Multi-Microgrids Operation With Interruptible Loads in Local Energy and Reserve Markets

Author(s): Sheikhahmadi, Pouria; Bahramara, Salah; Mazza, Andrea; Chicco, Gianfranco; Shafie-Khah, Miadreza; Catalão, João P. S.

Title: Multi-Microgrids Operation With Interruptible Loads in Local Energy and Reserve Markets

Year: 2022

Version: Accepted manuscript

Please cite the original version:

Sheikhahmadi, P., Bahramara, S., Mazza, A., Chicco, G., Shafie-Khah, M. & Catalão, J. P. S. (2022). Multi-Microgrids Operation With Interruptible Loads in Local Energy and Reserve Markets. *IEEE Systems Journal*. https://doi.org/10.1109/JSYST.2022.3177637

Multi-Microgrids Operation With Interruptible Loads in Local Energy and Reserve Markets

Pouria Sheikhahmadi, Salah Bahramara, Andrea Mazza, *Senior Member, IEEE*, Gianfranco Chicco, *Fellow, IEEE*, Miadreza Shafie-Khah, *Senior Member, IEEE*, and João P. S. Catalão, *Fellow, IEEE*

***Abstract*—In the evolution of the power systems, a particular case is the presence of a number of microgrids (MGs) operated with mutual interconnection, but without connection to the main distribution system. The interconnected MGs form a structure in which the overall system operation and resource scheduling can be determined by considering centralized or decentralized approaches. This article introduces local energy and reserve markets (LERMs) in which the MG managers (MGMs) can meet their required energy and reserve with optimal scheduling of their resources, besides competing with the other MGs. To model such decision-making framework for MGMs, a bilevel optimization approach is developed in which the MGMs' problem is modeled as the upper level problem and the LERMs clearing problem is modeled as the lower level problem. This model is transformed into a mathematical programming with equilibrium constraints (MPEC) using the primal-dual transformation. Then, the resulting MPEC for each MG is replaced with its Karush–Kuhn–Tucker conditions, obtaining an equilibrium problem with equilibrium constraints (EPEC) model. The nonlinear terms of the model are linearized through different approaches. Finally, the EPEC model is transformed into a mixed-integer linear problem considering the objective function of all MGMs. The model is applied to a test system with three interconnected MGs. Moreover, the sensitivity of the results to the probability of calling reserve is investigated.**

***Index Terms*—Bilevel optimization, energy and reserve, equilibrium problem with equilibrium constraints (EPECs), microgrids (MGs).**

Pouria Sheikhahmadi is with the Department of Electrical and Computer Engineering, University of Kurdistan, Sanandaj 66714, Iran (e-mail: pouria.sheikhahmadi@yahoo.com).

Salah Bahramara is with the Department of Electrical Engineering, Sanandaj Branch, Islamic Azad University, Sanandaj 6616935391, Iran (e-mail: s_bahramara@yahoo.com).

Andrea Mazza and Gianfranco Chicco are with the Dipartimento Energia "Galileo Ferraris,", Politecnico di Torino, 10129 Torino, Italy (e-mail: andrea.mazza@polito.it; gianfranco.chicco@polito.it).

Miadreza Shafie-Khah is with the School of Technology and Innovations, University of Vaasa, 65200 Vaasa, Finland (e-mail: miadreza@gmail.com).

João P. S. Catalão is with the Faculty of Engineering of the University of Porto and INESC TEC, 4200-465 Porto, Portugal (e-mail: catalao@fe.up.pt).

NOMENCLATURE

Acronyms

DG	Distributed generation.
EPEC	Equilibrium problem with equilibrium constraints.
IL	Interruptible loads.
KKT	Karush–Kuhn–Tucker.
LERM	Local energy and reserve market.
LEM	Local energy market.
LL	Lower level.
LM	Local market.
LMO	Local market operator.
LRM	Local reserve market.
MG	Microgrid.
MGM	Microgrid manager.
MILP	Mixed inter linear programming.
MPCC	Mathematical programming with complementarity constraints.
MPEC	Mathematical programming with equilibrium constraints.
UL	Upper level.

Indices/Sets

t/T	Index of/Total time period.
j/J	Index/Maximum number of MGs.
j^*/J^*	Index/Maximum number of MGMs.
Λ_{j^*}	Set of MGs related to each MGM.

Parameters

$\mathrm{C}_j^{\mathrm{DG}}$	Bid of DGs to provide energy (\$/MWh).
$\mathrm{C}_j^{\mathrm{DG}\_R}$	Bid of DGs to provide reserve (\$/MWh).
$\mathrm{C}_{j,t}^{\mathrm{IL}}$	Bid of ILs to provide energy (\$/MWh).
$\mathrm{C}_{j,t}^{\mathrm{IL}\_R}$	Bid of ILs to provide reserve (\$/MWh).
k^{Reserve}	Share of load considered as reserve (%).
$P_{j,t}^{\mathrm{MGL}}$	Demand of MGs (MW).
$\bar{\mathrm{P}}_j^{\mathrm{DG}}$	Maximum power generation of DG (MW).
$\bar{\mathrm{P}}_{j,t}^{\mathrm{IL}}$	Maximum amount of IL (MW).
$\bar{\mathrm{P}}_{j,t}^{\mathrm{MG\_in}}/\bar{\mathrm{P}}_{\mathrm{j,t}}^{\mathrm{MG\_out}}$	Maximum MG power trading with LM (MW).

γ_t^R	Probability of calling reserve.

Variables

$C_t^{\mathrm{LEM}}/C_t^{\mathrm{LRM}}$	Bids of MGMs to LM ($/MWh).
$P_{j,t}^{\mathrm{DG}}$	Power generation of DG (MW).
$P_{j,t}^{\mathrm{IL}}$	IL amount (MW).
$P_{j,t}^{\mathrm{MG\_in}}$	Power purchased from LEM (MW).
$P_{j,t}^{\mathrm{MG\_out}}$	Power sold to LEM (MW).
$R_{j,t}^{\mathrm{MG\_in}}$	Reserve purchased from LRM (MW).
$R_{j,t}^{\mathrm{MG\_out}}$	Reserve provided to LRM by MG (MW).
$R_{j,t}^{\mathrm{DG}}$	Reserve provided by DG (MW).
$R_{j,t}^{\mathrm{IL}}$	Reserve provided by IL (MW).
TC_{j*}^{E}	Cost of the MGM to provide energy ($).
TC_{j*}^{R}	Cost of the MGM to provide reserve ($).
$\mathrm{TC}_{j*}^{\mathrm{MG}}$	Total cost of the MGM ($).
λ_t^{LEM}	Local energy market clearing price ($/MWh).
λ_t^{LRM}	Local reserve market clearing price ($/MWh).

Constraints

$E^{\mathrm{MG}}, E^{\mathrm{LMs}}, E^{\mathrm{M}}$	Equality constraints of MG, LMs, and MPEC problems, respectively.
$N^{\mathrm{MG}}, N^{\mathrm{LMs}}, N^{\mathrm{M}}$	Nonequality constraints of MG, LMs, and MPEC problems, respectively.

Dual Variables

μ^{LMs}	Dual variables of nonequality constraints of LMs problem.
$\gamma^{\mathrm{M}}, \gamma^{\mathrm{LMs}}, \gamma^{\mathrm{MGs}}$	Dual variables of equality constraints of MPEC problem.
$\beta^{\mathrm{M}}, \beta^{\mathrm{LMs}}, \beta^{\mathrm{MGs}}$	Dual variables of nonequality constraints of MPEC problem.

Lagrangian Function

$\mathrm{L}^{\mathrm{LL}}/\mathrm{L}^{\mathrm{M}}$	Lagrangian function of the LL/MPEC problem.

Decision variable sets

$\boldsymbol{X}^{\mathrm{UL}}$	Decision variables of the UL problem.
$\boldsymbol{X}^{\mathrm{LL}}$	Decision variables of the LL problem.
Ξ_{j^*}	Decision variables of MPEC problem.

I. Introduction

In THE smart grid environment, the operation problem of distribution networks has changed in the presence of distributed generation (DG) and interruptible loads (ILs) [1]. DG and ILs can be integrated to achieve the better operation of the network and can be exploited as well within microgrids (MGs). In each MG, the MG manager (MGM) meets its local demand through optimal trading with the main grid and the other MGs, together with the scheduling of its DG and ILs.

The presence of MGs in a part of the distribution system facilitates supplying the demand of this part in isolated mode (that is, without connection to the distribution system) as an important capability of the future smart grids. The benefits of such operation for the system is mentioned in detail in the IEEE standard 1547.4 [2]. More extensively, the connection of MGs with each other forms a multi-MG (MMG) system, in which the operation and resource scheduling depends on the interactions among the MGMs, each of which tends to follow the most convenient operation of its MG. The decision-making problem of MGMs to supply their local demand in both grid-connected and isolated modes has been investigated in many studies.

The energy management problem of a grid-connected MG considering the uncertainties of renewable power generation is formulated as a mixed-integer linear programming (MILP) model in [3]. A two-stage robust model predictive control method is proposed in [4] to minimize the energy management problem of an isolated MG considering the uncertainties without determining any amount of the reserve. The authors of [5] proposed a co-optimization model for the operation problem of an isolated MG. In this model, the MG resources are scheduled to provide the required amount of energy and reserves of the system, simultaneously.

