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Interactive Multi-level planning for energy management in clustered microgrids considering flexible demands

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ABSTRACT

This paper presents a novel interactive multi-level planning strategy for the energy management of distribution networks with clustered microgrids (CMGs). CMGs are a group of microgrids with multiple renewable energy resources that comprise various technologies, such as photovoltaic systems, wind turbines, micro turbines and electric vehicles. This study develops an innovative multi-level optimization framework for the energy management coordination between microgrids and CMGs in the lower level, between clusters and distribution systems, and finally between distribution systems and upstream networks in the upper level. Accordingly, an hourly optimal energy management (HOEM) system is applied to minimize the multi-objective objective function for each level. The lower level may be operated in islanded or grid-connected mode in some hours. This is decided by changing switches between MGs, clusters, and grids, while the upper level is only operated in the grid-connected mode. Moreover, a demand response program that has a great effect on the hourly planning of switches is modeled in the upper level. The proposed model is tested on CMGs and actual distribution systems. The results show the significance of this planning strategy in the techno-economic aspects and optimal power transaction in the distribution system operation.

1. Introduction

Renewable energy sources (RESs) have been extended in the power grid as one of the main solutions in decreasing environmental greenhouse gasses. High penetration of RESs may, however, bring several challenges to the operation of distribution systems. To cope with this challenge, the concept of microgrid has been introduced. Microgrids (MGs) are a group of interconnected distributed energy resources (DERs) and loads with well-characterized electrical restrictions, which operate as a sole controllable entity corresponding to the upstream grid. MGs can operate in both grid-connected and islanded mode. Since the MGs can contribute to energy transactions and provide the anticipation of the required distribution system agent with service providers, the energy management of MGs has an excellent contribution to the technical and economic performance enhancement.

The traditional methods of electrical energy transmission have undergone some changes in the past few years. One of the main problems to be solved has been the reliability of the system, especially in critical situations. Hence, an important purpose of smart grid development was to achieve a higher contribution of RES in power grids. However, a high penetration of RES in power grids reduces the generation flexibility because of the unpredictability of the generation of these resources. Thus, applying demand response program (DRP) methods seems to be an increasing necessity [1].

From distribution system point of view, since the MGs contribute to energy marketing and provide the distribution system operator (DSO) with auxiliary services, the energy management of MGs is vital and can result in better techno-economic performances. One of the possible clarifications is clustering the MGs based on energy management strategies. A cluster is a set of MGs and a division of a distribution system that can be interconnected with other clusters for transaction power among clusters or between clusters and an upstream network. Clustered microgrids (CMGs) can be considered as effective tools to optimally operate a group of MGs with multiple RESs. A simple strategy for energy management of distribution networks with multiple microgrids is to

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Nomenclature

Indices

i, j, b	Index for network buses
t	Index for time
m, n	Index for the network of MGs
c	Index for clusters

Sets

Ω_b	Set of system distribution system buses
$\widetilde{\mu}_q$	Membership functions of fuzzy min–max decision maker
Ψ	Objective functions in lower level

\Upsilon Pareto optimal solutions

Ω_{MG}	Set of MG buses
Ω_{Sub}	Set of substations
Ω_C	Set of clusters
Ω_t	Set of time

