematically formulated. The bidding strategy problem of the MGs is modeled in the first level problem, with the aim of obtaining an optimal cost. In the second level problem, the LEM clearing process problem is modeled regarding the bids/offers of the MGs. The formulations of these two levels are presented below.

A. MGs operation problem (First level)

Eq. (1) defines the total operation cost of each MG $j = 1,\ldots, J$. The first two terms are associated with the operation cost of DGs and the cost of MG load interruption. The last term describes the cost/revenue of/from power trading with the LEM.

$$Min\,Cost_j = \sum_{t=1}^{T}\left(P_{j,t}^{\mathrm{DG}} C_j^{\mathrm{DG}} + P_{j,t}^{\mathrm{IL}} C_{j,t}^{\mathrm{IL}} + P_{j,t}^{\mathrm{MG\_LEM}} \lambda_t^{\mathrm{MG\_LEM}}\right) \quad \forall j \quad (1)$$

Eq. (2) enforces the demand-supply balance in each MG. In this equation the power supply produced by the DG, the interruptible loads, and power exchange with the LEM must be equal to the amount of MG load.

$$P^{\mathrm{DG}}_{j,t} + P^{\mathrm{MG\_LEM}}_{j,t} = P^{\mathrm{Demand}}_{j,t} - P^{\mathrm{IL}}_{j,t} : C^{\mathrm{MG\_LEM}}_{j,t} \quad \forall j \tag{2}$$

Eq. (3) restricts the output power of DGs regarding their respective upper and lower limitations. Eq. (4) describes the minimum and maximum amounts of load interruption.

$$0 \le P^{\mathrm{DG}}_{j,t} \le P^{\mathrm{DG,Max}}_{j} \quad \forall j,t \tag{3}$$

$$0 \le P^{\mathrm{IL}}_{j,t} \le P^{\mathrm{IL,Max}}_{j} \quad \forall j,t \tag{4}$$

The decision variables set of this level is $\{P^{\mathrm{DG}}_{j,t},\ P^{\mathrm{IL}}_{j,t},\ C^{\mathrm{MG\_LEM}}_{j,t}\}$. It should be noted that, the MG bid/offer to the LEM ($C^{\mathrm{MG\_LEM}}_{j,t}$) is specified according to either the dual variable of the demand-supply balance constraint or the LEM clearing price in the former iterations.

B. LEM clearing process problem (Second level)

The total cost (minus social welfare) of the LEM is minimized (maximized) as modeled in Eq. (5) consisting of the revenue/cost from/of purchased/sold power to/from MGs in the first term and the cost/revenue of/from power exchange with wholesale energy market in the second term.

$$\mathrm{Min}\left\{ Cost_{\mathrm{LEM}} = \sum_{t=1}^{T}\left(-\sum_{j=1}^{J}\left(P^{\mathrm{MG\_LEM}}_{j,t} b^{\mathrm{MG\_LEM}}_{j,t}\right) + P^{\mathrm{WEM}}_{t}\pi^{\mathrm{WEM}}_{t}\right)\right\} \tag{5}$$

Eq. (6) represents the purchased/sold power by the MGs through trading power with the WEM. In other words, the MGM can act as a prosumer due to interactions with their DERs, and the LEMM as a non-profit entity is responsible for managing the MGM's decision-making in coordination with the WEM outcomes.

$$\sum_{j} P^{\mathrm{MG\_LEM}}_{j,t} - P^{\mathrm{WEM}}_{t} = 0 : \lambda^{\mathrm{LEM}}_{t} \quad \forall t \tag{6}$$

Eq. (7) contains the maximum and minimum power trading among MGs and LEMM, which are addressed by each MG as the technical data in the LEM. Eq. (8) limits the exchanged power between the LEM and the WEM.