In some studies, the MGMs supply their demands when they trade energy with the distribution company (Disco) through fixed and variable retail prices [6]–[9]. In [6], the energy trading among the Disco and the MGs is modeled considering fixed retail prices using the system of systems framework. The energy management of a hybrid ac–dc distribution network with several MGs is modeled in [7] as a two-stage robust bilevel optimization approach considering uncertainties of renewable energy sources. The proposed bilevel model is transformed into a mathematical programming with complementarity constraints (MPCC) using the Karush–Kuhn–Tucker (KKT) conditions. The bilevel optimization approach is adopted to model the decision-making problem of the Disco in the presence of the MGs when the Disco acts in the wholesale energy market as a price-taker [8] and price-maker [9] player. In such models [8], [9], the prices of power exchange between the Disco and the MGs are determined in the optimization process. Moreover, the proposed models are transformed into a mathematical programming with equilibrium constraints (MPEC) using the KKT conditions and dual theory [10].

The distribution network is modeled as an MMG network considering the MG cooperation in [11]–[13]. In [11], the energy management problem in the MMG system is addressed using a dynamic programming approach. Load management in many grid-connected MGs is optimized in [12] using a cooperative power dispatching algorithm to minimize the network operation cost under demand uncertainty. The cooperation among MMGs is modeled in [13] using a multiagent system to minimize the system operation cost.

The operation problem of MMGs not connected to the main distribution system is addressed in some studies. In this case, the MGMs can only trade energy and/or reserve capacity with the other MGs. Since each MGM can try to maximize its profit, the MGMs have conflict of interest to obtain the maximum market share. Therefore, appropriate models are needed to model such decision-making framework among MGs.

TABLE I
COMPARISON OF THE MODEL PROPOSED IN THIS ARTICLE WITH THE ONES PROPOSED IN THE LITERATURE

Ref.	Decision makers			Mode of MG operation		The trading power environment		Type of LMs/retail price		Modeling strategic behavior of other players	Type of model
	Disco	MG	MMG	Grid-connected	Not connected	Retail price	LMs	Energy	Reserve		
[3]	-	✓	-	✓	-	✓	-	✓	-	-	MILP
[4]	-	✓	-	-	✓	✓	-	✓	-	-	Model predictive control
[5]	-	✓	-	-	✓	✓	-	✓	✓	-	MILP
[6]	✓	-	✓	✓	-	✓	-	✓	-	-	System of systems
[7]	✓	-	✓	✓	-	✓	-	✓	-	-	MPCC
[8]	✓	-	✓	✓	-	✓	-	✓	-	-	MPEC
[9]	✓	-	✓	✓	-	✓	-	✓	-	-	MPEC
[11]	-	-	✓	✓	-	✓	-	✓	-	-	Dynamic Programming
[12]	-	-	✓	✓	-	✓	-	✓	-	-	Statistical cooperative power dispatching
[13]	-	-	✓	✓	-	✓	-	✓	-	-	Multi-agent system
[14]	-	-	✓	-	✓	✓	-	✓	-	-	MILP
[15]	-	-	✓	-	✓	✓	-	✓	-	-	Multi-step algorithm
[16]	-	-	✓	-	✓	✓	-	✓	-	-	Wild goat algorithm
[17]	-	-	✓	-	✓	✓	-	✓	-	-	Genetic algorithm
[18]	-	-	✓	-	✓	✓	-	✓	✓	-	MILP
[19]	-	-	✓	-	✓	✓	-	✓	-	-	Hierarchical distributed algorithm
[20]	-	-	✓	✓	✓	✓	-	✓	-	-	Coalitional game theory
[21]	-	-	✓	-	✓	✓	-	✓	-	-	MILP
[22]	-	-	✓	✓	✓	✓	-	✓	-	-	MILP
This article	-	-	✓	-	✓	-	✓	✓	✓	✓	EPEC

A bilevel energy management system is proposed in [14] for the optimal energy scheduling of MMGs. The energy scheduling of every single on-fault MGs operated in isolated mode and the power and information trading among MGs are modeled in the inner level and the outer level, respectively. The performance of the MMG system in a standalone mode is investigated in [15] through four indices consisting of power generation penetration, power exchange, reliability, and economic indices. For this purpose, a multistep algorithm is developed to schedule the energy exchange among the MGs to improve the mentioned indices.

The energy management problem of an isolated MMG is modeled in [16], in which the price of power exchange between two MGs is determined by the seller MG. Then, the buyer MG sells power to its consumers with high prices to increase profit. A new optimization problem is developed in [17] to minimize the operation cost of the MGs in a standalone MMG system considering the underfrequency load shedding scheme. Energy management in a standalone MMG is modeled in [18] using the primary and secondary reserves to enhance frequency security. To this aim, the MGs trade energy and reserve with each other with fixed prices.

In [19], the operation problem of a particular system with electrically isolated MGs connected through ships that transport natural gas and are equipped with storage is analyzed using a new multienergy management approach. In the framework presented, two types of MGs for resource island and load island are managed by the operators and the aggregators, respectively. The power exchange problem among several MGs is modeled in [20] from the viewpoint of a virtual operator. In this approach, each MG meets its load with local energy resources, determining the status of the MG to act as a seller (with extra energy) or a buyer (with shortage energy). Then, two approaches are proposed to trade energy among the MGs.

The power trading among some MGs is carried out using a hybrid energy management approach in [21]. For this purpose, a bilevel optimization framework is developed where the cost minimization problem of each MG is modeled in the lower level (LL) problem, and the total operation cost of the networked MGs is modeled in the upper level (UL) one. In this study, the power exchange among the MGs and the MG community is done through bilateral contracts. A day-ahead self-healing energy management problem of an isolated networked MG is formulated using a bilevel optimization approach in [22]. In this model, the UL problem aims at scheduling the MGs in the normal conditions, and the LL one manages the operation of the MGs in self-healing and the islanded mode during the occurrence of fault. The price of power exchange among the MGs is assumed to be equal to the MG marginal cost.

Table I shows a comparison between the models reported in the literature. The main research gaps concluded from the previous studies are as follows.

1) Since each MGM, as an independent decision maker, wants to sell/purchase energy to/from other MGs at the maximum/minimum price, an appropriate framework is required in which the behavior of all MGs is modeled strategically. In this case, no MG is willing to change its strategies from the obtained results in the optimum point (Nash equilibrium point). As shown in Table I, different approaches are proposed to trade energy among the MGs, such as bilateral contracts, cooperation among the MGs, or energy management through an operator.[1] None of these proposed models can satisfy the mentioned trading strategy among the MGs.[2]

[1]The price of trading energy among the MGs in these approaches is named as the retail price in comparison with the price determined in LERMs in this article (see Table I).

[2]It should be noted, although the proposed model in [19] guarantees the Nash equilibrium among the players, it only can be used in the frameworks where the producers (operator in that study) sell energy to the consumers (aggregator in that study). In fact, the proposed model in [19] cannot be used for the MGs since the MG role in trading energy with the other MGs changes constantly from producers to consumers and vice versa.

2) In an isolated mode, each MGM is responsible for the economic, secure, and reliable operation of its MG, and determines a specific amount of the reserve capacity needed to ensure MG supply adequacy. For this purpose, the MGMs decide to supply this capacity from their resources or purchasing this capacity from the other MGs. Also, some of the MGs with extra capacity can provide the reserve capacity for the other ones. Considering the previous reason, it is required to model the behavior of all the MGs to provide the reserve capacity for each other strategically. The previous studies have not either addressed providing the reserve capacity [14]–[17], [19]–[22] or, despite of addressing that, these studies have not considered the competition among the MGs to meet the required reserve of the system [18]. For example, in [20], it is assumed that if there is not enough power to trade energy among the MGs, the MGs can receive energy from the main grid.
3) The MGM decisions to provide the reserve capacity for each other have effect on their strategies to trade energy with each other. Therefore, the strategic behavior of the MGMs to trade energy and the reserve capacity with each other is needed to be modeled simultaneously. However, this issue is not addressed in the previous studies.

Therefore, an appropriate decision-making framework is required to model the competition of the MGMs to trade energy and reserve capacity with each other to address the mentioned gaps in the previous studies. For this purpose, the competition among the MGMs is modeled in a local energy market (LEM) and a local reserve market (LRM) managed by the local market operator (LMO). In the proposed model, the behaviors of all the MGMs are modeled strategically, so that the resulting model guarantees the presence of the Nash equilibrium point among the MGMs.

To model such framework, a bilevel optimization approach is formulated, where the problems of the MGMs and clearing markets are modeled in the UL and LL, respectively. The LL problem is replaced with its primal-dual conditions, obtaining a MPEC problem for each MG. The MPEC of each MG is then replaced with its KKT conditions to obtain the equilibrium points between the MGs in the form of an equilibrium problem with equilibrium constraints (EPEC).

The EPEC model proposed in this article leads to a better computation time in comparison with the iterative approach used to solve the MPEC model. Moreover, the EPEC model guarantees the presence of the Nash equilibrium point where each MG cannot obtain more profit from changing its strategies from the initial ones.

The main contributions of this article compared with previous studies are as follows.

1) Modeling the local energy and reserve markets (LERMs) where the individual MGs can trade energy and reserves with each other and meet their required energy and reserves.
2) Modeling the MG decision-making problem in the proposed LERMs when the MGs model the strategic behavior of other MGs in the markets.
3) Transforming the proposed bilevel optimization problem into an EPEC model to obtain the optimal scheduling of MG resources, the optimal power trading among MGs, and the LERM prices.

The rest of this article is organized as follows. The problem description is presented in Section II. The proposed decision-making problem is mathematically formulated in Section III. The numerical results are given in Section IV. Finally, Section V concludes this article.

II. Problem Description

In this article, the decision-making problem of the MGMs to meet their loads in an MMG system is investigated, while they can trade energy and reserves with the local markets (see Fig. 1). The distribution network (if any) is not connected. Hence, there is no wholesale energy nor reserve market that involves an upstream system. In this system, the MGMs can trade energy among them through the common bus that connect them to each other. Also, the MGM decisions to trade energy with each other are determined in LERMs cleared by the LMO. To this aim, each MGM models its decision-making problem in the local markets considering the strategic behavior of the other MGMs.