Variables

$P_{i,t}^{Sub^{low}}/Q_{i,t}^{Sub^{low}}$	Active/reactive power import/export from substation to bus i at time t in lower level
$P_{i,t}^{Sub^{up}}/Q_{i,t}^{Sub^{up}}$	Active/reactive power import/export from substation to bus i at time t in upper level
$P_{i,t}^{MG}/Q_{i,t}^{MG}$	Active /reactive power transfer between MGs and distribution system in upper level
$P_{b,t}^{sch}$	Active power scheduled in buses
$P_{c,t}^{G}$	Total Active power generation in clusters
λ_t	Electric energy price (\$/MWh)
$P_{mn,t}^{MG}/Q_{mn,t}^{MG}$	Active /reactive power transfer between MGs
$P_{m,t}^{G}$	Total active power generation in MGs
$P_{mt}^{WT/PV/MT}$	Active power output of WT/PV/MT
$Q_{m,t}^{WT/MT}$	Reactive power output of WT/MT
$\Im$	Best compromise solution
$\varphi_{lead/lag}$	Lag or lead angle of reactive power
$P_{m,t}^{DisCh}$	Active power discharge of ESS in MGs
$P_{m,t}^{Ch}$	Active power charge of ESS in MGs
$P_{C,t}^{Ch}$	Total active power discharge of ESS in clusters
$P_{C,t}^{DisCh}$	Total active power charge of ESS in clusters
N_{CO_2}	CO_2 Emission penalty price (\$/MWh)
N_{SO_2}	SO_2 Emission penalty price (\$/MWh)
N_{NO_x}	NO_x Emission penalty price (\$/MWh)
$\kappa_{mn,t}^{MG}/\kappa_{mn,t}^{C}/\kappa_{mn,t}^{N}$	Binary variable indicating the connection status of MGs/ clusters /buses in lower level
$R_{mn,t}^{L}$	Resistance of line (pu)
$P_{m,t}^{L}$	Power consumption of MG nodes
$P_{m,t}^{DR}$	Power consumption of MG nodes after DRP
$\gamma_{m,t}^{DR}$	Demand response index
α_t^{WT}	Forecasted available wind power
ρ_t^{PV}	Forecasted available solar power
$\eta_{m,t}^{ch/dch}$	Charging/discharging efficiencies of ESSs
$\chi_{m,t}^{ch}/\chi_{m,t}^{dch}$	Charging/discharging statement of ESSs(one notes allowed and zero notes not allowed)
$I_{mn,t}^{L}$	Current flow of lines (pu)
$I_{R_{ijt}}$	Real current flow of branches
$I_{M_{ijt}}$	Imaginary current flow of branches
$\theta_{ij,t}$	Phase angle between buses i and j at time t
$V_{i,t}$	Voltage magnitude of bus m at time t

Parameter

$\varepsilon_1, \varepsilon_2$	Limiting parameters in ε-constraint method in lower level
$\zeta_1, \zeta_2, \zeta_3$	Penalty factors of multi objective functions in the upper level
$I_{MAX_{ij}}$	Maximum current flow
$SOC_m^{max/min}$	Maximum/minimum limits of SOC of ESS installed at bus m
$P_{m,t}^{L}/Q_{m,t}^{L}$	Active /reactive power consumption of MG nodes
$P_{c,t}^{L}$	Total active power consumption of clusters
$P_{b,t}^{D}$	Power consumption in buses
$\gamma_m^{Max}/\gamma_m^{Min}$	Maximum flexibility of responsive loads
$P_{i,t}^{D}/Q_{i,t}^{D}$	Active/reactive consumption of load
$P_{m,t}^{MT_{max}}$	Maximum active power of MT
$P_{m,t}^{WT_{max}}$	Maximum active power of WT
$P_{m,t}^{PV_{max}}$	Maximum active power of PV
$P_{m,t}^{Ch}/P_{m,t}^{DisCh}$	Charge/discharge power of ESS installed in bus m at time t (pu)
G_{ij}/B_{ij}	Conductance/ susceptance of line between buses i and j (pu)
$\kappa_{mn,t}^{MG}/\kappa_{mn,t}^{C}/\kappa_{mn,t}^{N}$	Binary variables for connectivity status of MGs/ clusters /buses in lower level
$V_i^{max/min}$	Maximum/minimum voltage magnitude
$SOC_{m,t}^{ESS}$	State of charge of ESS installed in bus m (pu)
Δt	Time slot duration (hour)

operate them as a single entity or cluster [2]. In the application of MGs, the restriction of RESs that affects network efficiency is one of the important topics to be considered [3]. MGs have several restrictions, namely: uncertainty of RESs, feeder capacity constraints, increasing feeder losses, and optimal power flow transaction. In this study, for overcoming these constraints, a CMG has been proposed in islanding and grid-connected forms.

The operation of a distribution network with MGs has been studied in present investigations. The corresponding control systems in the distribution networks containing MGs can be considered as a tri-level classified system where: a) the primary is the droop control associated with inverters of power electronic devices; b) the secondary is the voltage/ frequency synchronization and restoration control; c) the tertiary is the active/reactive power control [4]. The third level is pertinent to energy management systems (EMSs), and this is what is going to be discussed in this paper.

Reference [5] proposed a method for energy hub modelling in a MG for steady-state operation analysis. The developed method had the capability to overcome several identified limitations for the conventional model of the energy hub. A leader–follower approach for energy management has been applied in [6]. In [7], a stochastic approach was conducted to control the active power exchange between grid-connected MGs and the upstream grid. In [8], an intelligent method was presented for managing the thermal and energy comfort level in grid-connected MGs with an assorted occupancy schedule. Those studies were focused on a single period dispatching without energy storage systems (ESS).

