Northumbria Research Link

University**Library**

Coalition Formation of Microgrids with Distributed Energy Resources and Energy Storage in Energy Market

Jaber Valinejad, *Student Member, IEEE*, Mousa Marzband, *Senior Member, IEEE*, Mert Korkali, *Senior Member, IEEE*, Yijun Xu, *Member, IEEE*, and Ameena Saad Al-Sumaiti, *Member, IEEE*

Abstract—Power grids include entities such as home-microgrids (H-MGs), consumers, and retailers, each of which has a unique and sometimes contradictory objective compared with others while exchanging electricity and heat with other H-MGs. Therefore, there is the need for a smart structure to handle the new situation. This paper proposes a bilevel hierarchical structure for designing and planning distributed energy resources (DERs) and energy storage in H-MGs by considering the demand response (DR). In general, the upper-level structure is based on H-MG generation competition to maximize their individual and/or group income in the process of forming a coalition with other H-MGs. The upper-level problem is decomposed into a set of low-level market clearing problems. Both electricity and heat markets are simultaneously modeled in this paper. DERs, including wind turbines (WTs), combined heat and power (CHP) systems, electric boilers (EBs), electric heat pumps (EHPs), and electric energy storage systems, participate in the electricity markets. In addition, CHP systems, gas boilers (GBs), EBs, EHPs, solar thermal panels, and thermal energy storage systems participate in the heat market. Results show that the formation of a coalition among H-MGs present in one grid will not only have a significant effect on programming and regulating the value of the power generated by the generation resources, but also impact the demand consumption and behavior of consumers participating in the DR program with a cheaper market clearing price.

J. Valinejad (corresponding author) and Y. Xu are with the Bradley Department of Electrical and Computer Engineering, Virginia Tech, Northern Virginia Center, Greater Washington D.C., VA 22043, USA, and J. Valinejad is also with the Department of Computer Science, Virginia Tech, Northern Virginia Center, Greater Washington D.C., VA 22043, USA (e-mail: Jabervalinejad@vt.edu; yijunxu@vt.edu).

M. Marzband is with the Department of Mathematics, Physics, and Electrical Engineering, Northumbria University, Newcastle, UK, and he is also with the Center of Research Excellence in Renewable Energy and Power Systems, King Abdulaziz University, Jeddah 21589, Saudi Arabia (e-mail: mousa.marzband@northumbria.ac.uk).

M. Korkali is with the Computational Engineering Division, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA (e-mail: korkali1@llnl.gov).

A. S. Al-Sumaiti is with the Advanced Power and Energy Center, Electrical Engineering and Computer Science, Khalifa University, Abu Dhabi, P.O. Box 127788, UAE (e-mail: ameena.alsumaiti@ku.ac.ae).

DOI: 10.35833/MPCE.2019.000116

Index Terms—Microgrids, distributed energy resource (DER), electricity market, heat market, demand response (DR), coalition formation, energy storage.

I. INTRODUCTION

IN recent years, there have been significant efforts to improve the technical and economic performance of smart grids, with the presence of different players making decisions in these grids [1], [2]. Such a small-scale grid inside the market environment permits energy exchange among distributed energy resources (DERs) and home-microgrids (H-MGs) through a pool market [3], [4]. In this market, the importance of the demand response (DR) in the energy management of microgrids is clear. Demand-side management (DSM) topics are focused on energy consumption control at the consumer side [5], [6]. Such energy control is coordinated by electric utilities, companies, and enterprises without controlling DERs [7]-[9]. When the latter is controlled, it is defined as energy management [10], [11]. The DR considering the energy optimization of heating ventilation and air conditioning (HVAC) systems is considered in [12]-[14]. In [12], the authors develop a price-responsive DR for HVAC systems of buildings. They also consider DERs, including photovoltaic (PV) generation and energy storage (ES).

The objective of this paper is first to propose a base framework for the demand of consumers encompassing H-MGs, and second, to determine profits that can be made from independently operating H-MGs or in a coalitional structure in a daily energy-hub market [15], [16]. Energy-hub markets have been investigated in various models. In [17], the authors propose a stochastic bilevel model for the energy-hub market from the perspective of energy hub managers. In this paper, the energy-hub manager is modeled at the first level, while the clients are modeled at the second level. A mathematical program that uses an equilibrium constraint framework to model the strategic behaviors of multi-carrier energy systems is proposed in [18]. In [19], the authors provide an operation optimization model for electricity, natural gas, and heat systems by considering DSM as well as ES. In [20], the effects of individuals, sharing markets, and aggregation in the energy-hub market are studied under a stochastic scheme with probabilistic demand forecasts. In [21], the authors propose a stochastic optimal bidding strate-

gy for an energy hub to benefit from day-ahead and real-time markets. The uncertainty encompasses real-time market prices, day-ahead market prices, as well as wind generation. A three-level energy-hub framework is proposed in [22] to model the effect of multiple energy suppliers and end-users. The first level includes an electricity utility company and a natural gas utility company; the second level includes multiple same-structured smart energy hubs; finally, the third level includes multiple users. In this paper, the energy exchange among H-MGs is formulated as a scheduling game, and competitive monopolies are modeled and simulated in a formulated non-linear optimization problem [23], [24]. These monopolies are based on three contradictory objectives: income maximization of H-MGs and retailers, reduction of consumer costs, and reduction of demand peak [25].

To satisfy objective functions, a bilevel hierarchical interactive architecture (BL-HIA) algorithm on the condition of reaching a maximum profit is proposed for both the consumer and the power generator sides [26]-[28]. The optimum performance problem is presented for all DERs present in multiple H-MGs as a BL-HIA [29], [30]. The upper-level targets maximize the profit of H-MGs through energy exchange among H-MGs as well as between H-MGs and retailers to achieve the central optimum performance of a decision-maker [30], [31]. By contrast, the lower level of the hierarchal structure of the problem represents an equilibrium problem that incorporates DSM to obtain the optimal performance of multiple H-MGs [5], [10]. This way, while considering an independent or a coalitional performance of all H-MGs, a central optimum performance decision-maker is included in an upper-level decision-maker to obtain energy optimum exchange among H-MGs and with retailers in an independent and a coalitional performance to maximize the profit of H-MGs [32]-[34]. The interaction between the two levels of the hierarchal structure of the game is a factor in the search for the optimal solution at both levels [8], [10], [35]. Consideration of the optimal scheduling of all H-MGs and DERs that exist in them in multiple H-MGs requires solving mathematical programming with equilibrium constraints (MPECs) that are equivalent to the bilevel problem [36]. This bilevel problem can be considered as a multiple-leader-common-follower game. The aim of implementing this game structure is to find a final equilibrium point in which none of the H-MGs or consumers can increase their profit by varying the generation or consumption schedules. Furthermore, the BL-HIA structure accounts for decisions resulting from the formation of a coalition among H-MGs to maximize the profit as well as to exchange energy among them.

The contribution in this work can be summarized as follows. First, the proposed BL-HIA structure is preferred over the proposed structure in [37] as it is a multi-ownership structure that permits the formation of a coalition among H-MGs or explicitly increases the competition among H-MGs and consumers, rather than an independent operation of H-MGs. Second, the BL-HIA is adequate for modeling problems with several leaders (i.e., H-MGs) having individual objective functions when operating independently or in a coalitional manner (upper-level problem). Such a game aims to

optimize several followers, i.e., consumers inserted in the bilevel structure. These models are related to situations where actions and followers' performances in BL-HIA have a significant effect on decisions made by leaders. This fact is related to the case in which the profit of H-MGs (a leader) depends on the amount of energy that is supplied to the existing consumers in a power grid (as a follower). The general view of the hierarchical structure and optimization problems is shown with the proposed model in Fig. 1, where UL:A... LL:BC implies that the HMG A is modeled at the upper level, while HMGs B and C are modeled at the lower level; DERs encompass a set of distributed generation, electric, and thermal ES systems; EMS stands for energy management system; CEMS stands for centralized energy management system. Third, a better strategy that maximizes consumers' satisfaction in terms of demand-supply as well as the profit of H-MGs is presented compared with a single-level structure. Finally, the BL-HIA structure is solved by formulating an equivalent one-level model deploying the Karush-Kuhn-Tucker (KKT) optimization conditions.
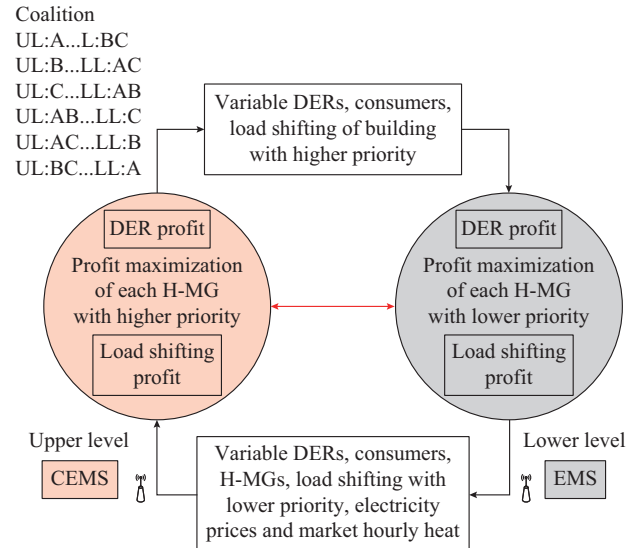
Fig. 1. Proposed BL-HIA structure illustrating a variety of coalition formations among H-MGs.

The innovations in this paper can be summarized as follows:

1) Development of an optimum programming solution within H-MG generation as a BL-HIA structure.

2) Providing a multiple-leader-common-follower game that indicates the effectiveness of the market competition in multiple H-MGs by solving a BL-HIA structure.

3) Development of a new model for DSM.

4) Facilitating both DR resources and storage devices in the market operation to achieve a comprehensive solution that exploits all flexibilities.

5) Proposal for advanced electricity and heat markets for active distribution networks based on game theory.