A bilevel optimization approach is proposed, as described in Step 1 of Fig. 2. The cost minimization of each MGM is represented in the UL problem considering the technical constraints of the UL problem.

In each MG, the DG and the IL send their bids to provide energy and reserve to the MGMs, regarding which the MGMs decide on the optimal scheduling of these resources and their bids are sent ($C_{j,t}^{\mathrm{LEM}}$, $C_{j,t}^{\mathrm{LRM}}$) to the LERMs. The LERMs clearing process problem is modeled as the LL problem. The LMO receives the bids from MGMs and clears the LERMs with the aim of minimizing the objective function considering the related constraints. The set of variables $\boldsymbol{X}^{\mathrm{LL}}$ of the LL problem, are sent to the UL problem and have important impacts on the decisions of the MGM. On the other hand, the decisions of the MGM to meet its required energy and reserve including its bids sent to the LERMs impact on the market output results.

To model such decision-making framework for each MGM when it models the strategic behavior of other MGs in the LERMs, at first, the proposed bilevel model for each MGM is transformed into an MPEC model. For this purpose, the primal-dual transformation is used to transform the LL problem into several constraints as presented in Step 2 of Fig. 2. It should be noted that, both the primal-dual transformation and the KKT conditions can be used in this step. Since there are several binary variables in the KKT conditions which lead to nonconvexity of the model and the MPEC model must be convex to obtain the EPEC one, the primal-dual transformation is used in this step.

Therefore, the MPEC model for each MGM is obtained with the same objective function of the UL problem, the UL constraints, and the new form of the LL problem. There are two main approaches to solve the MPEC problem. In the first approach, the MPEC problem is replaced with its KKT conditions, obtaining the EPEC model. This approach can be used when the MPEC is

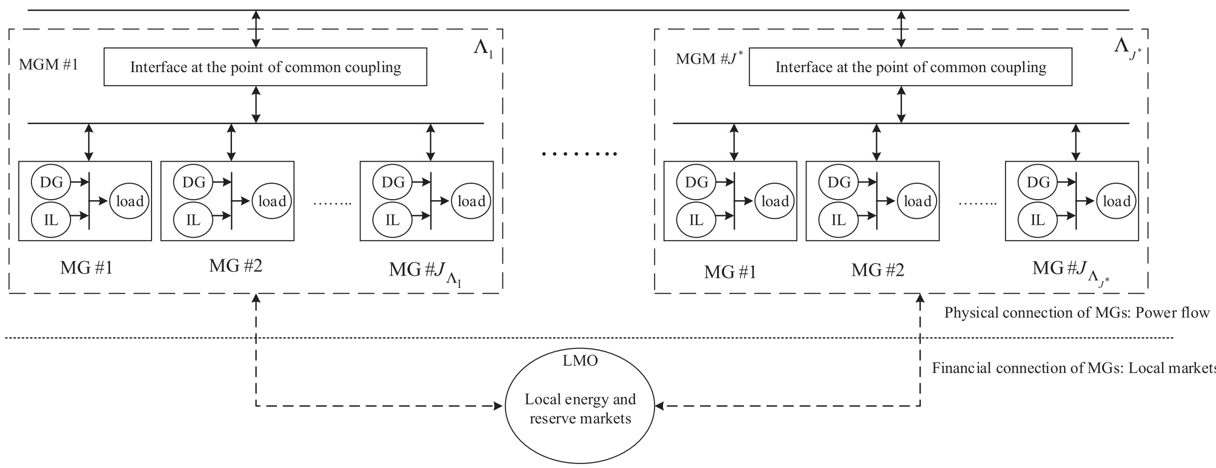

Fig. 1. MMG system considered in this article.

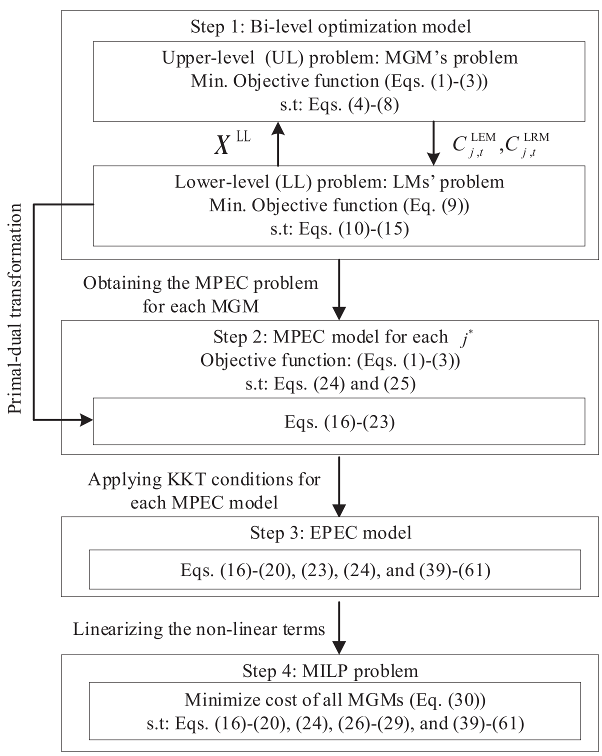

Fig. 2. Proposed approach to transform the bilevel optimization model into an MILP problem.

linear and thus convex. When the MPEC is nonlinear, iterative approaches are used to solve the model. For this reason, since the resulted MPEC model in this article is linear and, thus, convex, it is replaced with its KKT conditions to obtain the EPEC model.

This approach has the following two main advantages in comparison with iterative ones.

1) The computation efficiency of the KKT approach is better than the iterative one because in the KKT approach, one optimization model (EPEC) is solved while in the iterative approach, some optimization problems are solved [23].
2) Iterative algorithms might result in either nonconvergence or local optimal solution. This is while, the resulted EPEC model, which is transformed into an MILP one in this article, which guarantees the global optimal solution [10].

Therefore, in this article, the KKT conditions are applied to each MPEC problem as described in Step 3 of Fig. 2, regarding, which the EPEC model is obtained. Then, several nonlinear terms in the EPEC model are linearized using appropriate approaches. The resulted EPEC model consists of several equality and nonequality constraints. To obtain the equilibrium point among the MGs, the EPEC model needs an objective function. For this purpose, the total cost of the MGs is considered as the objective function, and the MILP problem is formulated as shown in Step 4. The mathematical expressions referring to the proposed approach illustrated in Fig. 2 are detailed in the following section.

III. Mathematical Formulation

The proposed bilevel model is formulated in this section.

A. *MGMs Problem: UL Problem*

The decision-making problem of the MGMs as the UL problem is modeled as follows.

1) Objective Function: The total operation cost of the MGM is modeled in (1), consisting of the cost of providing energy and reserve, respectively. The first term of (1), modeled in (2), is the sum of the cost of trading power with the LEM, the cost of power generation of DGs, and the cost of load curtailment. The second term of (2), modeled in (3), consists of the cost of trading reserve with the LRM, the cost of providing reserve by the DG and IL, and the cost of providing reserve when the reserve is called. The probability γ_t^R of calling reserve is used as a parameter.

$$\min_{\boldsymbol{X}^{\mathrm{UL}}} \mathrm{TC}_{j^*}^{\mathrm{MG}} = \mathrm{TC}_{j^*}^{E} + \mathrm{TC}_{j^*}^{R} \ \forall j^* \tag{1}$$

$$\mathrm{TC}_{j^*}^{\mathrm{E}} = \sum_{t=1}^{T} \sum_{j \in \Lambda_{j^*}} \begin{bmatrix} \lambda_t^{\mathrm{LEM}} \left(P_{j,t}^{\mathrm{MG\_in}} - P_{j,t}^{\mathrm{MG\_out}} \right) \\ + \mathrm{C}_j^{\mathrm{DG}} P_{j,t}^{\mathrm{DG}} + \mathrm{C}_{j,t}^{\mathrm{IL}} P_{j,t}^{\mathrm{IL}} \end{bmatrix} \tag{2}$$

$$\mathrm{TC}_{j^*}^R = \sum_{t=1}^{T} \sum_{j\in\Lambda_{j^*}} \begin{bmatrix} \lambda_t^{\mathrm{LRM}} \left(R_{j,t}^{\mathrm{MG\_in}} - R_{j,t}^{\mathrm{MG\_out}} \right) + \mathrm{C}_j^{\mathrm{DG}\_R} R_{j,t}^{\mathrm{DG}} \\ + \mathrm{C}_{j,t}^{\mathrm{IL}\_R} R_{j,t}^{\mathrm{IL}} + \mathrm{C}_j^{\mathrm{DG}} R_{j,t}^{\mathrm{DG}} \gamma_t^R + \mathrm{C}_{j,t}^{\mathrm{IL}} R_{j,t}^{\mathrm{IL}} \gamma_t^R \\ + \lambda_t^{\mathrm{LEM}} \left(R_{j,t}^{\mathrm{MG\_in}} - R_{j,t}^{\mathrm{MG\_out}} \right) \gamma_t^R \end{bmatrix} \tag{3}$$

2) UL Constraints: The power and reserve balance constraints of each MGM[3] are modeled as (4) and (5), respectively.[4]

$$E_{j,t}^{\mathrm{MG},1} : P_{j,t}^{\mathrm{DG}} + P_{j,t}^{\mathrm{IL}} + P_{j,t}^{\mathrm{MG\_in}} - P_{j,t}^{\mathrm{MG\_out}} - P_{j,t}^{\mathrm{MGL}} = 0 \quad \forall j,t \tag{4}$$

$$E_{j,t}^{\mathrm{MG},2} : R_{j,t}^{\mathrm{DG}} + R_{j,t}^{\mathrm{IL}} + R_{j,t}^{\mathrm{MG\_in}} - R_{j,t}^{\mathrm{MG\_out}} - k^{\mathrm{Reserve}} P_{j,t}^{\mathrm{MGL}} = 0 \ \forall j,t. \tag{5}$$