In [9], the impact of CMGs on network stability during shutdowns has been investigated. Then, a method of crisis management by DERs in blackout times was considered. The stability improvement during blackout and islanding of the cluster was also investigated by increasing the inertia constant of the MG generators. Another study [10] presented power fluctuations of MG clusters as the research objective, where the

Table 1
Summary of compared to the other related works.

Reference	RES	CMG	DR	Optimal switching	HOEM	Techno-economic assessment	Multi-level optimization
Perevious works	✓	✓	✓	–	–	–	–
This study	✓	✓	✓	✓	✓	✓	✓

dynamic dispatch model of power fluctuation entropy of the MG cluster was established, and then solved by a quantum particle swarm optimization (QPSO) approach to realize the optimization control. Reference [11] introduced two levels of optimization for energy management coordination between the distribution network and the CMGs, including RES. The first level includes the management and coordination of power exchange between the network and the MGs, while the second involves the inter-coordination of power exchange among CMGs. A multi-objective function with several constraints was optimized by a heuristic algorithm. The transaction of power between clusters and MGs was done via the distribution network.

In [12], the types (i.e., technologies) and applications of energy storage systems were investigated. In addition, the available ESS technologies were compared in terms of rated power, capacity, discharge, and response time, as well as lifetime. The study also analyzed the possibility of using different ESS technologies together in microgrids. This enables researchers to have a hybrid ESS with a lower cost in order to achieve different performance characteristics. In [13], the system performance by optimizing the design of MGs with various types of energy resources in the distribution network was improved. Clustering has been implemented to maximize the self-sufficiency on MGs' design and to maximize the possibility of islanding the MGs. Reference [14] develops an approach for capacity optimization of microgrids in distribution networks with various DERs. The proposed methodology contains the essential conditions for MGs to reach a proper operation in the grid-connected mode and an effective performance in standalone mode.

In [15], a hierarchical bi-level structure was conducted for energy management by considering PCC congestion in a system with multi microgrids. In [16], an EMS was developed based on the multi-agent system concept for a hybrid MG with solar PV and small hydro. The available DERs in the microgrid were controlled by analyzing the local information in the EMS to reach a stable and efficient system operation. In [17], an intelligent agent for energy management between MGs was proposed, allowing the loads to contribute to a demand response program (DRP) with various patterns of load consumptions. In [18], a method to select the optimal size and location of ESSs in the grid by the distribution grid operator was proposed. This approach is based on the reconfiguration of the distribution network and utilizes the optimal load distribution method.

RESs play a main role in the electricity supply of MGs. The stochastic nature of the generated power of RESs, however, is a challenging subject that should be considered in systems, benefiting from these kinds of energy suppliers. In [19], the authors proposed a robust optimization methodology to consider the stochastic behavior of RESs in the unit-commitment problem. The problem was solved using a column-and-constraint generation approach in a two-stage manner. In [20], the stochastic behavior of electricity profiles and generated power of RESs was modelled using a min–max-min robust technique.

In [21], the self-organization and decentralized energy management of a cluster microgrid islanded from main grid, after a disturbing event, is studied. In the self-organization stage, depending on the available generation resources, each microgrid decides on whether to connect to the cluster; and the microgrid energy management systems then negotiate on the optimal power transactions with each other in the cluster. In [22], the propositions mathematical models are developed for microgrid clusters using a transactive energy construction to manage energy transaction in the smart grid. In order to make an informed decision for the operation of microgrid clusters, chance-constrained programming is employed to consider the uncertainties in balancing collective and individual interests under the transactive energy management. In [23], components classifying is considered to define a cloud-based architecture and ensure the suitability administered learning functionality under a microgrids cluster environment. In [24], an energy management system is proposed in which hierarchical control structure of islanded multi-microgrid clusters is specifically modeled. The proposed energy management system aims to minimize the total operation cost of islanded multi-microgrid cluster while primary and secondary reserves are programmed for frequency security in a predefined range.

The proposed model is compared to the other related works as Table 1. This table shows the efficiency of the proposed model.