II. PROPOSED BL-HIA STRUCTURE

The problem encountered by H-MGs for an independent

or a coalitional operation can be modeled as a bilevel structure that is a decision-making problem, including several agents that try to optimize their corresponding objective functions on a connectable dependent set. In fact, an agent is an object that can act as a DER or that is connected to other units. The BL-HIA structure is shown in Fig. 2. The upper-level problem focuses on maximizing the profit of H-MGs having a higher priority of operating in an independent or a coalitional operation on the condition that satisfies upper-level constraints and a set of lower-level problems. H-MGs with a higher priority of operation in the upper-level problem are identified based on their price bids. Upper-level constraints include limits on the quantity and supply bids of DERs, the minimum accessible power capacity by the market regulator, and purchasing/selling quantities by H-MGs and retailers. The lower-level problem states the market clearing prices (MCPs) to maximize the profit of H-MGs having lower priority of operation subject to meeting equilibrium constraints for each H-MG, generation/consumption limits, and the number of consumers participating in the DSM program.
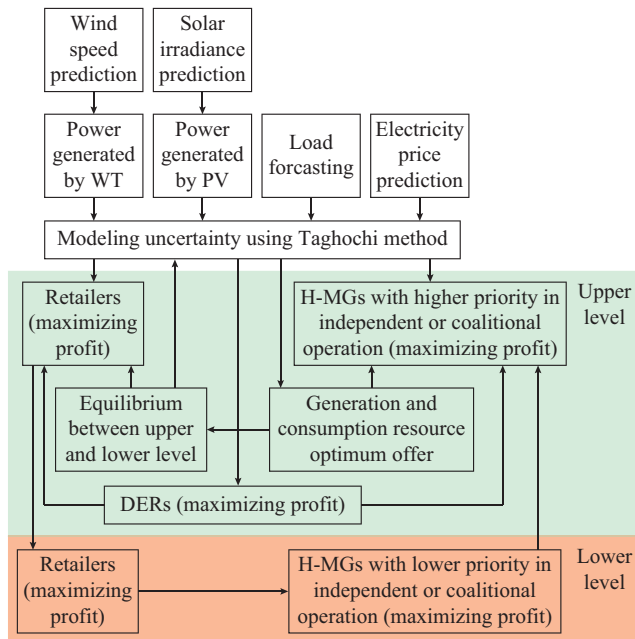

Fig. 2.   BL-HIA structure.

As shown in Fig. 2, the higher priority of H-MG operation (in an independent or a coalitional operation) is defined by the energy excess/shortage gap and the supply/demand bid that permits a maximization of an expected profit. Maximizing the profit of each H-MG is achieved by considering that each agent in the lower-level problem shows an optimal operation corresponding to the income of H-MGs with the higher priority of operation based on the offered price. This optimal operation includes an estimation of the demand supplied and shifted by each consumer in an independent or a coalitional operation. It should be noted that the competition among H-MGs with higher and lower priority (or competitor's H-MGs) is explicitly modeled at the upper and lower levels. It should also be noted that the upper-level and lower-

level problems shown in Fig. 2 are related to each other. In other words, lower-level problems estimate the price and the number of competitor H-MGs, which directly affect the profit of H-MGs inserted in the above problem. In other words, decisions related to the formation of a coalition or that take a bidding strategy by the competitor's strategic H-MGs in the upper-level problem also have a significant effect on the MCP that results from the lower-level problem.

In the BL-HIA structure, the uncertainty of pool prices, electric/thermal load demands, and purchasing/selling prices of H-MGs are also considered. In [38] and [39], the authors use a polynomial chaos method to consider uncertainties. In addition, the proposed bilevel model has been simplified as a one-level problem using the KKT method [40].

III. DECISION-MAKING PROCESS USING BL-HIA STRUCTURE

The decision-making process in the BL-HIA structure of H-MGs, consumers, and retailers can be summarized as shown in Fig. 3. At the beginning of the scheduling horizon, each H-MG presents the necessary decisions on DSM for an independent or a coalitional operation with other H-MGs. Moreover, supply/demand bids are provided to the consumers during this horizon. These decisions are made considering the uncertainties of future pool market prices, consumers' load profiles, and supply bids of H-MGs of the competitor. The supply bids are a function of the cost of the DER installed in the H-MG.
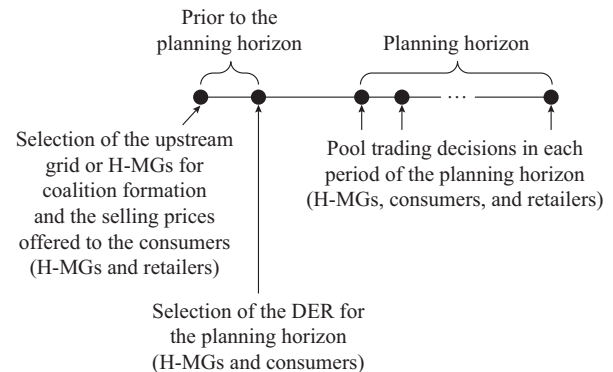
Fig. 3.   Decision-making process.

1) Consumers' choice of energy provider: when each H-MG offers a supply bid, consumers are to choose an H-MG as an energy provider to their electric/thermal load during the scheduling horizon. These decisions are made based on reliable information on such prices, which are estimated considering the uncertainties of pool prices and demand. For modeling purposes, several sets of consumers are created by grouping consumers with similar specifications responding to offered prices of the H-MG.

2) Energy exchange by H-MGs in a pool market: after stabilizing the performance of H-MGs (an independent or a coalitional operation) and setting supply and demand bids, each H-MG can decide in each time interval of the scheduling horizon on the quantity (to/from other H-MGs in the pool market) to supply the demand of their consumers.

IV. PROBLEM FORMULATION

The scheduling problem of H-MGs is formulated in a BL-HIA structure. It should be noted that dual variables have been separated by a comma after equality and inequality constraints. This section briefly presents models deployed for load shifting, and those representing the interaction among DER, H-MGs, consumers, and retailers as well as the coalition among H-MGs. Then, BL-HIA problem formulation is presented.

The consumers of H-MGs are considered to be responsive loads, so they participate in DSM. Hence, we first provide our DR model. In addition, because each H-MG consists of a set of DERs, we offer the comprehensive model of wind turbine (WT), CHP system, EB, EHP, GB, and solar thermal panel (STP). In addition to DERs, H-MGs can include ES. Therefore, we provide models for both electric ES and thermal energy storage (TES). The constraints related to electric and thermal price bids are explained in the next step. Finally, we provide detailed explanations regarding independent and coalitional operation of H-MGs.

A. DR Objective Function and Constraints

The responsive load demand (RLD) constraints describe DR programs where consumers can reduce their consumption during certain time intervals and/or shift part of their consumption to the next time intervals or before the main time interval. The initial load demand value is defined as the sum of the predicted power demand and the value of the load participating in the RLD program in each H-MG. The initial load demand value can be defined as the value of the load shifting to time interval t and/or as the negative value of the load shifting from this time to other time. The maximum H-MG demand consumed in each time interval t is equal to the sum of the initially expected demand and the RLD+ value when the load is shifted to this time interval minus the value of RLD−, where RLD+ is the amount of RLD that goes from other time periods to time t and RLD− is the amount of RLD that comes to other time period from time t.

The profit resulting from the participation of consumers in DSM program is calculated from (1).

$$\max \mathbb{R}_i^{\mathrm{DSM}} = 0.5 \sum_{t'=1}^{T} P_{it'w}^{\mathrm{DSM,e}} \left(\tilde{\lambda}_{tw}^{\mathrm{MCP}} - \tilde{\lambda}_{t'w}^{\mathrm{MCP}} \right) \tag{1}$$

$$P_{itw}^{\mathrm{DSM,e}} = \tilde{P}_{itw}^{\mathrm{DSM,e}} + \sum_{t'} P_{itt'w}^{\mathrm{DSM,e}} : \gamma_{itw}^{\mathrm{DSM,e}} \tag{2}$$

$$\sum_{t \to t'} P_{itt'w}^{\mathrm{DSM,e}} \leq \tilde{P}_{itw}^{\mathrm{DSM,e}} : \overline{\eta}_{itw}^{\mathrm{DSM,e}} \quad \forall \tilde{\lambda}_{tw}^{\mathrm{MCP}} > \tilde{\lambda}_{t'w}^{\mathrm{MCP}}, \forall P_{itt'w}^{\mathrm{DSM,e}} > 0 \tag{3}$$

$$P_{itt'w}^{\mathrm{DSM,e}} > 0 : \underline{\eta}_{itt'w}^{\mathrm{DSM,e}} \tag{4}$$

$$P_{itt'w}^{\mathrm{DSM,e}} = 0 : \eta_{itt'w}^{\mathrm{DSM,e}} \quad \forall t = t' \tag{5}$$

where $P_{itw}^{\mathrm{DSM,e}}$ and $P_{it'w}^{\mathrm{DSM,e}}$ are the active power consumed by the consumers at H-MG i at time t and t' in scenario w, respectively; $\tilde{P}_{itw}^{\mathrm{DSM,e}}$ is the predicted load power consumed by the consumers in H-MG i at time t in scenario w; $P_{itt'w}^{\mathrm{DSM,e}}$ is the shifted load power from time interval t to time interval t' at H-MG i in scenario w; $\tilde{\lambda}_{tw}^{\mathrm{MCP}}$ and $\tilde{\lambda}_{t'w}^{\mathrm{MCP}}$ are the values of predicted MCP at time t and t' in scenario w, respectively; and T is the number of time periods.

Constraint (3) states that if the value of the demand shifted from time interval t to t' is given when $\tilde{\lambda}_{tw}^{\mathrm{MCP}} > \tilde{\lambda}_{t'w}^{\mathrm{MCP}}$, this value is not to exceed the predicted load value at t, i.e., $\tilde{P}_{itw}^{\mathrm{DSM,e}}$. Constraints (4) and (5) are set to ensure that the load shifting is not defined for the same interval. The load shifted from t to t' is equivalent to the negative value of the demand deducted from the predicted demand at t, as described by:

$$P_{itt'w}^{\mathrm{DSM,e}} = -P_{itt'w}^{\mathrm{DSM,e}} : \eta_{itt'w}^{\mathrm{DSM,e}} \tag{6}$$

Figure 4 provides the presented model diagram for RLD where $P_{itw}^{\mathrm{DSM+,e}}$ is the positive DR (final demand increases) and $P_{itw}^{\mathrm{DSM-,e}}$ is the negative DR (final demand decreases). The proposed RLD model has been developed to join both RLD and DERs in each H-MG. From the supply perspective, each H-MG can use its DERs to generate power under certain conditions to sell to other H-MGs and/or retailers that are constrained by the value of its maximum generated power and which is proportional to the price and gained profit. In this way, H-MG can use its DERs at the power level and specified price offer during each time interval. Therefore, the DERs of each H-MG can be planned in combination with other DERs of other H-MGs by investigating the constraints related to the value of the price bid of RLDs of the same H-MG and other RLDs. With this method, it is assumed that H-MGs satisfy their load demand need while presenting a reward to consumers to reduce the consumed load demand as well as the DER units for desirable production. From the perspective of consumers, it is assumed that each H-MG can manage its load demand as accumulated by gathering all existing loads in that H-MG. The proposed EMS estimates the value of load shifting during each time interval proportional to the load shifting cost for each shift possibility and is also proportional to the profit obtained by the H-MG. With this method, the H-MG operator minimizes the total performance costs of the total daily programming and/or the maximum total gained profit. Similar concepts can also be generalized for coalition formation.
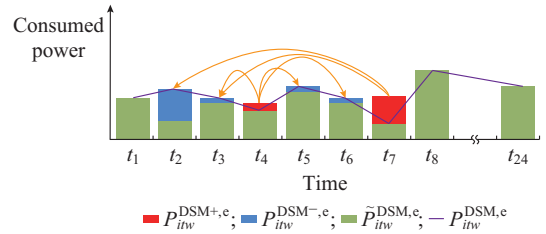
Fig. 4 Model diagram for RLD.