$$P^{\mathrm{MG\_LEM,Min}}_{j,t} \le P^{\mathrm{MG\_LEM}}_{j,t} \le P^{\mathrm{MG\_LEM,Max}}_{j,t} \quad \forall j,t \tag{7}$$

$$P^{\mathrm{WEM,Min}} \le P^{\mathrm{WEM}}_{t} \le P^{\mathrm{WEM,Max}} \quad \forall t \tag{8}$$

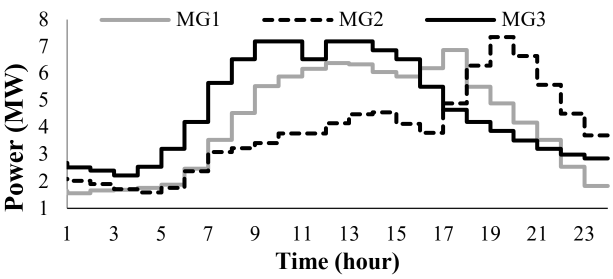


Fig. 4. MG loads consumption.

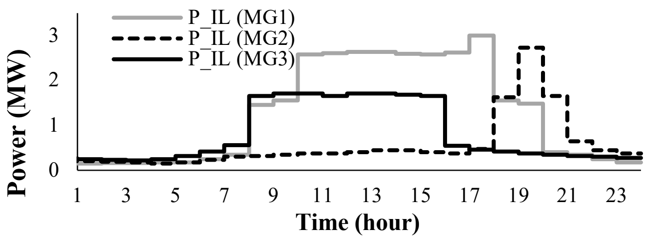


Fig. 5. The amount of load interruption in each MG.

TABLE I. WEM AND LOAD CURTAILMENT PRICE IN 24 HOURS

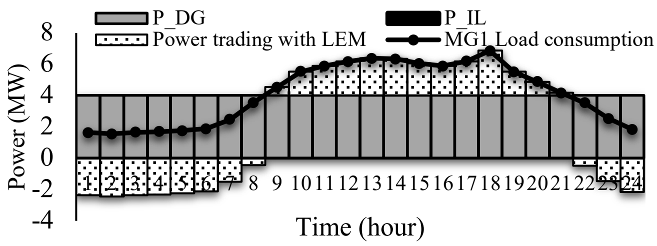
Time	WEM Price ($/MWh)	Load interruption Price($/MWh)	Time	WEM Price ($/MWh)	Load interruption Price($/MWh)
1	27.375	50	13	35.03	87
2	26.7	30	14	36.345	80
3	26.465	35.5	15	35.5	70
4	26.5	41	16	34.616	65
5	26.67	50	17	53.82	65
6	28.25	65	18	66.22	80
7	31.43	68	19	67.8	80
8	49.735	75	20	43	85
9	56.47	78	21	33	89
10	56.53	76	22	30.6	75
11	54.88	65	23	29.4	65
12	39.28	85	24	28.3	65

The decision variables set of the LEM problem contains $\{\lambda^{\mathrm{LEM}}_{t},\ P^{\mathrm{MG\_LEM}}_{j,t},\ P^{\mathrm{WEM}}_{t}\}$. Note that $\lambda^{\mathrm{LEM}}_{t}$ is the dual variable corresponding to the power balance constraint, which indicates the LEM price at each time step. Finally, to solve the proposed hierarchical framework, it is implemented in MATLAB® environment on a 2.8-GHz Core i7 computer with 6GB RAM.