The literature review indicated that the CMG concept has been studied from various aspects by the previous works. However, to the best of the author's knowledge, multiple important viewpoints have not been properly investigated in the existing studies, as follows:

- The interaction among MGs has been studied by several studies in the literature review. However, the literature lacks in considering the open/close status of the switches between SMGs. In fact, nothing in the literature has mentioned the reconfiguration of clusters and MGs.
- The contribution of ESSs to provide energy services has not been properly conducted.
- The participation of clients in MG's energy management system is a necessary challenge, which has not been observed in the existing studies.
- The DC power flow and unit commitment approaches have been considerably used by the previous studies. However, security constraints like the buses' voltage level in the distribution network were not considered.
- Multi-level optimization with technical constraints and planning power transaction in islanding and grid-connected modes have not been conducted in previous works.

To overcome the aforementioned challenges of the literature review, this paper proposes an innovative multi-level optimization model for hourly optimal energy management (HOEM) and hourly planning of switches (HPOS) of distribution systems connected to CMGs by considering the stochastic behavior of wind and solar generation using hourly prediction of wind turbine (WT), photovoltaic (PV), and electricity profile. The lower level contains an optimization strategy for the coordinated EMS between MGs and CMGs, and the upper level contains the power transaction between CMGs and distribution system loads, and finally between the distribution system and upstream networks. In this context, a comprehensive approach is conducted by considering the interactions among clusters, between each cluster and MGs, and the power transaction between the distribution network and the clusters, with the target of minimizing a multi-objective problem. Each MG contains PVs, WTs, micro turbines (MT, ESSs and controllable loads that contribute to DRP.

The proposed optimization model is solved as a multi-level problem. In the lower level, the problem is solved through organizing the energy management between MGs and CMGs. The obtained result from the lower level is utilized in the upper level, which corresponds to the power transaction between CMGs and distribution system loads, and between the distribution system and the upstream network.

The main contributions of this study can be highlighted as follows:

- An EMS technique is conducted for CMGs by considering multi-level HOEM with techno-economic constrains.