B. Objective Function and Constraints of DERs

1) Objective Function and Constraints of CHP System

The objective is to maximize the profit that can be made through participation of CHP systems in the DSM program, as in (7).

$$\max \mathbb{R}_{ij}^{\mathrm{CHP}} = \sum_{t=1}^{T} P_{ijtw}^{\mathrm{CHP,e}} \pi_{ijtw}^{\mathrm{CHP,e}} + P_{ijtw}^{\mathrm{CHP,h}} \pi_{ijtw}^{\mathrm{CHP,h}} - \frac{P_{ijtw}^{\mathrm{CHP,h}}}{N_i^{\mathrm{CHP,h}}} \pi^{\mathrm{FU}} \tag{7}$$

$$\underline{P}_{ij}^{\mathrm{CHP,e}} \leq P_{ijtw}^{\mathrm{CHP,e}} \leq \overline{P}_{ij}^{\mathrm{CHP,e}} : \underline{\eta}_{ijtw}^{\mathrm{CHP,e}}, \overline{\eta}_{ijtw}^{\mathrm{CHP,e}} \tag{8}$$

$$\underline{P}_{ij}^{\mathrm{CHP,h}} \leq P_{ijtw}^{\mathrm{CHP,h}} \leq \overline{P}_{ij}^{\mathrm{CHP,h}} : \underline{\eta}_{ijtw}^{\mathrm{CHP,h}}, \overline{\eta}_{ijtw}^{\mathrm{CHP,h}} \tag{9}$$

$$P_{ijtw}^{\mathrm{CHP,e}} = \zeta_{ij}^{\mathrm{CHP,e}} \cdot FU_{tw}^{CHP} + \zeta_{ij}^{\mathrm{CHP,e}\prime} : \gamma_{ijtw}^{\mathrm{CHP,e}} \tag{10}$$

$$P_{ijtw}^{\mathrm{CHP,h}} = FU_{tw}^{CHP} \cdot \zeta_{ij}^{\mathrm{CHP,h}} : \gamma_{ijtw}^{\mathrm{CHP,h}} \tag{11}$$

where $P_{ijtw}^{\mathrm{CHP,e}}$ and $P_{ijtw}^{\mathrm{CHP,h}}$ are the electric power and thermal power consumed by CHP system j at H-MG i at time t in scenario w, respectively; $\pi_{ijtw}^{\mathrm{CHP,e}}$ and $\pi_{ijtw}^{\mathrm{CHP,h}}$ are the electric and thermal selling price bids of CHP system j at H-MG i at time t in scenario w, respectively; π^{FU} is the offer price of natural gas; $N_i^{\mathrm{CHP,h}}$ is the CHP fuel factor; $\underline{P}_{ij}^{\mathrm{CHP,e}}$ and $\overline{P}_{ij}^{\mathrm{CHP,e}}$ are the lower and upper limitations of $P_{ijtw}^{\mathrm{CHP,e}}$, respectively; $\underline{P}_{ij}^{\mathrm{CHP,h}}$ and $\overline{P}_{ij}^{\mathrm{CHP,h}}$ are the lower and upper limitations of $P_{ijtw}^{\mathrm{CHP,h}}$, respectively; $\zeta_{ij}^{\mathrm{CHP,e}}$ and $\zeta_{ij}^{\mathrm{CHP,e}\prime}$ are the electrical efficiencies of the CHP system, and $\zeta_{ij}^{\mathrm{CHP,e}}$ together with the amount of fuel influences the amount of electricity produced by CHP, and $\zeta_{ij}^{\mathrm{CHP,e}\prime}$ directly influences the amount of electricity produced by CHP by itself (not dependent on the amount of fuel); $\zeta_{ij}^{\mathrm{CHP,h}}$ is the thermal efficiency of CHP system; and FU_{tw}^{CHP} is the fuel consumed by CHP system at time t in scenario w.

Constraints (8) and (9) state upper and lower limits on the power generated by the CHPs. Equations (10) and (11) describe the power and heat generated by the CHPs as a function of the system efficiency and fuel.

2) Objective Function and Constraints of WT

The profit resulting from the participation of WT in the DSM program is calculated by (12).

$$\max \mathbb{R}_{ij}^{\mathrm{WT}} = \sum_{t=1}^{T} P_{ijtw}^{\mathrm{WT}} \pi_{ijtw}^{\mathrm{WT}} \tag{12}$$

$$0 \leq P_{ijtw}^{\mathrm{WT}} \leq \overline{P}_{ij}^{\mathrm{WT}} : \underline{\zeta}_{tw}^{\mathrm{WT,e}}, \overline{\zeta}_{tw}^{\mathrm{WT,e}} \tag{13}$$

where P_{ijtw}^{WT} is the power consumed by WT j at H-MG i at time t in scenario w; π_{ijtw}^{WT} is the selling price bid by WT j at H-MG i at time t in scenario w; and $\overline{P}_{ij}^{\mathrm{WT}}$ is the maximum power generated by WT j at H-MG i.

Constraint (13) and similar constraints for determining the limit on DER resources state the programmed power generation of controllable and non-controllable resources of DER. Constraint (13) is related to the electric power of WT whose maximum limit is a parameter having some degree of uncertainty.

3) Constraints of EB

The profit made by the participation of EB in the DSM program is calculated by (14).

$$\max \mathbb{R}_{ij}^{\mathrm{EB}} = P_{ijtw}^{\mathrm{EB,h}} \pi_{ijtw}^{\mathrm{EB,h}} - P_{ijtw}^{\mathrm{EB,e}} \pi_{ijtw}^{\mathrm{EB,e}} \tag{14}$$

$$P_{ijtw}^{\mathrm{EB,h}} = \zeta_{ij}^{\mathrm{EB}} P_{ijtw}^{\mathrm{EB,e}} \cdot \zeta_{tw}^{\mathrm{EB,h}} \tag{15}$$

$$0 \leq P_{ijtw}^{\mathrm{EB,h}} \leq \overline{P}_{ij}^{\mathrm{EB,h}} : \underline{\eta}_{ijtw}^{\mathrm{EB,h}}, \overline{\eta}_{ijtw}^{\mathrm{EB,h}} \tag{16}$$

where $P_{ijtw}^{\mathrm{EB,e}}$ and $P_{ijtw}^{\mathrm{EB,h}}$ are the electric power and thermal power consumed by EB, respectively; $\pi_{ijtw}^{\mathrm{EB,e}}$ and $\pi_{ijtw}^{\mathrm{EB,h}}$ are the electric and thermal selling price bids of EB, respectively; $\overline{P}_{ij}^{\mathrm{EB,h}}$ is upper limitation of $P_{ijtw}^{\mathrm{EB,h}}$; and ζ_{ij}^{EB} is the thermal efficiency of EB.

Constraints (15) and (16) state the consumed amount of electric power and the generated heat in the EB, respectively.

4) Objective Function and Constraints of EHP

The profit made by the participation of EHP in the DSM program is calculated by (17).

$$\max \mathbb{R}_{ij}^{\mathrm{EHP}} = P_{ijtw}^{\mathrm{EHP,h}} \pi_{ijtw}^{\mathrm{EHP,h}} - P_{ijtw}^{\mathrm{EHP,e}} \pi_{ijtw}^{\mathrm{EHP,e}} \tag{17}$$

$$P_{ijtw}^{\mathrm{EHP,h}} = COP^{\mathrm{EHP}} \cdot P_{ijtw}^{\mathrm{EHP,e}} : \gamma_{ijtw}^{\mathrm{HP,h}} \tag{18}$$

$$0 \leq P_{ijtw}^{\mathrm{EHP,h}} \leq \overline{P}_{ij}^{\mathrm{EHP,h}} : \underline{\eta}_{ijtw}^{\mathrm{EHP,h}}, \overline{\eta}_{ijtw}^{\mathrm{EHP,h}} \tag{19}$$

where $P_{ijtw}^{\mathrm{EHP,e}}$ and $P_{ijtw}^{\mathrm{EHP,h}}$ are the electric power and thermal power consumed by EHP, respectively; $\pi_{ijtw}^{\mathrm{EHP,e}}$ and $\pi_{ijtw}^{\mathrm{EHP,h}}$ are the electric and thermal selling price bids of EB, respectively; $\overline{P}_{ij}^{\mathrm{EHP,h}}$ is the upper limitation of $P_{ijtw}^{\mathrm{EHP,h}}$; and COP^{EHP} is the coefficient of performance of EHP.

Equation (18) describes the relation between the consumed amount of electric and thermal power generated by the thermal pump. In addition, (19) represents limits on the thermal generation.

5) Objective Function and Constraints of GB

The profit made by the participation of GB in the DSM program is calculated by (20).

$$\max \mathbb{R}_{ij}^{\mathrm{GB}} = \sum_{t=1}^{T} \left(P_{ijtw}^{\mathrm{GB}} \pi_{ijtw}^{\mathrm{GB}} - \frac{P_{ijtw}^{\mathrm{GB}}}{N_{ij}^{\mathrm{GB}}} \pi^{\mathrm{FU}} \right) \tag{20}$$

$$0 \leq P_{ijtw}^{\mathrm{GB}} \leq \overline{P}_{ij}^{\mathrm{GB}} : \underline{\eta}_{ijtw}^{\mathrm{GB,h}}, \overline{\eta}_{ijtw}^{\mathrm{GB,h}} \tag{21}$$

$$P_{ijtw}^{\mathrm{GB,h}} = FU_{tw}^{\mathrm{GB}} \cdot \zeta_{ij}^{\mathrm{GB,h}} \cdot \gamma_{ijtw}^{\mathrm{GB,h}} \tag{22}$$

where P_{ijtw}^{GB} is the power consumed by GB; π_{ijtw}^{GB} is the selling price bid by GB; N_{ij}^{GB} is the GB fuel factor ; FU_{tw}^{GB} is the fuel consumed by GB; $\zeta_{ij}^{\mathrm{GB,h}}$ is the thermal efficiency of GB; $\overline{P}_{ij}^{\mathrm{GB}}$ is the maximum power generated by GB; and $P_{ijtw}^{\mathrm{GB,h}}$ is the thermal power consumed by EB.