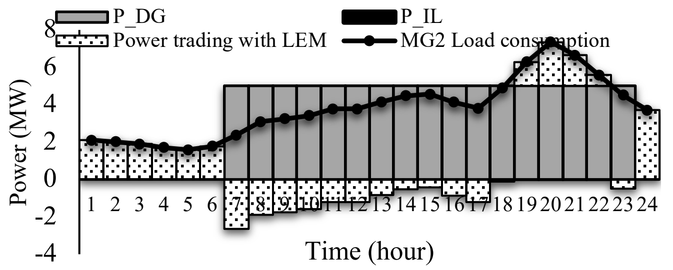
IV. NUMERICAL RESULTS

A. Input data

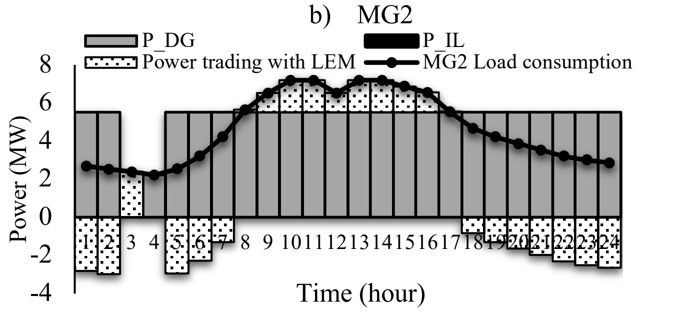
The proposed model and its solution methodology are applied on a distribution network with three MGs. The important information related to the MGs such as MG load consumption and the amount of load interruption are presented in Fig. 4 and Fig. 5 [19, 20]. The operation costs of DGs are 25 $/MWh, 29 $/MWh, and 26.5 $/MWh for MG1, MG2 and MG3, respectively. The maximum DGs output powers are 4 MW, 5 MW, and 5.5 MW, respectively [8, 21]. Moreover, the WEM prices used in [7] and the cost of load interruption in each MG are indicated in Table 1. For simplicity, the load interruption prices are equal for all MGs. Also, the upper and lower limitations of power trading between DSO and TSO are specified as -2 MW and 2 MW.



a) MG1



b) MG2



c) MG3

Fig. 6. Demand-supply Balance in each MG in Case I.

B. *Results*

To investigate the optimal behavior of the MGs in the proposed LEM market, two case studies are considered in this sub-section. In Case I, the cooperation of the MGs in a LEM is not modeled and MGs are optimized individually. The cooperation of them in the LEM environment to maximize the social welfare of this market is investigated in Case II. The detailed results of these cases are presented as follows.

B.1. Case I

In this case, each MG minimizes its operation problem individually. In fact, each MG directly trades power with the WEM based on the WEM prices. Furthermore, the MGs act as price-taker players and do not participate in a competitive environment where the social welfare of all participants is maximized. The results obtained by implementing this approach are presented in Fig. 6 and Fig. 7. As shown in these figures, the MG1 utilizes the entire capacity of its DG throughout the operation period. Also, it prefers to purchase power from the WEM at hours 9-21 instead of interacting with the interruptible loads based on the WEM prices. The remaining power of the DG is allocated to sell power to the WEM. On the other hand, the other MGs have almost the same behavior as MG1. For instance, MG2 and MG3 act either as consumers in hours 1-6, 19-22, and 24 (for MG2) and 3, 8-17 (for MG3) or as producers in hours 7-17 and 23 (for MG2) and 1-2, 5-7, and 18-24 (for MG3). The total operation costs of the MGs are 2905.84 $, 2466.13 $, and 2990.05 $, respectively. The important shortcomings of this process can be specified as: 1) the MGs may not be capable of selling all power in the real operation so as to ignore the strategic behavior of other players, 2) the network limitations defined by the DSO will affect the amount of purchased/sold power of MGs and the total power exchange with the WEM. Moreover, each MG minimizes the operation costs individually, but the cooperation with each other to achieve a maximum social welfare of all MGs is neglected.

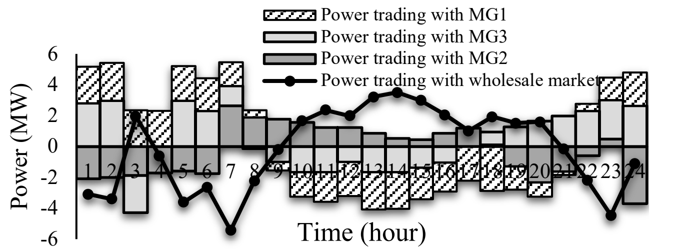


Fig. 7. The power balance between summation of purchased/sold power of MGs from WEM in Case I.