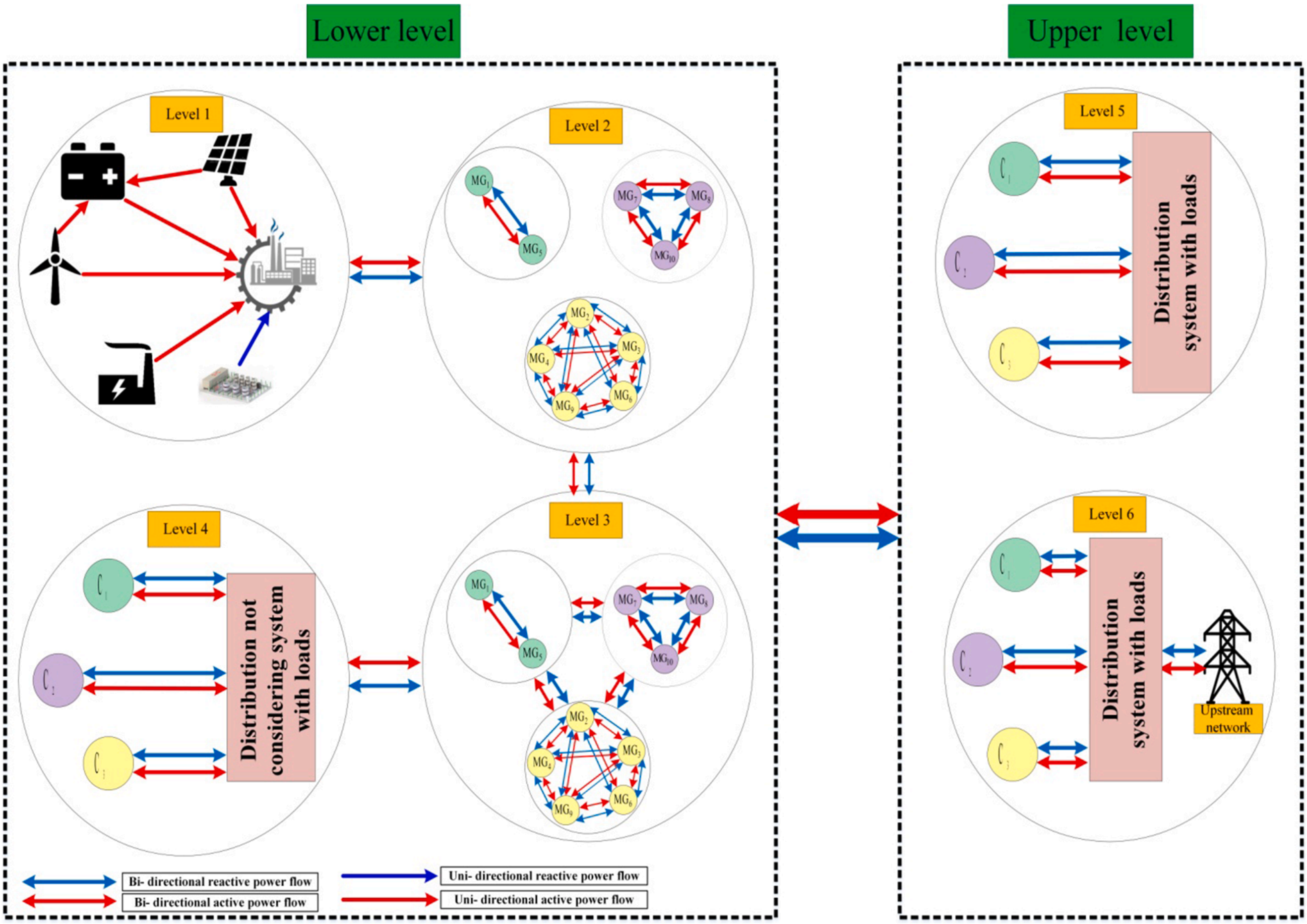

Fig. 1. The framework of the proposed multi-level model.

- A multi-level optimization framework for the coordinated energy management between MGs and CMGs in the lower level, between clusters and distribution systems and finally between distribution systems and upstream networks in the upper level, is applied.
- The status of interconnection lines between CMGs as well as the distribution network and MG is selected as a decision variable, which can make the decision to open or close the switches.
- The role of RESs with ESS, responsive loads in HPOS and HOEM is highlighted in multi levels.

Section II discusses the proposed model. Section III details the formulation of the conducted method. Section IV describes numerical results, and Section V draws the conclusions.

2. The proposed model

In this research, an HOEM is applied that contains optimization steps by applying algorithms in three CMGs and ten MGs, including PV, WTs, MTs and ESSs in the distribution network. By considering the uncertainty phenomena of WTs and PV, the required reserve power for technical and economic improvements of the power distribution at different times and conditions is conducted. The transaction energy contains the lower level (including four sub-levels) and the upper level (including two sub-levels). The framework of the conducted model is presented in Fig. 1.

The power transaction in the lower level and the flowchart of solving each sub-level is presented as follows (Fig. 2):

Level 1: In this level, MGs can provide the power required for their loads, through their own RESs and MTs. In fact, in this level the MGs act in islanding mode and they are managed by their owners. Of course, their hourly management information is communicated to the distribution system agent.

Level 2: According to level 1 flowchart, if the required power for the MG is not delivered from its own internal resources, by changing the switches position between the MGs of each cluster, it will be supplied by other MGs in the same CMGs in the best way possible. In this level, this is a notable point that extra power in each MG can be traded or stored via ESSs in optimal conditions. Also, each cluster can act in islanding mode, being managed by the network agent.

Level 3: In this level, if each cluster could not provide its power by changing the switches position between the CMGs, it will be powered by other MGs in other CMGs, in the best way possible.

Level 4: According to level 3 flowchart, if the required power for all clusters is not delivered from the network of clusters, by changing the switches position between clusters and the distribution network, it will be supplied by the network. In this level, the network is assumed as a no-load; therefore, network loads do not participate in this level, but due to the existence of the distribution system, active losses are considered in the HOEM. By energy transaction to distribution system, MGs go out from islanding mode.

The information and results obtained from the lower-level optimization are considered as the upper-level inputs. HOEM is simplest on the upper level because the impact of MGs on the HOEM is seen at the lower level. But, by applying DRP, loads participation has been considered in the upper level. The power transaction in upper level and the flowchart of solving each sub-level is presented as follows (Fig. 2):

Level 5: In this level, by applying distribution system loads in the presence of CMGs, HOEM is executed. By changing the switches position