Constraint (21) states the allowable limits on the heat generated by the GB.

6) Objective Function and Constraints of STP

The profit made by the participation of STP in a DSM program is calculated by (23).

$$\max \mathbb{R}_{ij}^{\mathrm{STP}} = \sum_{t=1}^{T} P_{ijtw}^{\mathrm{STP}} \pi_{ijtw}^{\mathrm{STP}} \tag{23}$$

$$0 \leq P_{ijtw}^{\mathrm{STP}} \leq \overline{P}_{ij}^{\mathrm{STP}} : \underline{\eta}_{ijtw}^{\mathrm{STP,h}}, \overline{\eta}_{ijtw}^{\mathrm{STP,h}} \tag{24}$$

where P_{ijtw}^{STP} is the power consumed by STP; $\pi_{ijtw}^{\mathrm{STP}}$ is the selling price bid by STP; and $\overline{P}_{ij}^{\mathrm{STP}}$ is the maximum power generated by STP.

Constraint (24) states the allowable limits of heat generation for the operation of an STP. Together with a WT, the maximum limit of STP is also considered to be an uncertainty factor.

C. Objective Functions and Constraints of ES/TES

The profit realized by the participation of an ES/TES system in a DSM program is measured by (25).

$$\max \mathbb{R}_{ij}^{\mathrm{ES/TES}} = \sum_{t=1}^{T} P_{ijtw}^{\mathrm{ES/TES}} \pi_{ijtw}^{\mathrm{ES/TES}} \tag{25}$$

$$\underline{P}_{ij}^{\text{ES/TES}} \le P_{ijtw}^{\text{ES/TES}} \le \overline{P}_{ij}^{\text{ES/TES}} : \underline{\eta}_{tw}^{\text{ES/TES}}, \overline{\eta}_{tw}^{\text{ES/TES}} \tag{26}$$

$$SOC_{ijtw}^{\text{ES/TES}} = SOC_{ij(t-1)w}^{\text{ES/TES}} + \frac{P_{ijtw}^{\text{ES/TES}}}{\overline{P}_{ij}^{\text{ES/TES}}} : \gamma_{ijtw}^{\text{ES/TES}} \tag{27}$$

$$\underline{SOC}_{ij}^{\text{ES/TES}} \le SOC_{ijtw}^{\text{ES/TES}} \le \overline{SOC}_{ij}^{\text{ES/TES}} : \underline{\eta}_{ijtw}^{\text{ES/TES, SOC}}, \overline{\eta}_{ijtw}^{\text{ES/TES, SOC}} \tag{28}$$

$$SOC_{ij(t-1)w}^{\text{ES/TES}} = SOC_{ij}^{\text{ES/TES, ini}} : \gamma_{ijtw}^{\text{ES/TES}} \text{'} \tag{29}$$

$$SOC_{ij(t-24)w}^{\text{ES/TES}} = SOC_{ij}^{\text{ES/TES, end}} : \gamma_{ijtw}^{\text{ES/TES}} \text{''} \tag{30}$$

where $P_{ijtw}^{\text{ES/TES}}$ is the power consumed by ES/TES; $\pi_{ijtw}^{\text{ES/TES}}$ is the selling price bid by ES/TES; $\underline{P}_{ij}^{\text{ES/TES}}$ and $\overline{P}_{ij}^{\text{ES/TES}}$ are the minimum and maximum power generated by ES/TES, respectively; $SOC_{ijtw}^{\text{ES/TES}}$ is the value of state of charge (SOC) related to ES/TES; $SOC_{ij}^{\text{ES/TES, ini}}$ and $SOC_{ij}^{\text{ES/TES, end}}$ are the initial and final values of SOC related to ES/TES, respectively; and $\underline{SOC}_{ij}^{\text{ES/TES}}$ and $\overline{SOC}_{ij}^{\text{ES/TES}}$ are the minimum and maximum values of SOC related to ES/TES, respectively.

The operation of ES/TES systems are represented by (26)-(30). The operation of an ES/TES system is subject to generation limits, as in (26), and the SOC limits, as in (27)-(30). It should be noted that (28) states the charging/discharging rate of the ES/TES system.

D. Bid Constraints of DER Price

$$0 \le \pi_{ijtw}^{X,\text{e}} \le \tilde{\lambda}_{tw}^{\text{MCP,e}} \tag{31}$$

$$0 \le \pi_{ijtw}^{Y,\text{h}} \le 2\tilde{\lambda}_{tw}^{\text{MCP,e}} \tag{32}$$

where $\tilde{\lambda}_{tw}^{\text{MCP,e}}$ is the value of predicted electric MCP at time t in scenario w.

Constraints (31) and (32) are related to the electric and thermal price bids governing the operation of DERs, where X includes CHP, ES, and WT; Y consists of CHP, EB, EHP, TES, GB, and STP. However, the value of the upper and lower bounds can vary with respect to the system deployed.

E. Independent and Coalitional Operation of H-MGs

We assume that there are I H-MGs, so the first I' H-MGs participate in the coalition formation to maximize their profit together. Two scenarios are implemented to simulate the performance of the proposed BL-HIA structure. These scenarios are described as follows.

1) Scenario 1

This scenario describes the independent operation of H-MGs. A single-level algorithm is deployed to model this scenario, as further clarified by the independent operation of H-MGs. Equation (33) gives the profit gained by selling energy by retailer k to all H-MGs.

$$\max \mathbb{R}_k^{\text{RET}} = \sum_{t=1}^{T} \sum_{i=1}^{n} (P_{kitw}^{\text{e}-} \pi_{kitw}^{\text{e}-} - P_{kitw}^{\text{e}-} \pi_{kitw}^{\text{e}-}) \tag{33}$$

where $P_{kitw}^{\text{e}-}$ is electric power purchased by retailer k from H-MG i; $\pi_{kitw}^{\text{e}-}$ is the supply bid for purchasing electric power from H-MG i; and n is the number of H-MGs.

Equation (34) gives the profit obtained through the independent operation of the H-MGs (MG^i). It is worth mentioning that if a DER does not exist in an H-MG, it is not considered in the respective objective function.

$$\mathbb{R}^{\text{MG}^i} = \sum_{t=1}^{T} \sum_{w=1}^{W} \sum_{j=1}^{J} (P_{ijtw}^{\text{ES}} \pi_{ijtw}^{\text{ES}} + P_{ijtw}^{\text{WT}} \pi_{ijtw}^{\text{WT}} + P_{ijtw}^{\text{STP}} \pi_{ijtw}^{\text{STP}} +$$
$$P_{ijtw}^{\text{EHP,h}} \pi_{ijtw}^{\text{EHP,h}} + P_{ijtw}^{\text{TES}} \pi_{ijtw}^{\text{TES}} + P_{ijtw}^{\text{EB,h}} \pi_{ijtw}^{\text{EB,h}} -$$
$$P_{ijtw}^{\text{EB,e}} \pi_{ijtw}^{\text{EB,e}} + P_{ijtw}^{\text{GB}} \pi_{ijtw}^{\text{GB}} + P_{ijtw}^{\text{CHP,e}} \pi_{ijtw}^{\text{CHP,e}} +$$
$$P_{ijtw}^{\text{CHP,h}} \pi_{ijtw}^{\text{CHP,h}} + P_{imtw}^{\text{e}-} \pi_{imtw}^{\text{e}-} + P_{iktw}^{\text{e}-} \pi_{iktw}^{\text{e}-} +$$
$$P_{imtw}^{\text{h}-} \pi_{imtw}^{\text{h}-} - P_{imtw}^{\text{e}+} \pi_{imtw}^{\text{e}+} + P_{iktw}^{\text{e}+} \pi_{iktw}^{\text{e}+} - P_{imtw}^{\text{h}+} \pi_{imtw}^{\text{h}+}) + \mathbb{R}_i^{\text{DSM}} \tag{34}$$

where $P_{iktw}^{\text{e}-}$ and $P_{iktw}^{\text{e}+}$ are the electric power purchased by H-MG i from retailer k and the electric power sold from H-MG i to retailer k, respectively; $\pi_{iktw}^{\text{e}-}$ and $\pi_{iktw}^{\text{e}+}$ are the supply bid for electric power purchased by H-MG i from retailer k and the supply bid for electric power sold from H-MG i to retailer k, respectively; $P_{imtw}^{\text{h}-}$ and $P_{imtw}^{\text{h}+}$ are the thermal power purchased by H-MG i from retailer k and the thermal power sold from H-MG i to retailer k, respectively; $\pi_{imtw}^{\text{h}-}$ and $\pi_{imtw}^{\text{h}+}$ are the supply bid for thermal power purchased by H-MG i from retailer k and the supply bid for thermal power sold from H-MG i to retailer k, respectively; W is the number of the scenarios; and J is the number of DERs.

2) Scenario 2

This scenario describes a coalition among H-MGs taking place at an upper level of the BL-HIA structure, which operates independently at the other level. This scenario also investigates the effect of the lower-level H-MGs forming a coalition on changes in the strategy of independent operations for the upper-level H-MG with a high priority. The mathematical model of this scenario is further clarified by the coalitional operation of H-MGs, as shown in (35) and (36). Equations (35) and (36) state the profit obtained through the coalitional operation of H-MGs at an upper level or a lower level.

$$\max \mathbb{R}^{MG^i MG^m} = \mathbb{R}^{MG^i} @ \mathbb{R}^{MG^m} \tag{35}$$

$$\max \mathbb{R}^{MG^i MG^m MG^{m'}} = \mathbb{R}^{MG^i} @ \mathbb{R}^{MG^m} @ \mathbb{R}^{MG^{m'}} \tag{36}$$

where @ represents the coalition among different H-MGs. In addition, the coalitional scenario of $\{(MG^1, MG^2, ..., MG^{I'})$, $(MG^{I'+1}, MG^{I'+2}, ..., MG^I)\}$ indicates that the first part (MG^1, $MG^2, ..., MG^{I'}$) is related to the objective function defined at the upper level, and a second part ($MG^{I'+1}, MG^{I'+2}, ..., MG^I$) is related to the coalition between H-MGs $I'+1$, $I'+2$, ..., I, which is defined at a lower level.