The technical constraints of DG to provide energy and reserve are modeled by the following equation:

$$N_{j,t}^{\mathrm{MG},1} : P_{j,t}^{\mathrm{DG}} + R_{j,t}^{\mathrm{DG}} \le \bar{\mathrm{P}}_j^{\mathrm{DG}}, \ N_{j,t}^{\mathrm{MG},2} : P_{j,t}^{\mathrm{DG}} \ge 0, \ N_{j,t}^{\mathrm{MG},3} : R_{j,t}^{\mathrm{DG}} \ge 0 \ \forall j,t. \tag{6}$$

The technical constraints of IL to provide energy and reserve are modeled by (7). A contract mechanism is defined between the MGM and the IL where the IL sends its bids to provide energy ($C_{j,t}^{\mathrm{IL}}$) and reserve capacity ($C_{j,t}^{\mathrm{IL}\_R}$) as well as the maximum amount of load that can be curtailed ($\bar{P}_{j,t}^{\mathrm{IL}}$) to the MGM. Then, the MGM problem is optimized, regarding which the amount of IL ($P_{j,t}^{\mathrm{IL}}$), and the reserve provided by the IL ($R_{j,t}^{\mathrm{IL}}$) are obtained. The MGM pays the related cost to the IL regarding the related terms modeled in (2) and (3).

$$N_{j,t}^{\mathrm{MG},4} : P_{j,t}^{\mathrm{IL}} + R_{j,t}^{\mathrm{IL}} \le \overline{\mathrm{P}}_{j,t}^{\mathrm{IL}}, \ \ N_{j,t}^{\mathrm{MG},5} : P_{j,t}^{\mathrm{IL}} \ge 0\,, \ \ N_{j,t}^{\mathrm{MG},6} : R_{j,t}^{\mathrm{IL}} \ge 0 \quad \forall j,t \tag{7}$$

The bids/offers of the MGM in the LERMs are considered as the nonnegative variables as modeled in the following equation:

$$N_{j,t}^{\mathrm{MG},7} : C_{j,t}^{\mathrm{LEM}} \ge 0 \ \ , N_{j,t}^{\mathrm{MG},8} : C_{j,t}^{\mathrm{LRM}} \ge 0 \quad \forall j \in \Lambda_{j^*}, t. \tag{8}$$

The price bids of the MGMs ($C_{j,t}^{\mathrm{LEM}}$, $C_{j,t}^{\mathrm{LRM}}$) are formally modeled in the objective function of the LL model, however, they do not appear in the UL problem, expect (8). In this respect, the objective function of the UL problem is optimized considering its constraints, i.e., (4)–(8) and also the LL optimization problem. The set of variables of the UL problem is $\boldsymbol{X}^{\mathrm{UL}} = \{P_{j,t}^{\mathrm{DG}}, P_{j,t}^{\mathrm{IL}}, R_{j,t}^{\mathrm{DG}}, R_{j,t}^{\mathrm{IL}}, C_{j,t}^{\mathrm{LEM}}, C_{j,t}^{\mathrm{LRM}}, X^{\mathrm{LL}}\}$. Therefore, the terms $C_{j,t}^{\mathrm{LEM}}$ and $C_{j,t}^{\mathrm{LRM}}$ are determined from solving the final MILP model obtained as indicated in Section III.G.

[3]The possible presence of energy storage in the MGs is assumed to be already considered in the definition of the MG demand ($P_{j,t}^{\mathrm{MGL}}$). In fact, the MG demand which is regarded as a parameter in this model can be changed to a variable considering charging/discharging of the energy storage within the energy management of the MGMs and considering the local market. Therefore, energy-management-related matters are seen as aspects that are defined locally and concur in the definition of the MG demand.

[4]For simplification using the equality and nonequality constraints in other sections, they are named with "*E*" and "*N*," respectively.

B. LERMs Problem: LL Problem

The problem of LMO to clear the LERMs is formulated in this section.

1) Objective Function: The objective function of the LERMs[5] is modeled as (9) consisting of the (negative) revenues from trading power with the MGs, from reserve provision for the MGs, and from providing energy after calling reserves.

$$\min_{\boldsymbol{X}^{\mathrm{LL}}} \mathrm{TC}^{\mathrm{LM}} = \sum_{t=1}^{T} \sum_{j=1}^{J} \begin{bmatrix} -C_{j,t}^{\mathrm{LEM}} (P_{j,t}^{\mathrm{MG\_in}} - P_{j,t}^{\mathrm{MG\_out}}) - \\ C_{j,t}^{\mathrm{LRM}} \left(R_{j,t}^{\mathrm{MG\_in}} - R_{j,t}^{\mathrm{MG\_out}} \right) - \\ C_{j,t}^{\mathrm{LEM}} \left(R_{j,t}^{\mathrm{MG\_in}} - R_{j,t}^{\mathrm{MG\_out}} \right) \gamma_t^R \end{bmatrix}. \tag{9}$$

2) LL Constraints: Equations (10) and (11) meet the energy and reserve balances among the MGs as either the producer or the consumer in the LEM and LRM, respectively.

$$E_t^{\mathrm{LMs},1} : \sum_{j}^{J} (P_{j,t}^{\mathrm{MG\_out}} - P_{j,t}^{\mathrm{MG\_in}}) = 0 \quad \forall t : \lambda_t^{\mathrm{LEM}} \tag{10}$$

$$E_t^{\mathrm{LMs},2} : \sum_{j}^{J} \left(R_{j,t}^{\mathrm{MG\_out}} - R_{j,t}^{\mathrm{MG\_in}} \right) = 0 \quad \forall t : \lambda_t^{\mathrm{LRM}} \tag{11}$$

The limitations of trading energy and reserve of the MGs with the LERMs are modeled as the following equations:

$$N_{j,t}^{\mathrm{LMs},1} : P_{j,t}^{\mathrm{MG\_in}} + R_{j,t}^{\mathrm{MG\_in}} \le \bar{\mathrm{P}}_j^{\mathrm{MG\_in}} \ \forall j,t : \mu_{j,t}^{\mathrm{LMs},1} \tag{12}$$

$$N_{j,t}^{\mathrm{LMs},2} : P_{j,t}^{\mathrm{MG\_in}} \ge 0 : \mu_{j,t}^{\mathrm{LMs},2},$$

$$N_{j,t}^{\mathrm{LMs},3} : R_{j,t}^{\mathrm{MG\_in}} \ge 0 : \mu_{j,t}^{\mathrm{LMs},3} \ \forall j,t \tag{13}$$

$$N_{j,t}^{\mathrm{LMs},4} : P_{j,t}^{\mathrm{MG\_out}} + R_{j,t}^{\mathrm{MG\_out}} \le \bar{\mathrm{P}}_j^{\mathrm{MG\_out}} \ \forall j,t : \mu_{j,t}^{\mathrm{LMs},4} \tag{14}$$

$$N_{j,t}^{\mathrm{LMs},5} : P_{j,t}^{\mathrm{MG\_out}} \ge 0 \ : \mu_{j,t}^{\mathrm{LMs},5},$$

$$N_{j,t}^{\mathrm{LMs},6} : R_{j,t}^{\mathrm{MG\_out}} \ge 0 \ : \mu_{j,t}^{\mathrm{LMs},6} \ \forall j,t. \tag{15}$$

The dual variables of the LL problem constraints are written at the right side of the constraints. Therefore, the set of variables of the LL problem is specified as $\boldsymbol{X}^{\mathrm{LL}} = \{ P_{j,t}^{\mathrm{MG\_LM\_in}}, P_{j,t}^{\mathrm{MG\_LM\_out}}, R_{j,t}^{\mathrm{MG\_LM\_in}}, R_{j,t}^{\mathrm{MG\_LM\_out}}, \lambda_t^{\mathrm{LEM}}, \lambda_t^{\mathrm{LRM}}, \mu_{j,t}^{\mathrm{LMs},1}, \ldots, \mu_{j,t}^{\mathrm{LMs},6}\}$.

The MGM considers the IL bids in its objective function, as shown in (2) and (3). Also, the decision variables related to ILs are modeled in the power and reserve balance constraints of the MGM in (4) and (5), respectively. Regarding these equations, the optimal decisions of the IL are linked to the decision variables of the LL problem (9)–(15) including the energy and reserve traded of the MGM with the market. The MGM optimizes its objective function considering the bids of the IL and its constraint, regarding which the MGM participates in the markets. Therefore, modeling the IL has effect on the LL problem through the MGM energy and reserve bids on the one hand, and on the amount of IL and the reserve provided by the IL on the other hand.

[5]In the superscripts used in the names of the variables, the acronym LERM is abbreviated as LM.

C. Primal-Dual Transformation

In this section, the LL problem is replaced with several constraints regarding the dual-primal transformation as described in Appendix A. The resulting equations from this transformation are described as (16)–(23).