B.2. Case II

In this case, the mentioned imperfections of the MMG energy management are overcome through modeling the LEM environment. Each MG receives the LEM clearing outcomes after presenting bids/offers, following which, the decisions are changed until the minimum operation cost and the maximum social welfare of the LEM are obtained. Figs. 8-10 reveal the LEM clearing prices and the MG operation results in this case. It is clear that the decision-making of the MGs changes the energy prices considered in the first case. For instance, the MGs can determine the LEM clearing prices at hours 11, 15-16 (for MG1 regarding Fig. 8 and Fig. 9a), 7, 8, and 23 (for MG2 regarding Fig. 8 and Fig. 9b), and 1-2, 5-6, 13-14, and 22 (for MG3 regarding Fig. 8 and Fig. 9c).

Also, Fig. 11 illustrates the optimization process of the total cost of MG operation individually and in cooperation with each other in the last six iterations. The final operation cost of MGs and the social welfare are 3301.70 $, 2383.47 $, 3265.93 $, and 1554.99 $, respectively. The results show that the MGs can change their roles in such LEM environment to increase the social welfare of the system. In some hours, the MGs want to act as a producer in the LEM regarding the capacity of their DGs, however, the MGs cannot sell power to the market regarding the clearing results of the market.

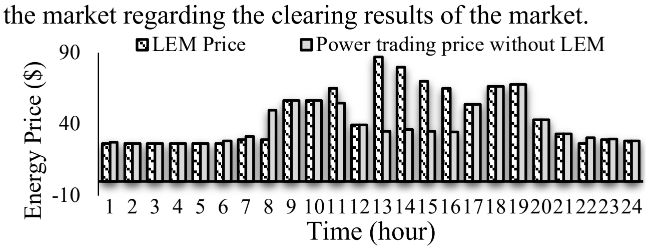
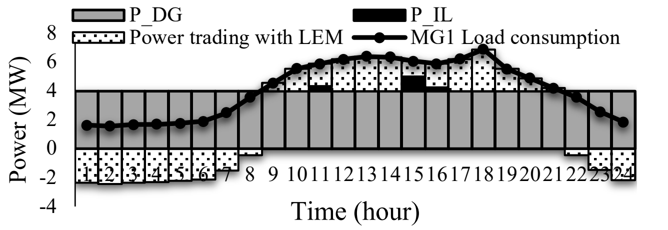
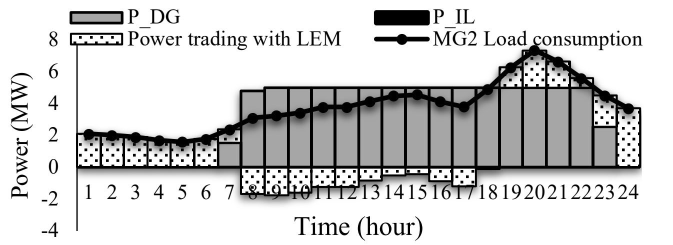


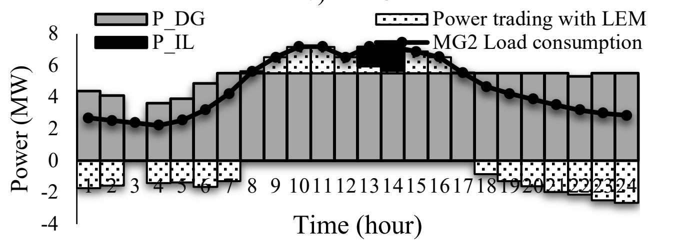
Fig. 8. LEM and WEM prices.



a) MG1



b) MG2



c) MG3

Fig. 9. Demand-supply Balance in each MG in Case II.