V. Mathematical Formulation of BL-HIA Structure

In the upper-level problem, each H-MG seeks to maximize its profit. The objective function of each upper-level problem states the income of each H-MG, with a higher-level priority for different scenarios. These objective functions that must be maximized have been defined as the sum of the product of electric/thermal price offers and the electric/thermal power sold to consumers of each H-MG minus the cost of operation of DERs.

The BL-HIA structure includes the upper-level problem and a set of lower-level problems in each scenario w. It should be noted that if an H-MG is considered at the upper level, its constraints from (1)-(32) are considered at the upper level; the same is true for the lower level. The upper-level problem includes decision making regarding the possibili-

ty of forming a coalition among H-MGs and their supply bids to achieve a higher profit. However, the quantity of DER/consumer resources along the DSM program is included in the lower-level problem. It should be noted that all of the power exchange among H-MGs and retailers' decisions are to be made on the upper-level problem. In comparison, decision-making variables at the lower level include all of the power generated using DER resources. The upper-level objective function is considered after maximizing the income of retailers or H-MGs in the case of independent operation, or in the coalitional operations with other H-MGs (under-investigated scenarios).

The income of H-MGs is defined as the product of the proposed price offers for selling power to H-MGs and the amount of power that is sold to them minus the product of the power purchase price offer received from H-MGs and the amount of power bought from other H-MGs.

A. Upper-level Problem

This subsection formulates the upper-level relationship. The formulae expressing the DER relationship given in (1)-(32) are applicable if the related DER is considered to be in the upper level.

1) Objective Function

As previously stated, the objective functions of the upper-level and lower-level problems may be in the form of (34)-(36). Here, the profit obtained from the coalition or the independent operation of H-MGs with greater priority describes the objective function of the upper-level problem. The upper-level problem is to maximize the expected profit to be made by each H-MG in the case of an individual or a group operation as well as a retailer.

2) Upper-level Problem Constraints

Formulae (1)-(32) are applicable to H-MGs with higher priority, so they participate in coalition formation. It is very obvious when an H-MG with a higher priority does not include any of the mentioned DERs. The corresponding constraints of such DERs are to be excluded from the problem formulation.

$$0 \leq P_{iktw}^{\mathrm{e}-} \leq \eta_i P_{itw}^{\mathrm{e}-} : \overline{\eta}_{iktw}^{\mathrm{Grid,\,e}}, \underline{\eta}_{iktw}^{\mathrm{Grid,\,e}} \tag{37}$$

$$0 \leq P_{iktw}^{\mathrm{e}+} \leq \eta_i P_{itw}^{\mathrm{e}+} : \overline{\eta}_{iktw}^{\mathrm{Grid,\,e}}, \underline{\eta}_{iktw}^{\mathrm{Grid,\,e}} \tag{38}$$

where $P_{itw}^{\mathrm{e}-}$ and $P_{itw}^{\mathrm{e}+}$ are the power transffred from H-MGs to retailers and from retailers to H-MGs, respectively; and η_i is the power exchange setting factor.

Equations (38) and (39) show the allowable limits on power exchange between retailers and H-MGs.

Each H-MG in the upper-level problem makes strategic decisions as follows: ① decisions of DERs on the supply bid at the lower level of the problem; ② price strategic offering decisions of consumers in an H-MG on price offers.

B. Lower-level Problem

Each lower-level problem aims to maximize the profit of an individual H-MG or a group of H-MGs with a lower priority over different scenarios. The objective of the lower-level problem is to increase the profit of DERs. Thus, the aim of CEMS is to reduce the operation cost given limitations ruling over each of the players, i.e., H-MGs, retailers, and consumers. Players in the BL-HIA structure declare the amount of their generated power and supply bids offered to the CEMS. After simulating the bilevel problem, the electric and thermal energy prices, and the power provided by each player are provided.

1) Objective Function

Considering the cases described in (34)-(36), the objective function of the lower-level problem can be taken from the numerator of the lower-level objective function.

2) Lower-level Problem Constraint for Load Shifting and DERs

Equations (1)-(32), (37) and (38) are applied to each H-MG with a lower priority. It is very obvious that if, for example, an H-MG with a lower priority has no CHP, then its constraints must not be considered.

Equation (39) gives the equilibrium relation between the generated and consumed electric power of H-MGs and the electric power exchange with retailers. The MCP in the grid is equal to the dual variable of (39).

$$P_{iktw}^{\mathrm{e}-} + P_{itw}^{\mathrm{DSM,\,e}} - (P_{ijtw}^{\mathrm{CHP,\,e}} + P_{ijtw}^{\mathrm{WT}} + P_{ijtw}^{\mathrm{ES}} - P_{ijtw}^{\mathrm{EB,\,e}} -$$

$$P_{ijtw}^{\mathrm{EHP,\,e}} + P_{iktw}^{\mathrm{e}+}) + \sum_{m=1}^{n} P_{imtw}^{\mathrm{e}+} - \sum_{m=1}^{n} P_{imtw}^{\mathrm{e}+} = 0 : \lambda_{tw}^{\mathrm{e}} \tag{39}$$

Equation (40) gives the relation between the thermal generated and consumed power. The thermal power price in the dual-variable grid corresponds to (40).

$$P_{itw}^{\mathrm{DSM,\,h}} - P_{ijtw}^{\mathrm{CHP,\,h}} + P_{ijtw}^{\mathrm{EB,\,h}} + P_{ijtw}^{\mathrm{EHP,\,h}} + P_{ijtw}^{\mathrm{TES}} + P_{ijtw}^{\mathrm{GB}} +$$

$$P_{ijtw}^{\mathrm{STP}} + \sum_{m=1}^{n} P_{imtw}^{\mathrm{h}-} - \sum_{m=1}^{n} P_{imtw}^{\mathrm{h}+} = 0 : \lambda_{tw}^{\mathrm{h}} \tag{40}$$

After the determination of price offers related to electricity and heat, as well as the amount of electric and thermal power generation and consumption of each player, the profit made by each of the players is determined.

It should be noted that the electricity price or MCP is the dual variable of the constraint related to power balance. In this model, we assume that the prices of electricity generated by all DERS, i.e., CHP, WT, and electric ES, are the same. Thus, we only need one MCP or one dual variable of the constraint related to the power balance at each time of the day. Hence, we only need to consider one power balance constraint for all H-MGs. Since we have only one power balance constraint, there is no need to consider power flow in this study. In the same way, we assume that the heating price, which is the dual variable of the constraint related to the heat balance, is the same for the heat generated for all DERs, including CHP, GB, EHP, EB, and TES. Hence, we only need to model one heat balance constraint for all H-MGs at each time of the day. In summary, we use the model for power and heat exchange regardless of whether the voltage angle and magnitude are considered owing to the similar energy hub price.

3) Application of KKT Conditions to Lower-level Problem

Since each of these lower-level problems is continuous and convex, it may be shown by its specific constraints, including KKT conditions [40]. Using KKT conditions, the constraints for an independent or a coalition operation of H-MGs include the following cases:

1) Primal constraints (1)-(32).

2) Equality constraints obtained from the derivative of a Lagrange expression relative to lower-level variables.

3) Complementary constraints obtained based on lower-level inequalities (3), (4), (8), (9), (13), (16), (19), (21), (24), (26), (28), (31), (32), (37), and (38).

The application of KKT conditions to the lower-level problem is provided in detail in the supplementary material.

VI. RESULTS AND DISCUSSION

The grid studied is shown in Fig. 5, where EDS stands for electric distribution system; FDS stands for fuel distribution system; E represents the electricity; and H represents the heat. The ES systems installed in H-MGs (A and C) are for storing excess electrical and thermal energy generation. The capacity and the quantity of installed equipment in each H-MG are shown in Table I. Profiles of the electric and thermal loads of the H-MGs and electricity prices for purchasing and selling are shown in Fig. S1 in the Supplemental Material. In addition, the shape of output power wave generated by WT and STP is shown in Fig. S2 in the Supplemental Material.
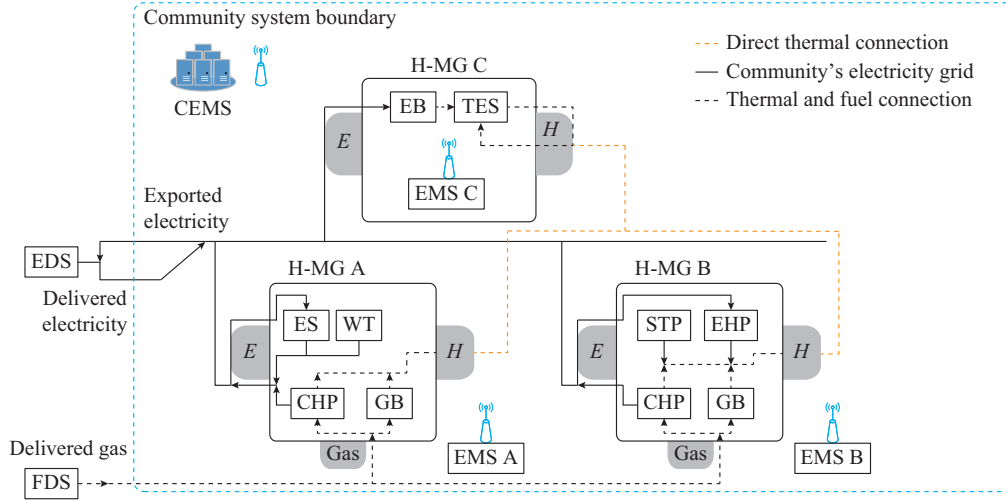

Fig. 5.   Grid under study.

TABLE I
CAPACITY AND QUANTITY OF EQUIPMENT INSTALLED IN EACH H-MG

Parameter	Value for each H-MG		
	H-MG A	H-MG B	H-MG C
CHP	-	-	-
Electric output (kW)	142	207	-
Thermal output (kW)	104	140	-
Thermal output of EHP (kW)	-	700	-
Electric output of WT (kW)	50	-	-
Electric output of STP (kW)	-	600	-
Electric output of ES (kW)	-	500	-
TES (m³)	-	-	4
Thermal output of GB (kW)	2×150	2×150	-
Thermal output of EB (kW)	-	-	2×100

According to the independent and coalitional operation of H-MGs, we can define the following scenarios for the grid under study.

1) Scenario 1 ({A}, {B}, {C}, {RET}): this scenario describes the independent operation of H-MGs. A single-level algorithm is deployed to model this scenario, as further clarified by the independent operation of H-MGs.