The dual variables ($\gamma^{\mathrm{M},1}_{j^*,j,t}-\gamma^{\mathrm{M},4}_{j^*,j,t}, \gamma^{\mathrm{LMs},1}_{j^*,t}-\gamma^{\mathrm{LMs},2}_{j^*,t}, \beta^{\mathrm{LMs},1}_{j^*,j,t}-\beta^{\mathrm{LMs},6}_{j^*,j,t}$, $\beta^{\mathrm{M},1}_{j^*,j,t}-\beta^{\mathrm{M},6}_{j^*,j,t}$, and $\gamma^{\mathrm{M},5}_{j^*}$) of LL problem constraints are written at the right side of them. The first derivation of the Lagrangian function of the LL problem with respect to its decision variables leads to obtaining the stationarity constraints which are shown in (16)–(19). To simplify using these equations in the EPEC model, they are named as $\mathrm{E}^{\mathrm{M},1}_{j,t},\ldots,\ \mathrm{E}^{\mathrm{M},4}_{j,t}$. Equation (20) indicates the same equality constraints of the LL problem, i.e., (10) and (11). Equation (21) indicates the same nonequality constraints (12)–(15) of the LL problem. Equation (22) is used to show that the dual variables of the LL problem are positive. The primal-dual constraint (23) shows that the primal and dual objective functions of the LL problem are equal.

3) Stationarity Constraints:

$$E^{\mathrm{M},1}_{j,t}:\ -C^{\mathrm{LEM}}_{j,t}+\lambda^{\mathrm{LEM}}_{t}+\mu^{\mathrm{LMs},1}_{j,t}-\mu^{\mathrm{LMs},2}_{j,t}=0\quad\forall j,t:\gamma^{M,1}_{j^*,j,t}\tag{16}$$

$$E^{\mathrm{M},2}_{j,t}:C^{\mathrm{LEM}}_{j,t}-\lambda^{\mathrm{LEM}}_{t}+\mu^{\mathrm{LMs},4}_{j,t}-\mu^{\mathrm{LMs},5}_{j,t}=0\quad\forall j,t:\gamma^{M,2}_{j^*,j,t}\tag{17}$$

$$E^{\mathrm{M},3}_{j,t}:\ -C^{\mathrm{LRM}}_{t}-C^{\mathrm{LEM}}_{t}\gamma^{R}_{t}+\lambda^{\mathrm{LRM}}_{t}+\mu^{\mathrm{LMs},1}_{j,t}-\mu^{\mathrm{LMs},3}_{j,t}=0\quad\forall j,t\ :\gamma^{M,3}_{j^*,j,t}\tag{18}$$

$$E^{\mathrm{M},4}_{j,t}:C^{\mathrm{LRM}}_{t}+C^{\mathrm{LEM}}_{t}\gamma^{R}_{t}-\lambda^{\mathrm{LRM}}_{t}+\mu^{\mathrm{LMs},4}_{j,t}-\mu^{\mathrm{LMs},6}_{j,t}=0\quad\forall j,t\ :\gamma^{M,4}_{j^*,j,t}\tag{19}$$

2) Primal Constraints:

$$E^{\mathrm{LMs},1}_{t}:\gamma^{\mathrm{LMs},1}_{j^*,t}\ ,\quad E^{\mathrm{LMs},2}_{t}:\gamma^{\mathrm{LMs},2}_{j^*,t}\tag{20}$$

$$\begin{gathered}N^{\mathrm{LMs},1}_{t}:\beta^{\mathrm{LMs},1}_{j^*,j,t}\ ,\ N^{\mathrm{LMs},2}_{t}:\beta^{\mathrm{LMs},2}_{j^*,j,t}\ ,\ N^{\mathrm{LMs},3}_{t}:\beta^{\mathrm{LMs},3}_{j^*,j,t}\\ N^{\mathrm{LMs},4}_{t}:\beta^{\mathrm{LMs},4}_{j^*,j,t}\ ,\ N^{\mathrm{LMs},5}_{t}:\beta^{\mathrm{LMs},5}_{j^*,j,t}\ ,\ N^{\mathrm{LMs},6}_{t}:\beta^{\mathrm{LMs},6}_{j^*,j,t}\end{gathered}\tag{21}$$

3) Dual Constraints:

$$\begin{gathered}N^{M,1}_{j,t}:\mu^{\mathrm{LMs},1}_{j,t}\geq 0:\beta^{M,1}_{j^*,j,t}\ ,\quad N^{M,2}_{j,t}:\mu^{\mathrm{LMs},2}_{j,t}\geq 0:\ \beta^{M,2}_{j^*,j,t}\\ N^{M,3}_{j,t}:\mu^{\mathrm{LMs},3}_{j,t}\geq 0:\beta^{M,3}_{j^*,j,t}\ ,\quad N^{M,4}_{j,t}:\mu^{\mathrm{LMs},4}_{j,t}\geq 0:\beta^{M,4}_{j^*,j,t}\\ N^{M,5}_{j,t}:\mu^{\mathrm{LMs},5}_{j,t}\geq 0:\beta^{M,5}_{j^*,j,t}\ ,\ N^{M,6}_{j,t}:\mu^{\mathrm{LMs},6}_{j,t}\geq 0:\beta^{M,6}_{j^*,j,t}\end{gathered}\tag{22}$$

4) Primal-Dual Constraint:

$$E^{M,5}_{j,t}:\mathrm{TC}^{\mathrm{LM}}-\sum_{t=1}^{T}\sum_{j=1}^{J}\Big[-\mu^{\mathrm{LMs},1}_{j,t}\overline{\mathrm{P}}^{\mathrm{MG\_in}}_{j}-\mu^{\mathrm{LMs},4}_{j,t}\overline{\mathrm{P}}^{\mathrm{MG-out}}_{j}\Big]=0:\gamma^{M,5}_{j^*}\tag{23}$$

D. MPEC Model

Obtaining the MPEC model for each MGM regarding the constraints of Step 1 is as follows:

Equations (1)–(3)

$$E^{\mathrm{MG},1}_{j,t}:\gamma^{\mathrm{MG},1}_{j^*,j,t}\ ,\quad E^{\mathrm{MG},2}_{j,t}:\ \gamma^{\mathrm{MG},2}_{j^*,j,t}\tag{24}$$

$$\begin{gathered}N^{\mathrm{MG},1}_{j,t}:\beta^{\mathrm{MG},1}_{j^*,j,t}\ ,\ N^{\mathrm{MG},2}_{j,t}:\beta^{\mathrm{MG},2}_{j^*,j,t}\ ,\\ N^{\mathrm{MG},3}_{j,t}:\beta^{\mathrm{MG},3}_{j^*,j,t}\ ,\ N^{\mathrm{MG},4}_{j,t}:\beta^{\mathrm{MG},4}_{j^*,j,t}\\ N^{\mathrm{MG},5}_{j,t}:\beta^{\mathrm{MG},5}_{j^*,j,t}\ ,\ N^{\mathrm{MG},6}_{j,t}:\beta^{\mathrm{MG},6}_{j^*,j,t}\ ,\\ N^{\mathrm{MG},7}_{j,t}:\beta^{\mathrm{MG},7}_{j^*,j,t}\ ,\ N^{\mathrm{MG},8}_{j,t}:\beta^{\mathrm{MG},8}_{j^*,j,t}\end{gathered}\tag{25}$$

Equations (16)–(23).

Since the dual variables are needed to define for the UL problem to transform the MPEC model into the EPEC one, the equality (4) and (5) and nonequality (6)–(8) constraints of the UL problem are rewritten as (24) and (25), respectively. This is done to define the dual variables for these equations to use them in the variable set of the MPEC problem, specified as $\Xi_{j^*}=\{X^{\mathrm{UL}},X^{\mathrm{LL}},\lambda^{\mathrm{LEM}}_{t},\ \lambda^{\mathrm{LRM}}_{t},\ \mu^{\mathrm{LMs},1}_{j,t}-\mu^{\mathrm{LMs},6}_{j,t}\}$. Dual variables of (24) and (25) are written at the right-hand side of the equations.

E. EPEC Model

For the formulation of the EPEC model, the KKT conditions of the MPEC problem used for each MGM in Step 2. Details are described in Appendix B. These equations are as follows.

1) Stationarity constraints: These constraints which are described as (39)–(60) are obtained by derivation from the Lagrangian function respective to its decision variables.
2) Primal equality constraints: (16)–(20), (23), and (24).
3) The primal nonequality, the dual, and complementary slackness constraints, (61).

F. Linearization

Three types of nonlinearity are linearized in this section.

1) To solve the resulted EPEC model, the total cost of the MGMs is considered as the objective function. The nonlinear terms, i.e., $\lambda^{\mathrm{LEM}}_{t}(P^{\mathrm{MG\_in}}_{j,t}-P^{\mathrm{MG\_out}}_{j,t})$ and $\lambda^{\mathrm{LRM}}_{t}(R^{\mathrm{MG\_in}}_{j,t}-R^{\mathrm{MG\_out}}_{j,t})$ are linearized using the approach proposed in Appendix C [24].
2) The primal-dual constraint (23) is a nonlinear constraint that is replaced with its complementary constraints, (26)–(29), as follows:

$$0\leq(\bar{\mathrm{P}}^{\mathrm{MG\_in}}_{j}-P^{\mathrm{MG\_in}}_{j,t}-R^{\mathrm{MG\_in}}_{j,t})\perp\mu^{\mathrm{LMs},1}_{j,t}\geq 0\tag{26}$$

$$0\leq R^{\mathrm{MG\_in}}_{j,t}\perp\mu^{\mathrm{LMs},3}_{j,t}\geq 0\quad,\quad 0\leq P^{\mathrm{MG\_in}}_{j,t}\perp\mu^{\mathrm{LMs},2}_{j,t}\geq 0\tag{27}$$

$$0\leq(\bar{\mathrm{P}}^{\mathrm{MG\_out}}_{j}-P^{\mathrm{MG\_out}}_{j,t}-R^{\mathrm{MG\_out}}_{j,t})\perp\mu^{\mathrm{LMs},4}_{j,t}\geq 0\tag{28}$$

$$0\leq P^{\mathrm{MG\_out}}_{j,t}\perp\mu^{\mathrm{LMs},5}_{j,t}\geq 0\quad,\quad 0\leq R^{\mathrm{MG\_out}}_{j,t}\perp\mu^{\mathrm{LMs},6}_{j,t}\geq 0\tag{29}$$

where each equation is linearized as proposed in (62).