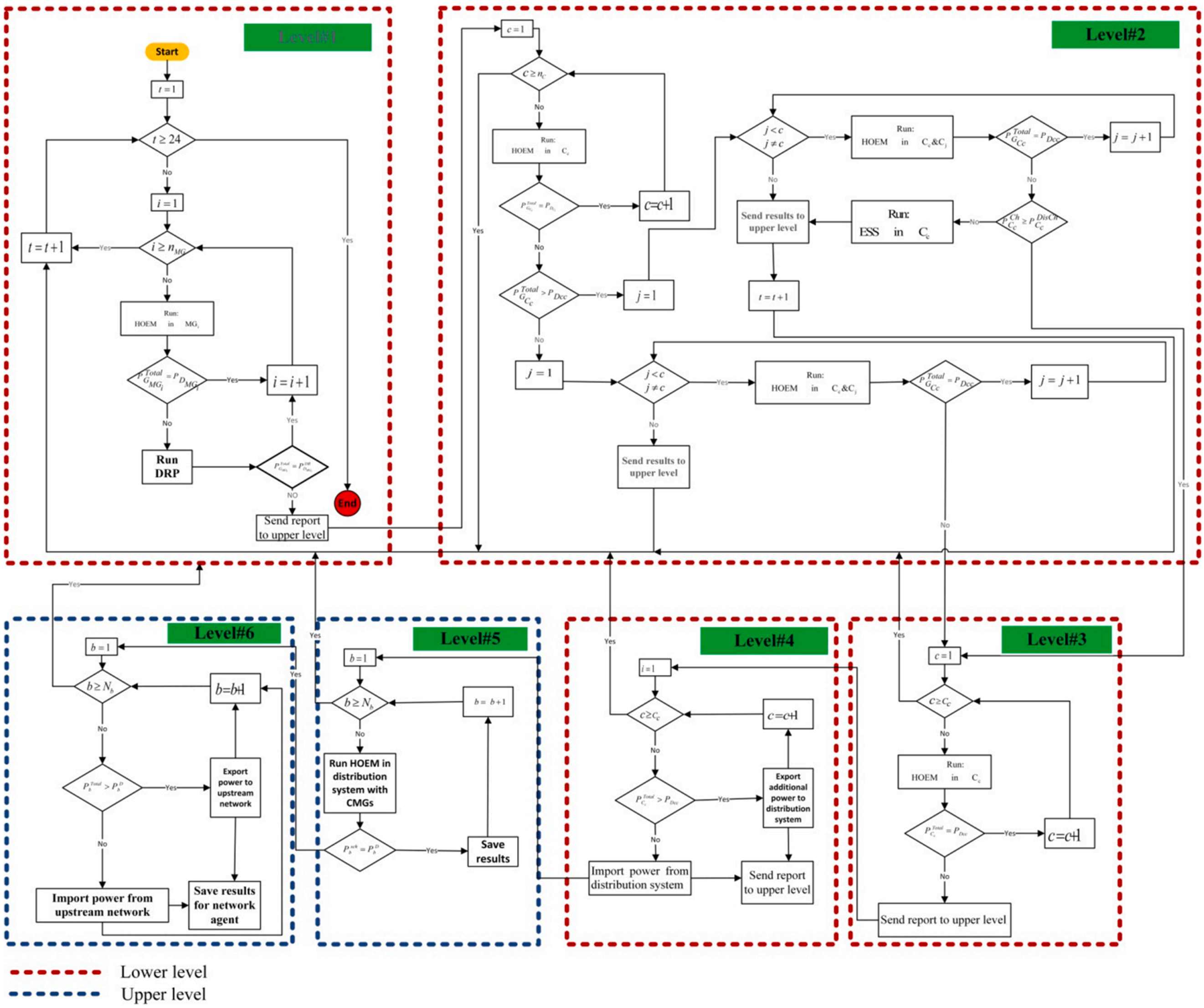

Fig. 2. The flowchart of the proposed multi-level model.

between clusters and the distribution system, the power transfer between CMGs and the distribution system is carried out. The difference is that at this level the optimization is from a distribution system perspective.

Level 6: In this level, the power transactions between distribution network with CMGs and upstream networks are provided via slack bus. In fact, after DRP, the extra power is traded to the upstream network and the lack of power is compensated by purchasing from the upstream network. Therefore, load shedding does not happen under any circumstances.

MGs programming studies focus on uncertainty modelling, which addresses the presence of potential variables such as the power output of WTs or the PVs [25]. Therefore, in order to have an anticipated relationship with the programming study, the uncertainty of the input variables and parameters must be modelled and the impact of this uncertainty on output variables such as costs should be realized. Several techniques have been proposed to model the uncertainties [26], including the Monte Carlo method, point estimation method, scenario method and other combinatorial methods. The Monte Carlo method is the most accurate of these methods, which despite its accuracy in modelling, may not be selected due to its high computational cost [27].