2) Scenario 2 ({A, {B, C}}, {{A, B}, C}, {{A, C}, B}, {B, {A, C}}, {{B, C}, A}, {C, {A, B}}): this scenario describes a coalition among H-MGs taking place at a single level of the BL-HIA structure and operating in an indepen-

dent operation at the other level. The representation of such a scenario can take the shape of ({A, BC}, {AB, C}, {AC, B}, {B, AC}, {BC, A}, {C, {AB}}). This scenario also investigates the effect of the lower-level H-MGs forming a coalition on independently changing the strategy of operating the upper-level H-MG with a high priority.

Equations (41) and (42) give the profit obtained through the coalitional operation of H-MGs ({A}, {B}, {C}) at an upper level or a lower level.

$$\max \mathbb{R}_i^{\{AB\}} = \mathbb{R}_i^{\{A\}} @ \mathbb{R}_i^{\{B\}} \tag{41}$$

$$\max \mathbb{R}_i^{\{ABC\}} = \mathbb{R}_i^{\{A\}} @ \mathbb{R}_i^{\{B\}} @ \mathbb{R}_i^{\{C\}} \tag{42}$$

In addition, the coalitional scenario of ({B, AC}) means that the first part (B) is related to the objective function defined at the upper level, and a second part (AC) is related to a coalition between H-MGs A and C but is defined at a lower level.

Equations (43)-(48) state the profit obtained from the coalitional operation of H-MGs A, B, and C at an upper level or a lower level. The right-hand side of these relations comprises of two parts. The first part is related to the objective function defined at the upper level, whereas the second part is related to the objective function defined at the lower level.

$$\max \mathbb{R}_i^{\{A, BC\}} = \mathbb{R}_i^{\{A\}} @ \mathbb{R}_i^{\{BC\}} \tag{43}$$

$$\max \mathbb{R}_i^{\{AB, C\}} = \mathbb{R}_i^{\{AB\}} @ \mathbb{R}_i^{\{C\}} \tag{44}$$

$$\max \mathbb{R}_i^{\{AC, B\}} = \mathbb{R}_i^{\{AC\}} @ \mathbb{R}_i^{\{B\}} \tag{45}$$

$$\max \mathbb{R}_i^{\{B, AC\}} = \mathbb{R}_i^{\{B\}} @ \mathbb{R}_i^{\{AC\}} \tag{46}$$

$$\max \mathbb{R}_i^{\{BC,A\}} = \mathbb{R}_i^{\{BC\}} @ \mathbb{R}_i^{\{A\}} \qquad (47)$$

$$\max \mathbb{R}_i^{\{C,AB\}} = \mathbb{R}_i^{\{C\}} @ \mathbb{R}_i^{\{AB\}} \qquad (48)$$

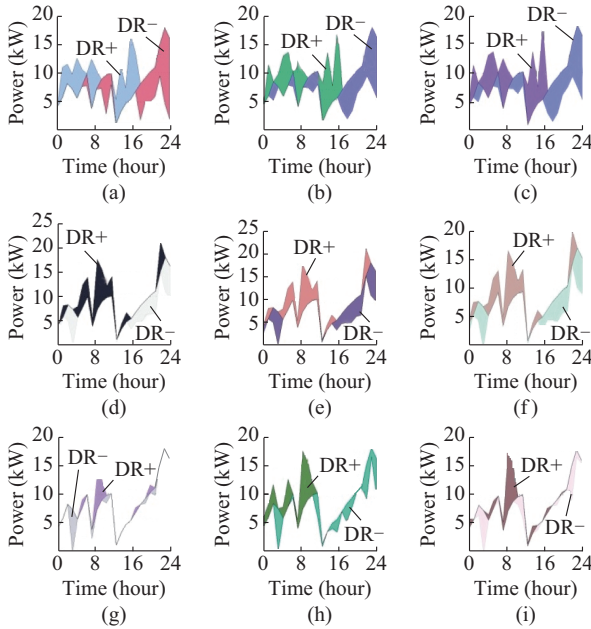The load profiles of H-MGs A, B, and C are shown in Figs. 6-8.

Fig. 6. Positive DR (DR+) and negaitive DR (DR−) in H-MG A in different scenarios. (a) {A}. (b) {B}. (c) {C}. (d) {A, BC}. (e) {AB, C}. (f) {AC, B}. (g) {B, AC}. (h) {BC, A}. (i) {C, AB}.
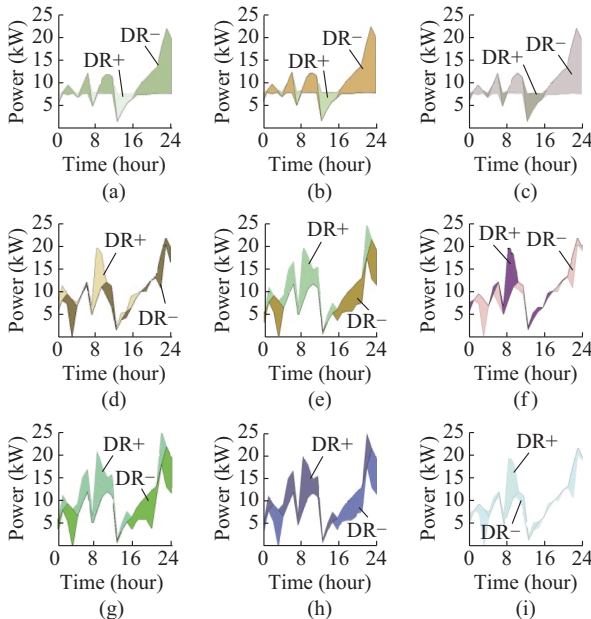

Fig. 7. Positive DR (DR+) and negaitive DR (DR−) in H-MG B in different scenarios. (a) {A}. (b) {B}. (c) {C}. (d) {A, BC}. (e) {AB, C}. (f) {AC, B}. (g) {B, AC}. (h) {BC, A}. (i) {C, AB}.

For the independent operation of H-MGs, most of RLDs of H-MG A are shifted from the time intervals with higher MCP to the time intervals with lower MCP. The amount of load that is shifted forms a high share of the total load of H-MGs. More specifically, 55% of the load is shifted from time intervals with higher MCP to other time intervals with lower MCP, with the aim to maximize the profit for H-MG owners. By contrast, the energy consumption in such a figure has reduced significantly when H-MGs operate in coalitional structures. This energy consumption is the lowest (21%) for the coalitional scenario of {B, AC}. The energy consumption is at the lowest level (21%) when the coalition scenario corresponds to {B, AC}. In addition, the reduction in the degree of load shift results from a DSM program aiming at achieving a higher pay-off for consumers by considering employing load shifting when the value of MCP is high, along with the maximum use of H-MG A interval resources, and effectively reducing the generation cost when load shifting is at a minimum level. Moreover, the load profile of H-MGs in a coalition structure {A, BC} is the same as that of the alternative coalition structure {AB, C} and does not have a significant effect on the consumption level in H-MG A. This trend is completely different from the case in H-MG B. More specifically, during the independent operation of H-MGs, the degree of load shifting in H-MG B is at a minimum level (almost 30% of the total load during 24 hours). Therefore, the formation of a coalition among H-MGs would increase consumers' participation in the DR program, which can reach almost 42% to 50%.
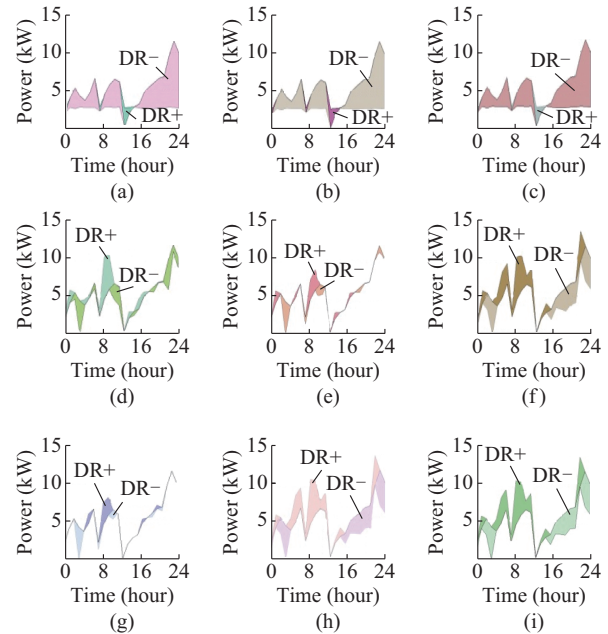

Fig. 8. Positive DR (DR+) and negative DR (DR−) in H-MG C in different scenarios. (a) {A}. (b) {B}. (c) {C}. (d) {A, BC}. (e) {AB, C}. (f) {AC, B}. (g) {B, AC}. (h) {BC, A}. (i) {C, AB}.

Such a reduction in the degree of load shifting is the result of a DSM program for achieving higher pay-off for consumers by considering criteria such as load shifting when the value of MCP is high, the maximum use of H-MG A interval resources, and also the reduction in generation costs in the best way and with the least amount of load shifting has taken place. Alternatively, the load profile of H-MGs in a coalitional structure {A, BC} is the same as that of such H-MGs in an alternative coalitional structure {AC, B}, and

does not significantly affect the consumption nature in H-MG A.

The least amount of load shifting is achieved when H-MGs B and A form a coalition at the lower level of the BL-HIA structure, while having the objective function at an upper level of the structure aiming at maximizing the profit of H-MG C. Furthermore, these conditions are comparable with the {AC, B} coalition structure, having similar nature. Under the previous conditions, a substantial share of the excess generation capacity is devoted to meeting H-MG C demand. As a result, a negligible part of such energy has been allocated for supplying responsive loads in H-MG B. It is important to clarify that in the case of H-MG C, in independent operation conditions, the value of the total DR− is significantly greater than the value of the total DR+. While accounting for only 17% of time intervals, H-MG C had experienced a DR+ algorithm, and such a figure would reach 83% when the DR− is experienced. Such a trend in the DR is comparable to the scenario of coalition structures, where the degrees of the total load shifting with the value of DR+ total load during the daily performance, are close to each other in terms of the value. The participation percentage of consumers in H-MG C has improved significantly by forming a coalition between H-MGs B and A, reaching more than 40% of the time. Only in the coalitional structure {B, AC} can such value be a minimum (21%).

Furthermore, these conditions are also identical to that of the coalitional structure {AC, B} and have a similar nature. Under the previous conditions, a big share of the amount of excess generation is spent supplying H-MG C demand.