1) There are nonlinear terms (i.e., multiplication of two variables) in the (39)–(46), (51), and (52), which are linearized using the approximate approach named as "McCormick" [25], [26], which is a convenient tool to linearize the nonlinear terms. Details are described in Appendix D.

TABLE II
MG TECHNICAL AND ECONOMIC DATA

# MG	$\overline{P}_j^{\text{MG\_LM\_in}}$, $\overline{P}_j^{\text{MG\_LM\_out}}$(MW)	$\overline{P}_j^{\text{DG}}$ (MW)	C_j^{DG} (\$/MWh)	$C_j^{\text{DG\_R}}$ (\$/MWh)	k^{Reserve}
1	9.0	7.0	12.0	3.6	0.1
2	9.5	7.5	14.0	4.2	0.1
3	10.0	8.0	11.0	3.3	0.1

G. MILP Problem

The final MILP problem is as follows:

$$\begin{aligned}\text{TC} &= \sum_{j^*=1}^{J^*}\left[\text{TC}_{j^*}^{E}+\text{TC}_{j^*}^{R}\right]\\ &= \sum_{t=1}^{T}\sum_{j}^{J}\begin{bmatrix} C_j^{\text{DG}}P_{j,t}^{\text{DG}}+C_{j,t}^{\text{IL}}P_{j,t}^{\text{IL}}+\\ C_j^{\text{DG\_R}}R_{j,t}^{\text{DG}}+C_{j,t}^{\text{IL\_R}}R_{j,t}^{\text{IL}}+\\ C_j^{\text{DG}}R_{j,t}^{\text{DG}}\gamma_t^{\text{R}}+C_{j,t}^{\text{IL}}R_{j,t}^{\text{IL}}\gamma_t^{\text{R}}\end{bmatrix}\end{aligned} \tag{30}$$

subject to (16)–(20), (24), (26)–(29), and (39)–(61).

IV. NUMERICAL RESULTS

A. Input Data

To investigate the effectiveness of the proposed model, an MMG system with three MGs has been considered. The characteristics of the MG resources and loads consist of the maximum output power of DGs and the bids of DGs to provide energy and reserve, the maximum power trading with the LERMs, and the share of load associated with the required reserve (set to 10% in each MG), as shown in Table II.

Moreover, the demand profiles of MGs during the operation day, the bid of ILs to provide energy, and the maximum amount of ILs are drawn out from [8], [9].

The bid of ILs to provide reserve in each MG is considered as 30% of their bids to provide energy. In addition, the percentage of calling reserve in the base case is indicated to be 0 (different values are considered in the sensitivity analysis shown in Section IV-C).

To solve the proposed mathematical model under GAMS 24.1.2 with the CPLEX12 solver, a personal computer with the CPU speed of 2.6 GHz and 6 GB RAM is used.

B. Results

This section analyzes the base case results, considering the input data illustrated in the previous section. The outcomes of clearing the LERMs based on trading energy and reserve among the MGMs contain LERMs prices, the energy and reserve trading among MGs in the LERMs, the demand–supply balance as well as the reserve balance in each MG are presented in the next figures. Fig. 3 shows the LEM and LRM clearing prices. From Fig. 4, the MGMs 2 and 3 act as the consumer and the producer in the LEM, respectively, as well as MGM1 acts as the prosumer. As can be seen in Figs. 3–5, the LEM clearing prices are equal to 11 \$/MWh (the bid of MG3 DG) at hours 1–6, regarding which the MGMs 1 and 2 purchase power from LEM instead of using their DGs to meet their demands.

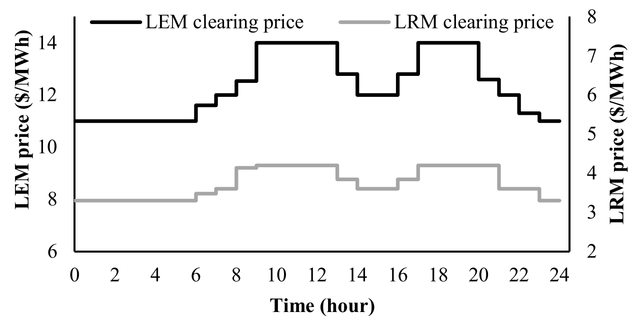

Fig. 3. LEM and LRM clearing prices.

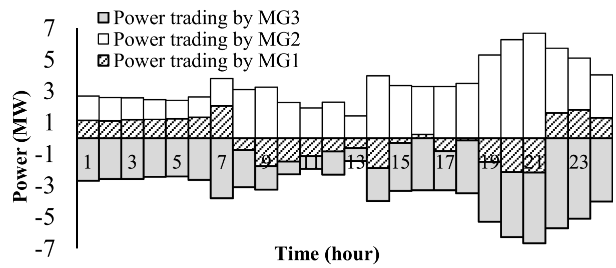

Fig. 4. Energy balance in the LEM.

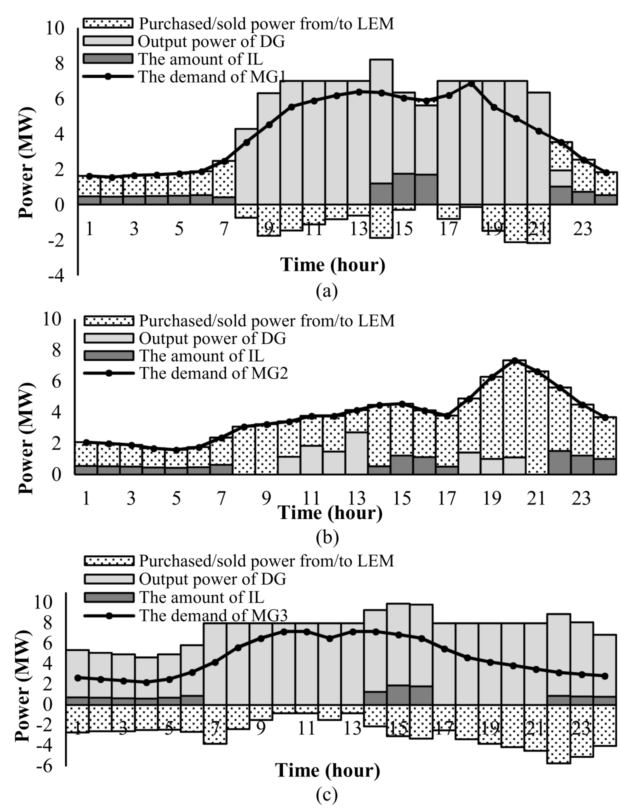

Fig. 5. Energy balance in each MG. (a) MG1. (b) MG2. (c) MG3.

It is noteworthy that the operation cost of MG3 would remain unchanged when MGM3 uses its DG either to only supply the demand of MG3 or to sell power to the LEM. However, MGM3 participates as a producer in the LEM with the aim of maximizing the social welfare of the market. At hour 7, the LEM

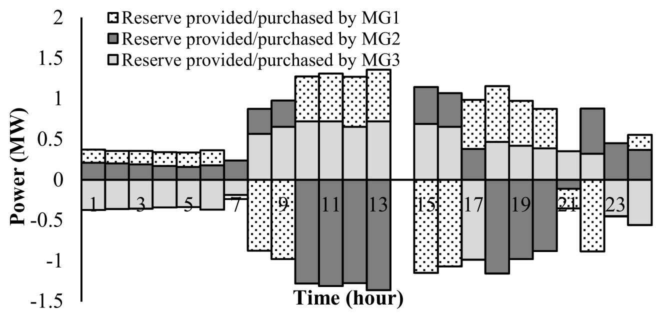

Fig. 6. Reserve balance in LRM. Positive values relate to reserve provided.

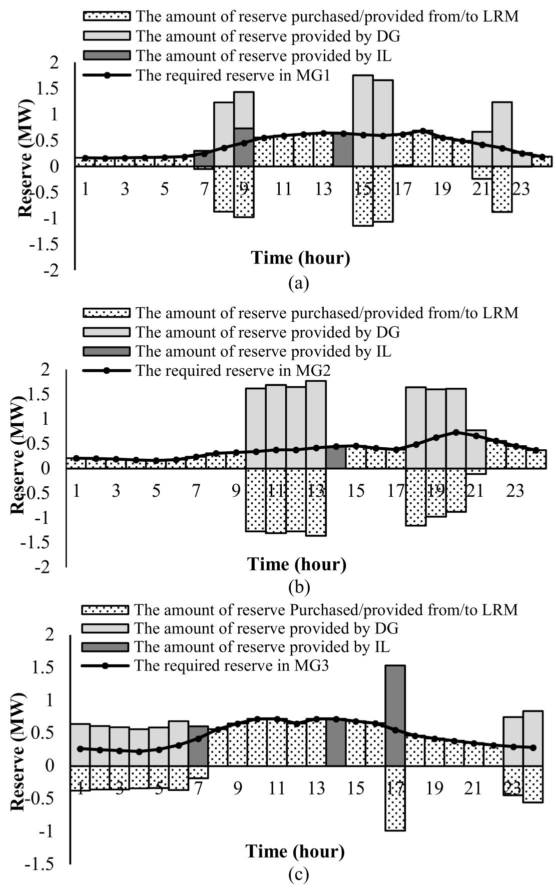

Fig. 7. Reserve balance in each MG. (a) MG. (b) MG2. (c) MG3.

price (11.6 \$/MWh) is specified by MGM3 as the producer. In fact, MGM3 exploits its DG with the lower bid than the LEM price to sell energy to other MGs. The LEM price at hours 8 and 9 is 12 \$/MWh and 12.54 \$/MWh, respectively. MGMs 1 and 3 act as the producers and MGM2 satisfies its demand by purchasing energy from LEM due to the LEM price, which is lower than its DG and IL bids. At hours 10–13, the LEM prices are cleared at 14 \$/MWh based on the bid of MG2 DG. As the matter of fact, MGM2 prefers to use a considerable part of its DG capacity to provide reserve in the LRM. Hence, MGMs 1 and 3 meet the required energy of MG2 with the higher LEM price than their DGs.