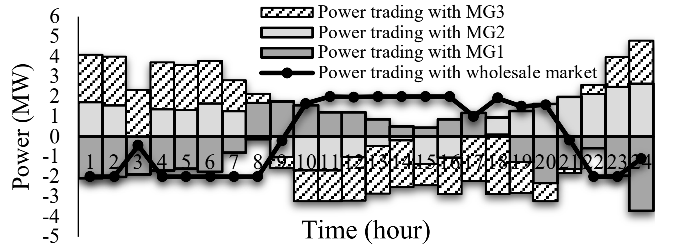


Fig. 10. Share of purchased/sold power by the MGs (from LEM) and by the LEMM (from WEM) in Case II.

Therefore, the MG changes its role to consumer and it participates in the LEM with a bid equal to its DGs, regarding which it can purchase the power from the LEM. In this case, the operation cost of this MG does not change, while the operation cost of other MGs and the LEM outcomes such as social welfare, LEM prices and the amount of power trading with other MGs change. For instance, a comparison between the results of iterations 5 and 6 can prove the above claim. At hour 7, the MGs present the offers of 25 $/MWh, 29 $/MWh, and 26.5 $/MWh to sell power of 1.52 MW, 2.63 MW, and 1.29 MW to the LEM, respectively. After clearing the LEM, the MG1 and the MG3 can sell 1.52 MW and 0.48 MW, respectively, and the MG2 cannot sell power to the market. Also, the LEM price and the social welfare are 26.5 $/MWh and 1518.06 $. If the MG2 changes its bid to 29 $/MWh for purchasing power from the market (without any change in the MG2 operation cost), the other two MGs can sell 1.52 MW and 1.29 MW, while the LEM price and the social welfare are 29 $/MWh and 1520.09 $, respectively. Furthermore, at hour 23, according to changing the role of MG2 from producer to consumer, the LEM clearing price increases from 26.5 $/MWh to 29 $/MWh, and the social welfare reaches 1554.99 $. Therefore, the operation cost for MG1 and MG3 increase, and for MG2 remain unchanged.

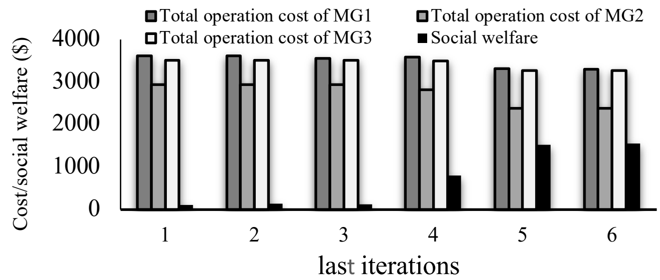


Fig. 11. Total operation cost of MGs and social welfare in the last 6 iterations.

V. Conclusions

In this paper, a new decision making scheme has been proposed for the operation problem of the electrical distribution networks with the aim of modeling a LEM in the presence of MGs. For this purpose, a two-level model has been presented, in which the decision-making problem of the MGs are modeled as the first-level problem and the LEM clearing process is modeled as the second-level one. The proposed decentralized model is solved using an iterative approach to minimize the operation cost of the MGs and to maximize the social welfare of the market. Two cases have been defined to investigate the effect of the proposed model on the decision making problem of a distribution network with three MGs. The main results are as follows:

- Enhancing the behavior of the MGs as price-maker players due to proposed LEM model managed by the LEMM, which is much closer to the real operation (the differences between results of Case I and Case II).
- Increasing the ability of the MGs in the role of prosumers within the LEM environment for the purpose of changing the energy price (as shown in the application example at hours 11, 15-16 (for MG1), 7, 8, and 23 (for MG2), and 1-2, 4-6, 13-14, and 22 (for MG3))
- Obtaining an acceptable social welfare through changing the role of MGs in the LEM from producers to consumers and vice versa (e.g., at hours 7 and 23 in the example).

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