It should be noted that for H-MG C, the value of the total DR− in H-MGs under independent operation conditions is much more than such a value when there is DR+. Such a trend in DR is quite similar to the scenario of coalitional structures, where the total load shifting and the value of the DR+ total load during the daily performance are close to each other in terms of the value. The increasing trend of the income of each H-MG during an independent and coalitional performance with other H-MGs is shown in Fig. 9.
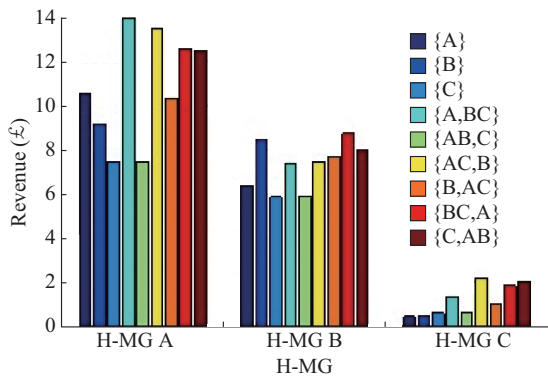

Fig. 9.   H-MG income in different scenarios.

Based on this figure, each structure can be useful for one H-MG, while it may have no benefit for other H-MGs. The best structure, which may be useful for H-MG A, results from the formation of a coalition between H-MG B and H-

MG C, excluding the participation of H-MG A in this coalition. These conditions may also be useful for H-MG B on the condition of forming a coalition with H-MG C in a higher priority of operation. For H-MG C, the highest income is experienced when this H-MG forms a coalition with H-MG A at an initial stage given that H-MG B works independently. Under these conditions, the income of H-MG A is close to the maximum value. For H-MG C, because of the lower generated power, it is appropriate to form a coalition in all cases with other H-MGs. In all cases in which H-MG C has formed a coalition with other H-MGs, an increasing trend in the income is observed. In comparison, when used independently, the income resulting from H-MG B is significantly improved when compared with other configurations such as coalition formation with other H-MGs. Furthermore, in some cases, it is possible for coalition forming to have a detrimental effect on the H-MGs that form part of the coalition.

It is also observed that the coalition between H-MG A and H-MG B at the initial level leads to a significant reduction in the income independently obtained by this H-MG. Moreover, it is desirable to prevent H-MG A from forming a coalition with H-MG B, and to negotiate with H-MG C to form the coalition. In comparison, the income resulting from the independent performance of H-MG B is also significant compared to other cases, e.g., coalition formation with other H-MGs, and in some cases it is harmful to form a coalition to these H-MGs. For H-MG C , because of the small generated power, it is appropriate to form a coalition in all cases with other H-MGs. Figure 10 shows the values of the electric and thermal MCP.
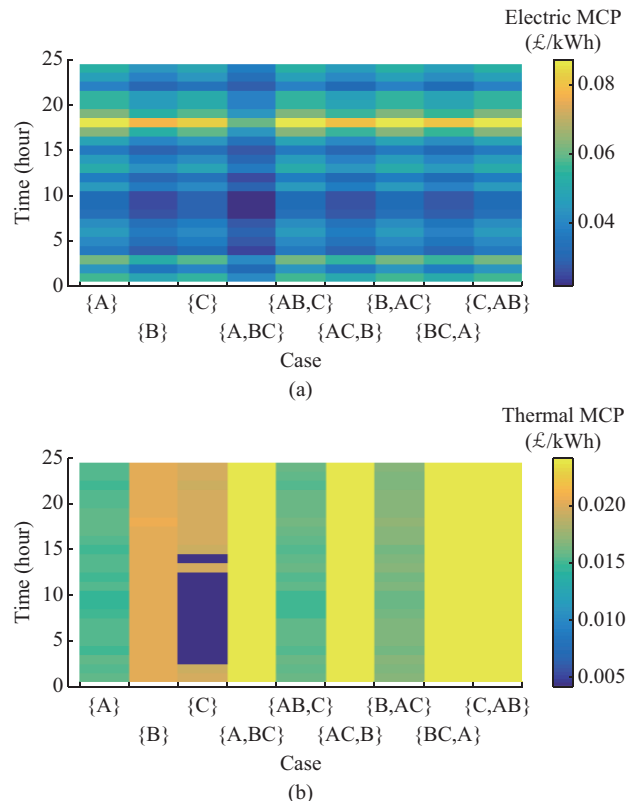

(a)

(b)

Fig. 10.   Electrical and thermal MCP during 24-hour-long system performance. (a) Electric MCP. (b) Thermal MCP.

Although the average value of the electrical MCP in the case of independent operation of H-MG C is at its minimum during the system's daily performance, such values can be significantly improved when investigated at individual time intervals, i.e., one hour after forming a coalition among H-MGs. In some of the time intervals, the formation of a coalition causes neither a degradation in the electric MCP, nor a small increase in its value. Moreover, at certain intervals, its value may not change significantly when a coalition exists compared with the scenario where H-MGs work independently. In about 54% of the times, the electric MCP value in the coalition {A, BC} becomes more than its value in the combination {A, BC}. That is why no differences are observed in the values of the electric MCP for coalitions {A, BC}, {AC, B}, {BC, A}, and {C, AB}. Furthermore, by changing the structure from {A, BC} to {B, AC}, the MCP value is reduced by about 33%.

Such an analysis is also applied to the thermal MCP for the structures investigated. Finally, we can conclude from the simulation results that the formation of a coalition among H-MGs in one grid will not only have a significant effect on programming and regulating the value of the power generated by the generation resources, but also affect the change in the demand consumption and the behavior of consumers participating in the DR program with a cheaper MCP.

VII. Conclusion

This paper presents an optimum development that combines the problem of the quantity of power generated in a deregulated electricity market environment. A methodology is presented to investigate the possibility of increasing the incomes of H-MGs, consumers, and retailers in multiple H-MGs. These performances of participants are properly modeled in the market environment. An H-MG programmer tries to increase its income as long as it is freely negotiating energy exchange with DERs and its consumers. It can also incorporate on its agenda the potential of forming a coalition with other H-MGs. The H-MGs seek to estimate the value of the power generated by DERs and also supply/demand bids to consumers. Meanwhile, the possibility of forming a coalition among H-MGs to maximize the income in an independent or a coalitional operation in a scheduling horizon is also investigated. In this way, the H-MGs encounter pool price uncertainties and the value of electric and thermal loads. Furthermore, if the supply bid of one H-MG is not competitive enough, consumers may choose another H-MG to supply their demand. To investigate how the formation of a coalition among H-MGs can affect the market behavior and the gained income of H-MGs, different scenarios are presented. These scenarios are solved by employing a bilevel structure, which can be transformed into one NLP problem. The proposed model not only presents solutions of higher-income achievements of each H-MG in an independent or a coalitional operation but also provides a higher income/lower cost for each of the retailers/consumers relative to a single-level model.

The BL-HIA structure presents an adequate framework for modeling both the H-MG reaction for better participation in the generation and the effect on the electricity price, as well as increases in competition between H-MGs and retailers. In the upper-level problem, H-MGs change their capacity to maximize their income by predicting the behavior of other competitors (H-MGs) resulting from the lower-level problem and noting quantities and prices proposed by DERs and consumers. An optimum pricing strategy is implemented to enable dynamic market behaviors related to H-MG decisions. Furthermore, a daily generation schedule is presented. For a selected case study, an infinite number of Nash equilibrium values is observed for the case where no players tend to change their pricing strategies unilaterally. In these obtained equilibrium points, there is no change in the total expected profit of all players, although it is distributed among them.

Simulation results show that by forming a coalition among H-MGs, there may be changes in their profit, the demand value of the supplied load, and the generated power of DER in those H-MGs. Furthermore, computational simulations show the convergence of the proposed model for solving real problems and simultaneously presenting solutions to increase the income of H-MGs and retailers, as well as to reduce the MCP. The following results can be extracted from the structure of the developed model:

1) The hierarchical structure of the bilevel model is suitable for modeling the strategic behavior of each H-MG in reaction to the behavioral change and decision making of other H-MGs and their supply bid. Furthermore, the proposed structure can effectively encourage consumers to participate in the electricity market, and affect their use of the DSM program.

2) It has been shown that in addition to increasing the profit of each player, the energy exchange among H-MGs would have a significant impact on leveling the load and reducing consumers' power consumption during the peak time.

3) Results show that the formation of a coalition among H-MGs in one grid will not only have a significant effect on programming and regulating the value of the power generated by the generation resources, but also affect the changes in the demand consumption and the behavior of consumers participating in the DR program with a cheaper MCP.

References

[1] K. Moslehi and A. B. R. Kumar, "Autonomous resilient grids in an iot landscape vision for a nested transactive grid," *IEEE Transactions on Power Systems*, vol. 34, no. 5, pp. 4089-4096, Sept. 2019.

[2] A. Shamisa, B. Majidi, and J. C. Patra, "Sliding-window-based real-time model order reduction for stability prediction in smart grid," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 326-337, Jan. 2019.

[3] F. Li, J. Qin, and Y. Kang, "Multi-agent system based distributed pattern search algorithm for non-convex economic load dispatch in smart grid," *IEEE Transactions on Power Systems*, vol. 34, no. 3, pp. 2093-2102, May 2019.

[4] J. Valinejad, M. Marzband, Y. Xu *et al*., "Dynamic behavior of multi-carrier energy market in view of investment incentives," *Electrical Engineering*, vol. 101, no. 3. pp. 1033-1051, Oct. 2019.

[5] W. Kohn, Z. B. Zabinsky, and A. Nerode, "A micro-grid distributed intelligent control and management system," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 2964-2974, Nov. 2015.

[6] Y. Liu, C. Yuen, N. U. Hassan *et al*., "Electricity cost minimization for a microgrid with distributed energy resource under different information availability," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2571-2583, Apr. 2015.

[7] C. Li, X. Yu, W. Yu *et al.*, "Efficient computation for sparse load shifting in demand side management," *IEEE Transactions on Smart Grid*, vol. 8, no. 1, pp. 250-261, Jan. 2017.

[8] J. Zazo, S. Zazo, and S. V. Macua, "Robust worst-case analysis of demand-side management in smart grids," *IEEE Transactions on Smart Grid*, vol. 8, no. 2, pp. 662-673, Mar. 2017.

[9] J. Valinejad and L. Milic. (2020, Apr.). Community resilience optimization subject to power flow constraints in cyber-physical-social systems in power engineering. [Online]. Available: https://arxiv. org/abs/2004.00772

[10] J. Ma, J. Deng, L. Song *et al.*, "Incentive mechanism for demand side management in smart grid using auction," *IEEE Transactions on Smart Grid*, vol. 5, no. 3, pp. 1379-1388, May 2014.

[11] J. Valinejad, Z. Oladi, T. Barforoshi *et al.*, "Stochastic unit commitment in the presence of demand response program under uncertainties," *International Journal of Engineering, Transactions B: Applications*, vol. 30, no. 8, pp. 1134-1143, Aug. 2017.