The LEM price is equal to bids of ILs (12.8 \$/MWh) at hour 14, as proposed by MGM2 which decides to apply the significant amount of the IL in MG2 to provide its own reserve. Thus, MGMs 1 and 3 sell the energy using their DGs as well as ILs to the LEM. MGM1 indicates the LEM prices (12 \$/MWh) at hours 15–16. Note that, MGM3 can sell the most significant power due to its DG with the lowest bid. Hence, MGM2 would have an opportunity to effectively participate in the LRM.

At hour 17, regarding the LEM price (12.8 \$/MWh), MGM2 uses a few parts of IL to provide energy and participate in the LEM as a consumer to purchase its required energy with the same price from other MGs as much as possible to maximize the social welfare of the LEM. The LEM price (14 \$/MWh) is indicated by MGM2 at hours 18–20. Since MGM2 makes decision to participate as a provider in the LRM, the other MGMs can sell the needed energy to MG2 in the LEM with an affordable LEM price. At hour 21, MGMs 1 and 3 would satisfy the whole energy for MGM2 using DGs 1 and 3 with the price of 12.6 \$/MWh. At hour 22, since MGM1 prefers to participate in the LRM as a provider using its DG, MGM3 would have an opportunity to satisfy other MG required energy with a price of 12 \$/MWh. In the last two hours, MGMs 1 and 2 can purchase energy from MG3 in the LEM with lower price than their DGs (11.3 \$/MWh and 11 \$/MWh, respectively).

According to Figs. 3, 6, and 7, the LRM is cleared at a price of 3.3 \$/MWh, which is related to the bid of DG3 to provide reserve at hours 1–6 and 24. The major reason is that there is no capacity of ILs in the MGs 1 and 2. Hence, MGM3 can participate in the LRM as a provider using its DG to meet the required reserve of MGs 1 and 2. At hour 7, MGM2 can purchase its required reserve from LRM with 3.48 \$/MWh instead of applying its DG with the bid higher than this price. At hour 8, MGMs 2 and 3 provide the reserve by their ILs with the bid of 3.84 \$/MWh, participating in the LRM with the price of 3.6 \$/MWh, which is equal to bid of DG1 to purchase their reserve. MGM1 provides the required reserve of the system in the LRM at hour 9 since the bid of DG2 is higher than the LRM price and the whole capacity of DG3 in used by MGM3 to meet the energy. MGMs 1 and 3 purchase their reserve from MG2 as the reserve provider in the LRM with a price of 4.2 \$/MWh (equal to the bid of DG2) at hours 10–13 and 18–20.

At hour 14, all the MGs satisfy their reserve by their respective ILs due to using the whole capacity of the DGs in the LEM by MGs 1 and 3 on the one hand, and the higher bid of DG compared to the IL bid in the MG2 on the other hand.

At hours 15 and 16, MGM3 has no own capacity to meet reserve and MGM2 can use only its DG with higher price than the bid of MGM1 to provide reserve in LRM. As a result, purchasing the reserve from MG1 with a price of 3.6 \$/MWh is the best choice. At hour 17, MGM2 decides to purchase reserve from the LRM with a lower price (3.84 \$/MWh) than its DG.

At hour 21, MGM3 prefers to purchase the reserve with a price of 4.2 \$/MWh instead of its IL with the bid of 5.94 \$/MWh. Note that at hour 21 MGMs 1 and 2 are the reserve providers where MGM1 has the priority for providing the reserve due to the lower bid of DG1. At hour 22, MGM2 should use its DG with the bid of 4.2 \$/MWh and also MGM3 has no resources to provide the reserve. Thus, both MGs can afford this problem

TABLE III
IMPACT OF THE CALLING RESERVE PARAMETER ON THE TOTAL COST OF MGS

γ_t^{R}	$TC_j^{\text{MG\_Energy}}$			$TC_j^{\text{MG\_Reserve}}$		
	MG1	MG2	MG3	MG1	MG2	MG3
0.0	1118.1	1111.1	1111.8	37.6	35	42.6
0.3	1116.4	1117.8	1106.8	82.5	50.3	101.8
0.5	1115.2	1122.3	1103.4	99.4	57	150.8
0.7	1126.9	1128	1145.7	123.3	167.7	33.4
1.0	1108.4	1135.4	1168.4	237.9	229.4	–83.3

TABLE IV
MGO DECISION-MAKING IN LERMS BASED ON CALLING RESERVE

γ_t^{R}	$\sum_t^T\left(P_{j,t}^{\text{MG\_LM\_in}} - P_{j,t}^{\text{MG\_LM\_out}}\right)$			$\sum_t^T\left(R_{j,t}^{\text{MG\_LM\_in}} - R_{j,t}^{\text{MG\_LM\_out}}\right)$		
	MG1	MG2	MG3	MG1	MG2	MG3
0.0	–1.482	68.655	–67.173	0.523	–3.996	3.473
0.3	–1.383	69.402	–68.019	0.391	–4.013	3.623
0.5	0.121	69.081	–69.201	–0.553	–4.522	5.075
0.7	–1.838	58.290	–56.451	1.150	5.863	–7.013
1.0	–6.794	56.946	–50.153	6.905	7.206	–14.111

due to purchasing their reserve from MG1 with the price of 3.64 \$/MWh in the LRM. At hour 23, MGM3 would have an opportunity to provide the reserve for MG2 at 3.6 \$/MWh in the LRM.

The results show the effectiveness of the model for representing the behavior of the MGMs, as explained hereafter.

1) The MGMs have an opportunity to purchase the required energy and reserve from the LERMs instead of using their resources with the higher bids than the LERM prices. For instance, MGM1 purchases its required energy and reserve from the LERMs with 11 \$/MWh and 3.3 \$/MWh instead of purchasing them from DG1 with the bids of 12 \$/MWh and 3.64 \$/MWh, respectively.
2) Using energy and reserve co-optimization, besides participating in both LERMs (LEM and LRM), the MGMs can make decisions to engage all the capacity of their own resources in only one LERM (LEM or LRM) to minimize their operation cost. For instance, MGM3 prefers to use the whole capacity of DG3 and IL3 to not only satisfy the demand of MG3, but also to sell energy to the LEM at hours 15–16. On the other hand, the required reserve in MG3 is met from the LRM.
3) The MGMs participate in the LERMs to maximize the social welfare at some hours without obtaining any revenue from trading energy and reserve with it (for instance, the participation of MGM 1 at hours 1–6 in the LERMs).

C. *Sensitivity Analysis*

In this section, the sensitivity of the total cost of the MGMs and their power and reserve trading with the LERMs to calling reserve parameter is investigated. Then, the tractability of the proposed model to the number of MGs is analyzed.

The changes in the percentage of calling reserve influence the decision-making of the MGMs in the LERMs. This may change the behavior of the MGMs to trade energy and reserve with each other. As shown in Tables III and IV, since the increase of calling reserve would raise the operation cost of the MGMs, they try to cope with this challenge by changing their simultaneous decision-making on the energy and the reserve scheduling. When the percentage of calling reserve increases from 0% to 50%, MGM3 purchases more reserve from the market, which increases the energy sold to the energy market. In this case, MGM1 changes its behavior in the LERMs so that it decides to purchase/sell energy/reserve from/to the market in $\gamma_t^R = 50\%$ instead of sell/purchase energy/reserve to/from the market in $\gamma_t^R = 0$. When the percentage of calling reserve increases from 50% to 100%, MGM1 decides to sell more energy to the market and purchase more reserve from the other MGs. MGM3 decides to provide more reserve for the other MGs, leading to decreasing the amount of energy sold to the energy market. MGM2 uses its resources to meet the required energy and purchases less energy from the energy market. This behavior leads to purchasing reserve from the market since MGM2 cannot meet its required reserve by its resources.

TABLE V
SOLUTION TIME OF THE ITERATIVE APPROACH FOR DIFFERENT INITIAL VALUES

Case #	Initial values			Solution time (s)
	MG #1	MG #2	MG #3	
1	Bid of its DG	Bid of its DG	Bid of its DG	1080
2	Bid of its DG	Bid of its DG	Bids of its IL	740
3	Bid of its DG	Bids of its IL	Bid of its DG	719
4	Bids of its IL	Bid of its DG	Bid of its DG	781
5	Bid of its DG	Bid of its DG	Bid of its DG in hours 1–6 and 22–24. Bid of its IL in other hours	627
6	Bid of its DG	Bid of its DG in hours 1–9, 14–17, and 22–24. Bid of its IL in other hours	Bid of its DG	641
7	Bid of its DG in hours 1–7, 15, 16, and 22–24. Bid of its IL in other hours	Bid of its DG	Bid of its DG	693

D. *Comparing the EPEC Approach With the Iterative One*

The computation time of the EPEC model is compared with the iterative approach in this section. For this purpose, at first, the resulted MPEC model in Section III-D is solved for each MG considering the initial values of bids of other MGs in the local market as shown in Table V. Then, the optimized bids of each MG are obtained, and the next iteration is executed. This process continues until the obtained results of two consecutive iterations are equal.