[12] M. Ostadijafari, A. Dubey, and N. Yu, "Linearized price-responsive HVAC controller for optimal scheduling of smart building loads," *IEEE Transactions on Smart Grid*, vol. 11, no. 4, pp. 3131-3145, Jul. 2020.

[13] M. Ostadijafari, D. Anamika, L. Yang *et al.*, "Smart building energy management using nonlinear economic model predictive control," in *Proceedings of 2019 IEEE PES General Meeting*, Atlanta, USA, Aug. 2019, pp. 1-8.

[14] M. Ostadijafari and D. Anamika. (2019, Jun.). Linear model-predictive controller (LMPC) for building's heating ventilation and air conditioning (HVAC) system. [Online]. Available: https://arxiv. org/abs/1906.00352

[15] W. Pei, W. Deng, Z. Shen *et al.*, "Operation of battery energy storage system using extensional information model based on IEC 61850 for micro-grids," *IET Generation, Transmission & Distribution*, vol. 10, no. 4, pp. 849-861, Mar. 2016.

[16] Y. Zhang, J. Zhou, Y. Zheng *et al.*, "Control optimisation for pumped storage unit in micro-grid with wind power penetration using improved grey wolf optimiser," *IET Generation, Transmission & Distribution*, vol. 11, no. 13, pp. 3246-3256, Oct. 2017.

[17] A. Najafi, H. Falaghi, J. Contreras *et al.*, "A stochastic bilevel model for the energy hub manager problem," *IEEE Transactions on Smart Grid*, vol. 8, no. 5, pp. 2394-2404, Sept. 2016.

[18] R. Li, W. Wei, S. Mei *et al.*, "Participation of an energy hub in electricity and heat distribution markets: an MPEC approach," *IEEE Transactions on Smart Grid*, vol. 10, no. 4, pp. 3641-3653, Jul. 2018.

[19] L. Ni, W. Liu, F. Wen *et al.*, "Optimal operation of electricity, natural gas and heat systems considering integrated demand responses and diversified storage devices," *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 3, pp. 423-437, May 2018.

[20] Y. Chen, W. Wei, F. Liu *et al.*, "Analyzing and validating the economic efficiency of managing a cluster of energy hubs in multi-carrier energy systems," *Applied Energy*, vol. 230, pp. 403-416, Nov. 2018.

[21] V. Davatgaran, M. Saniei, and S. S. Mortazavi, "Optimal bidding strategy for an energy hub in energy market," *Energy*, vol. 148, pp. 482-493, Apr. 2018.

[22] X. Luo, Y. Liu, J. Liu *et al.*, "Energy scheduling for a three-level integrated energy system based on energy hub models: a hierarchical Stackelberg game approach," *Sustainable Cities and Society*, vol. 52, pp. 1-9, May 2020.

[23] G. Liu, M. Starke, B. Xiao *et al.*, "Robust optimisation-based microgrid scheduling with islanding constraints," *IET Generation, Transmission & Distribution*, vol. 11, no. 7, pp. 1820-1828, May 2017.

[24] C. Liu, X. Wang, X. Wu *et al.*, "Economic scheduling model of microgrid considering the lifetime of batteries," *IET Generation, Transmission & Distribution*, vol. 11, no. 3, pp. 759-767, Feb. 2017.

[25] L. K. Panwar, S. R. Konda, A. Verma *et al.*, "Operation window constrained strategic energy management of micro-grid with electric vehicle and distributed resources," *IET Generation, Transmission & Distribution*, vol. 11, no. 3, pp. 615-626, Feb. 2017.

[26] N. Kinhekar, N. P. Padhy, F. Li *et al.*, "Utility oriented demand side management using smart AC and micro DC grid cooperative," *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1151-1160, Mar. 2016.

[27] J. Valinejad, M. Marzband, M. F. Akorede *et al.*, "Long-term decision on wind investment with considering different load ranges of power plant for sustainable electricity energy market," *Sustainability*, vol. 10, no. 10, pp. 3811-3829, Oct. 2018.

[28] A. K. Basu, A. Bhattacharya, S. Chowdhury *et al.*, "Planned scheduling for economic power sharing in a CHP-based micro-grid," *IEEE Transactions on Power Systems*, vol. 27, no. 1, pp. 30-38, Jan. 2012.

[29] S. Lee, B. Kwon, and S. Lee, "Joint energy management system of electric supply and demand in houses and buildings," *IEEE Transactions on Power Systems*, vol. 29, no. 6, pp. 2804-2812, Nov. 2014.

[30] D. Jayaweera, "Security enhancement with nodal criticality-based integration of strategic micro grids," *IEEE Transactions on Power Systems*, vol. 30, no. 1, pp. 337-345, Jan. 2015.

[31] P. Wang, Z. Gao, and L. Bertling, "Operational adequacy studies of power systems with wind farms and energy storages," *IEEE Transactions on Power Systems*, vol. 27, no. 4, pp. 2377-2384, Jul. 2012.

[32] A. Giusti, M. Salani, G. A. D. Caro *et al.*, "Restricted neighborhood communication improves de-centralized demand-side load management," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 92-101, Jan. 2014.

[33] J. Ni and Q. Ai, "Economic power transaction using coalitional game strategy in micro-grids," *IET Generation, Transmission & Distribution*, vol. 10, no. 1, pp.10-18, Jan. 2016.

[34] H. A. Gabbar and A. M. Othman, "Performance optimisation for novelgreen plug-energy economizer in micro-grids based on recent heuristicalgorithm," *IET Generation, Transmission & Distribution*, vol. 10, no. 3, pp. 678-687, Feb. 2016.

[35] J. Valinejad, M. Marzband, M. Elsdon *et al.*, "Dynamic carbon-constrained EPEC model for strategic generation investment incentives with the aim of reducing CO_2 emissions," *Energies*, vol. 12, no. 24. pp. 4813, Dec. 2019.

[36] J. Valinejad and T. Barforoushi, "Generation expansion planning in electricity markets: a novel framework based on dynamic stochastic MPEC," *International Journal of Electrical Power & Energy Systems*, vol. 70. pp. 108-117, Sept. 2015.

[37] M. Marzband, N. Parhizi, and J. Adabi, "Optimal energy management for stand-alone microgrids based on multi-period imperialist competition algorithm considering uncertainties: experimental validation," *International Transactions on Electrical Energy Systems*, vol. 30, no. 1, pp. 122-131, Mar. 2015.

[38] Y. Xu and L. Mili, "Probabilistic power flow analysis based on the adaptive polynomial chaos-anova method," in *Proceedings of 2018 IEEE PES General Meeting*, Portland, USA, Aug. 2018, pp. 1-10.

[39] Y. Xu, C. Huang, X. Chen *et al.*, "Response-surface-based bayesian inference for power system dynamic parameter estimation," *IEEE Transaction on Smart Grids*, vol. 10, no. 6, pp. 5899-5909, Nov. 2019.

[40] J. Valinejad, M. Marzband, M. F. Akorede *et al.*, "Generation expansion planning in electricity market considering uncertainty in load demand and presence of strategic GENCOs," *Electric Power Systems Research*, vol. 152, pp. 92-104, Nov. 2017.

Jaber Valinejad is currently pursuing his Ph.D. degree at the Bradley Department of Electrical and Computer Engineering, Virginia Tech, Greater Washington D.C., USA. His current research interests include power systems, resilience and community resilience, cyber-physical-social systems and social computing, artificial intelligence, and reinforcement learning.

Mousa Marzband received the Ph.D. degree in electrical engineering from the Department of Electrical Engineering, Polytechnic University of Catalunia, Barcelona, Spain, in 2014. After his Ph.D., he joined the University of Manchester, Manchester, UK, as a Post-Doctoral Research Fellow and then joined the University College Cork, Cork, Ireland, as a Senior Researcher. He is currently a Senior Lecture (Associate Professor) with the Department of Match, Physics, Electrical Engineering, Northumbria University, Newcastle, UK. Due to the high numbers of citations for his research, he has recently been appointed as an Honorary Distinguished Adjunct Professor by King Abdulaziz University, Jeddah, Saudi Arabia (judged to be the best university in the Arab World by THE in 2019). The reason behind this is that he is highly Cited Researcher in 2019. He is nominated in 2018 and 2019 by Thomson Reuters to be the world's top 1% researchers in engineering. His research findings have been published in two books and more than 80 top field journals and over 40 proceedings of the international conferences. Recently, as a co-investigator, he helped to secure the UK-India grant (£185K), funded by Britich Council and started in May 2019, to develop the power electronics schemes for a smart micro grid with high penetration of PV generation and electric vehicles. His research interests include operation and control strategies in DGs, mathematical modelling and control of optimal energy management system within multi-energy carrier systems, and cooperative and non-cooperative game theory applications in energy market.

Mert Korkali received the Ph. D. degree in electrical engineering from Northeastern University, Boston, USA, in 2013. He is currently a Research Staff Member at Lawrence Livermore National Laboratory, Livermore, USA. From 2013 to 2014, he was a Postdoctoral Research Associate at the University of Vermont, Burlington, USA. He is the co-chair of the IEEE Task Force on Standard Test Cases for Power System State Estimation. He is currently serving as an Editor of the IEEE Open Access Journal of Power and Energy and the IEEE Power Engineering Letters, and an Associate Editor of Journal of Modern Power Systems and Clean Energy. His current research interests include the broad interface of robust state estimation and fault location in power systems, extreme event modeling, cascading failures, uncertainty quantification, and probabilistic grid planning.

Yijun Xu received the Ph.D. degree from Bradley Department of Electrical and Computer Engineering at Virginia Tech, Falls Church, USA, in December, 2018. He is currently a Postdoc Associate at Virginia Tech-Northern Virginia Center, Falls Church, USA. He did the computation internship at Lawrence Livermore National Laboratory, Livermore, USA, and power engineer internship at ETAP-Operation Technology, Inc., Irvine, California, in 2018 and 2015, respectively. His research interests include power system uncertainty quantification, uncertainty inversion, and decision-making under uncertainty.

Ameena Saad Al-Sumaiti received the B.Sc. degree in electrical engineering from United Arab Emirates University, Al Ain, UAE, in 2008, and the M.A.Sc. and Ph.D. degrees in electrical and computer engineering from the University of Waterloo, Waterloo, Canada, in 2010 and 2015, respectively. She was a Visiting Assistant Professor with Massachusetts Institute of Technology (MIT), Cambridge, USA, in 2017. She is currently an Assistant Professor with the Advanced Power and Energy Center and the Department of Electrical Engineering and Computer Science, Khalifa University, Abu Dhabi, UAE. Her research interests include intelligent systems.