The iterative approach is done for seven cases with different initial values. In the first case, the bids of DG for each MG are considered as the initial values. In cases 2–4, the bids of DG are considered for two MGs and for the other one, the bids of its IL are considered. In the last three cases, the previous assumption is repeated with considering the bid of DG instead of bids of IL in the hours that the IL bids are lower than the DG bids. It should

TABLE VI
SENSITIVITY OF MODEL STATISTICS TO THE NUMBER OF MGS

# MG	# Single equations	# Single variables	# Discrete variables	Solution time (s)
3	28 715	13 022	4752	185.45
5	77 585	34 150	12 720	298.31
7	15 0263	65 262	24 528	365.26
10	30 3920	13 0650	49 440	492.50

be noted that, the bids of the MGs in the LRM are considered as 30% of their bids in the energy market.

As shown in Table V, the solution time of the iterative approach in all cases is greater than the solution time of the EPEC model, i.e., 185.45 s. Therefore, the solution time of the EPEC approach is better than the iterative one. Also, in these cases, the maximum solution time is obtained in the first case, and in the last three cases the solution time is decreased.

E. Checking the Nash Equilibrium

In this section, it is verified that the solution obtained in this model is a Nash equilibrium. The Nash equilibrium is defined as a situation where each player cannot obtain more profit from changing its strategies from the initial ones when the obtained results for other players are constant.

To check this equilibrium in the proposed model in this article, the diagonalization algorithm is used. In this algorithm, if there is no MG willing to change its strategies from the obtained results, the set of the MG's decisions satisfies the Nash equilibrium. The optimal decisions of the MGs obtained from solving the proposed EPEC model are named as X_1^*, X_2^*, and X_3^*.

To investigate that they satisfy the Nash equilibrium, the following steps are carried out.

1) The MPEC of MG #1 considering the optimum results of other MGs obtained from solving the EPEC model, i.e., X_2^*, and X_3^*, as the parameter, is solved. The obtained optimum decision of the MG #1 in the diagonalization algorithm is named as Y_1^*.
2) The previous step is repeated for MG #2 and MG #3 and the optimal solutions obtained are named as Y_2^* and Y_3^*.
3) The results obtained from the diagonalization algorithm, Y_1^*, Y_2^*, and Y_3^*, are compared with the ones obtained from the EPEC model, X_1^*, X_2^*, and X_3^*. Since these decision variables are equal to each other ($X_1^* = Y_1^*$, $X_2^* = Y_2^*$, and $X_3^* = Y_3^*$), it is confirmed that the obtained results of the EPEC model, i.e., X_1^*, X_2^*, and X_3^*, are a Nash equilibrium.

F. Computational Tractability

According to Table VI, the tractability of the proposed model has been investigated by increasing the number of MGs up to 10.

It should be noted, the same characteristics of the MGs given in Table II is considered for the new MGs. The numbers of equations and variables of the model remain acceptable, and the model can be solvable for a high number of MGs.

V. CONCLUSION

The optimal decision-making framework of MMGs to meet their required energy and reserve through their resources and trading power with each other in LERMs was addressed in this article. The proposed bilevel optimization approach that was used to model such framework was transformed into an MILP problem using the primal-dual transformation and KKT conditions. Results showed that the proposed model provided an appropriate framework for the MGMs to trade energy and reserve with each other to meet their required energy and reserve with the minimum cost. Moreover, the proposed model can be applied on a test system with high number of MGs. The sensitivity results on the percentage of calling reserve revealed that the MGMs changed their decisions in the LERMs to decrease their total cost when the percentage of calling reserve increased. The results obtained by the EPEC approach may be used for further reasoning about the possible use of the storage available in each MG to avoid or reduce IL curtailment or to charge the storage systems by using power inputs from the other MGs. Further work is in progress in this direction.

REFERENCES

[1] S. Bahramara, A. Mazza, G. Chicco, M. Shafie-khah, and J. P. S. Catalão, "Comprehensive review on the decision-making frameworks referring to the distribution network operation problem in the presence of distributed energy resources and microgrids," *Int. J. Elect. Power Energy Syst.*, vol. 115, 2020, Art. no. 105466.

[2] *IEEE Standards Coordinating Committee 21 (SCC21), Guide for Design, Operation, and Integration of Distributed Resource Island Systems With Electric Power Systems*, IEEE Std 1547.4, Jul. 2011.

[3] Z. Liang, H. Chen, X. Wang, S. Chen, and C. Zhang, "Risk-based uncertainty set optimization method for energy management of hybrid AC/DC microgrids with uncertain renewable generation," *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1526–1542, Mar. 2020.

[4] Y. Zhang, L. Fu, W. Zhu, X. Bao, and C. Liu, "Robust model predictive control for optimal energy management of island microgrids with uncertainties," *Energy*, vol. 164, pp. 1229–1241, 2018.

[5] S. Bahramara, P. Sheikhahmadi, and H. Golpîra, "Co-optimization of energy and reserve in standalone micro-grid considering uncertainties," *Energy*, vol. 176, pp. 792–804, 2019.

[6] A. K. Marvasti, Y. Fu, S. DorMohammadi, and M. Rais-Rohani, "Optimal operation of active distribution grids: A system of systems framework," *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1228–1237, May 2014.

[7] Y. Fu, Z. Zhang, Z. Li, and Y. Mi, "Energy management for hybrid AC/DC distribution system with microgrid clusters using non-cooperative game theory and robust optimization," *IEEE Trans. Smart Grid*, vol. 11, no. 2, pp. 1510–1525, Mar. 2020.

[8] S. Bahramara, M. P. Moghaddam, and M. R. Haghifam, "Modelling hierarchical decision making framework for operation of active distribution grids," *IET Gener., Transmiss. Distrib.*, vol. 9, pp. 2555–2564, 2015.

[9] S. Bahramara, A. Mazza, G. Chicco, M. Shafie-khah, and J. P. S. Catalão, "A risk-based decision framework for the distribution company in mutual interaction with the wholesale day-ahead market and microgrids," *IEEE Trans. Ind. Informat.*, vol. 16, no. 2, pp. 764–778, Feb. 2020.

[10] S. A. Gabriel, A. J. Conejo, J. D. Fuller, B. F. Hobbs, and C. Ruiz, *Complementarity Modeling in Energy Markets*, vol. 180. New York, NY, USA: Springer-Verlag, 2012.

[11] J. Wu and X. Guan, "Coordinated multi-microgrids optimal control algorithm for smart distribution management system," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 2174–2181, Dec. 2013.

[12] M. Fathi and H. Bevrani, "Statistical cooperative power dispatching in interconnected microgrids," *IEEE Trans. Sustain. Energy*, vol. 4, no. 3, pp. 586–593, Jul. 2013.

[13] J. Ni and Q. Ai, "Economic power transaction using coalitional game strategy in micro-grids," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 1, pp. 10–18, 2016.

[14] S. E. Ahmadi and N. Rezaei, "A new isolated renewable based multi microgrid optimal energy management system considering uncertainty and demand response," *Int. J. Elect. Power Energy Syst.*, vol. 118, 2020, Art. no. 105760.

[15] S. Wang, X. Zhang, L. Wu, and S. Sun, "New metrics for assessing the performance of multi-microgrid systems in stand-alone mode," *Int. J. Elect. Power Energy Syst.*, vol. 98, pp. 382–388, 2018.

[16] A. Jafari, H. Ganjeh Ganjehlou, T. Khalili, and A. Bidram, "A fair electricity market strategy for energy management and reliability enhancement of islanded multi-microgrids," *Appl. Energy*, vol. 270, 2020, Art. no. 115170.

[17] S. M. S. Kalajahi, H. Seyedi, and K. Zare, "Under-frequency load shedding in isolated multi-microgrids," *Sustain. Energy, Grids Netw.*, vol. 27, 2021, Art. no. 100494.

[18] M. Mazidi, N. Rezaei, F. J. Ardakani, M. Mohiti, and J. M. Guerrero, "A hierarchical energy management system for islanded multi-microgrid clusters considering frequency security constraints," *Int. J. Elect. Power Energy Syst.*, vol. 121, 2020, Art. no. 106134.

[19] M. Hu, Y.-W. Wang, J.-W. Xiao, and X. Lin, "Multi-energy management with hierarchical distributed multi-scale strategy for pelagic islanded microgrid clusters," *Energy*, vol. 185, pp. 910–921, 2019.

[20] J. Mei, C. Chen, J. Wang, and J. L. Kirtley, "Coalitional game theory based local power exchange algorithm for networked microgrids," *Appl. Energy*, vol. 239, pp. 133–141, 2019.

[21] A. Jani, H. Karimi, and S. Jadid, "Hybrid energy management for islanded networked microgrids considering battery energy storage and wasted energy," *J. Energy Storage*, vol. 40, 2021, Art. no. 102700.

[22] S. E. Ahmadi, N. Rezaei, and H. Khayyam, "Energy management system of networked microgrids through optimal reliability-oriented day-ahead self-healing scheduling," *Sustain. Energy, Grids Netw.*, vol. 23, 2020, Art. no. 100387.

[23] X. Jin, Q. Wu, and H. Jia, "Local flexibility markets: Literature review on concepts, models and clearing methods," *Appl. Energy*, vol. 261, 2020, Art. no. 114387.

[24] S. J. Kazempour, A. J. Conejo, and C. Ruiz, "Generation investment equilibria with strategic producers—Part I: Formulation," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 2613–2622, Aug. 2013.

[25] D. G. Luenberger and Y. Ye, *Linear and Nonlinear Programming*, vol. 2, New York, NY, USA: Springer-Verlag, 1984.

[26] A. V. Fiacco and G. P. McCormick, *Nonlinear Programming: Sequential Unconstrained Minimization Techniques*, vol. 4, Philadelphia, PA, USA: SIAM (Soc. Ind. Appl. Math.), 1990.