Therefore, due to the different levels of optimization in this paper and the complexity of the problem, the method of predicting hourly uncertainty parameters has been used. The electricity profile of this system, as well as the hourly forecasted PV and WT output power are extracted from [28–31].

3. Mathematical formulation

The general formulation of the system is presented in this section.

3.1. Mathematical formulation for the lower level

The objective functions for lower level in this problem are defined in the form of three equations, including the cost function of the generation as generation cost (GC) units in each MG, the cost of the pollutant emissions as emission cost (EC), and the cost of active power losses.

3.1.1. Generation cost

The first objective function indicates the various components of cost calculation in the microgrid, including cost of power transaction to network, generation cost of the technologies, and cost of ESS and DRP, as follows:

$$f_1^{low} = GC_{low} = \sum_{t\in\Omega_t}\sum_{i\in\Omega_b} P_{i,t}^{Sub^{low}} \times \lambda_t + \sum_{t\in\Omega_t}\sum_{m\in\Omega_{MG}} (P_{m,t}^{WT} + P_{m,t}^{PV} + P_{m,t}^{MT} + P_{m,t}^{DisCh}) \times \lambda_t - \sum_{t\in\Omega_t}\sum_{m\in\Omega_{MG}} P_{m,t}^{Ch} \times \lambda_t + \sum_{t\in\Omega_t}\sum_{m\in\Omega_{MG}} P_{m,t}^{DR} \times \lambda_t \tag{1}$$

3.1.2. Emission cost

The second objective function indicates the total emission cost of MGs and network, as follows:

$$f_2^{low} = EC_{low} = \sum_{t\in\Omega_t}\sum_{i\in\Omega_b} P_{i,t}^{Sub^{low}} \times (N_{CO_2} + N_{SO_2} + N_{NO_x}) + \sum_{t\in\Omega_t}\sum_{m\in\Omega_{MG}} P_{m,t}^{MT} \times (N_{CO_2} + N_{SO_2} + N_{NO_x}) \tag{2}$$

3.1.3. Active power losses

The third objective function indicates the active power losses, including losses of power transaction between CMGs and the network, losses of power transaction between clusters, and losses of power transaction between MGs. Losses of power transaction between MGs can be ignored because of the close distance of the MGs. For the minimization of the power losses in the lower level, the objective function is considered as follows:

$$f_3^{low} = P_{Loss_{low}}^{Total} = \sum_{t\in\Omega_t}\sum_{m,n\in\Omega_b}\left(\kappa_{mn,t}^{N} \times R_{ij}^{L} \times \left|I_{mn,t}^{L}\right|^2\right) + \sum_{t\in\Omega_t}\sum_{m,n\in\Omega_c}\left(\kappa_{mn,t}^{C} \times R_{kp}^{L} \times \left|I_{mn,t}^{L}\right|^2\right) \tag{3}$$

3.1.4. Power flow constraints in lower level

The proposed model in the lower level considers simultaneously the constraints of the CMGs and distribution network for level 2–4. Also, the important constraints of the grid (i.e., the operational and physical constraints), which should be considered into an AC power flow, are formulated as follows:

$$P_{i,t}^{Sub} + \sum_{m,n\in\Omega_{MG}} P_{mn,t}^{MG} - P_{i,t}^{L} = V_{i,t}\sum_{m,n\in\Omega_{MG}}\sum_{j\in\Omega_b}\kappa_{mn,t}^{N}\times V_{i,t}\times(G_{ij}cos\theta_{ij,t} + B_{ij}sin\theta_{ij,t}) \tag{4}$$

$$Q_{i,t}^{Sub^{low}} + \sum_{m,n\in\Omega_{MG}} Q_{mn,t}^{MG} - Q_{i,t}^{L} = V_{i,t}\sum_{j\in\Omega_b}\kappa_{ij}^{L}\times V_{j,t}\times(G_{ij}sin\theta_{ij,t} - B_{ij}cos\theta_{ij,t}) \tag{5}$$

$$V_i^{min} \leqslant V_{i,t} \leqslant V_i^{max} \tag{6}$$

The active and reactive power exchanges among MGs of each cluster and of other clusters should be equal to the total power generated by their resources (i.e., PV-WT-MT-ESS), as follows:

$$P_{m,t}^{MG} = P_{m,t}^{WT} + P_{m,t}^{PV} + P_{m,t}^{MT} + \left(P_{m,t}^{DisCh} - P_{m,t}^{Ch}\right) \tag{7}$$

$$Q_{m,t}^{MG} = Q_{m,t}^{WT} + Q_{m,t}^{MT} + Q_{m,t}^{SVC} \tag{8}$$

3.1.5. SOC constraints

Charging and discharging constraints on energy storage can be achieved by applying the charging and discharging coefficient at the charging and discharging power. The SOC constraints are illustrated as follows:

$$0 \leqslant P_{m,t}^{Ch} \leqslant \chi_{m,t}^{ch} \times P_{m,t}^{ch_{max}} \tag{9}$$

$$0 \leqslant P_{m,t}^{DisCh} \leqslant \chi_{m,t}^{dch} \times P_{m,t}^{dch_{max}} \tag{10}$$

$$\chi_{m,t}^{Ch} + \chi_{m,t}^{DisCh} \leqslant 1 \;,\quad (\chi_{m,t}^{Ch}, \chi_{m,t}^{DisCh} \in \{0,1\}) \tag{11}$$

$$SOC_{m,t}^{ESS} = SOC_{m,t}^{ESS} + \Delta t.(P_{m,t}^{Ch}\eta_{m,t}^{ch} - P_{m,t}^{DisCh}/\eta_{m,t}^{dch}) \tag{12}$$

$$SOC_m^{min} \leqslant SOC_{m,t}^{ESS} \leqslant SOC_m^{max} \tag{13}$$

$$\sum_{t\in\Omega_t} P_{m,t}^{Ch} \geqslant \sum_{t\in\Omega_t} P_{m,t}^{DisCh} \tag{14}$$

3.1.6. DER constraints

The active power of MTs is limited by its capacity between zero and the maximum under normal operating conditions, and its reactive power is constrained between the minimum and maximum values, as follows:

$$0 \leqslant P_{m,t}^{MT} \leqslant P_{m,t}^{MT_{max}} \tag{15}$$

$$Q_{m,t}^{MT_{min}} \leqslant Q_{m,t}^{MT} \leqslant Q_{m,t}^{MT_{max}} \tag{16}$$

The amount of power generated by the WTs is subject to the prediction coefficient; therefore, the amount of produced active power is limited by this coefficient and is limited by the amount of the lag or lead angle of reactive power. The limitation of WTs is illustrated as follows:

$$0 \leqslant P_{m,t}^{WT} \leqslant P_{m,t}^{WT_{max}} \times \alpha_t^{WT} \tag{17}$$

$$-tg(\varphi_{lead}) \times P_{m,t}^{WT} \leqslant Q_{m,t}^{WT} \leqslant tg(\varphi_{lag}) \times P_{m,t}^{WT} \tag{18}$$

The active power produced by solar cells is limited by the prediction coefficient that is taken into consideration:

$$0 \leqslant P_{m,t}^{PV} \leqslant P_{m,t}^{PV_{max}} \times \rho_t^{PV} \tag{19}$$

3.1.7. Branches constraints

The state of switches is a decision variable that is considered in the optimization problem, as follows:

$$\kappa_{mn,t}^{C} = \{0,1\} \quad ,\forall m,n \in \Omega_C \tag{20}$$

$$\kappa_{mn,t}^{MG} \in \{0,1\} \quad ,\forall m,n \in \Omega_{MG} \tag{21}$$

$$\kappa_{mn,t}^{N} \in \{0,1\} \quad ,\forall m,n \in \Omega_b \tag{22}$$

3.1.8. DRP constraints

The DRP program constraints are defined as a limitation of the active power loads to a certain value. The DRP program is illustrated as follows:

$$P_{m,t}^{DR} = P_{m,t}^{L} \times \gamma_{m,t}^{DR} \tag{23}$$

$$\sum_{t\in\Omega_t} P^{DR}_{m,t} = \sum_{t\in\Omega_t} P^{L}_{m,t} \tag{24}$$

$$(1-\gamma^{Min}_m)\leqslant\gamma^{DR}_{m,t}\leqslant(1-\gamma^{Max}_m) \tag{25}$$

where (22) and (23) are the values of electricity demand when the DRP is applied by load shifting in the system; $\gamma^{DR}_{m,t}$ represents the load shifting pattern. Equations (24) and (25) represent that the decrease/increase of load patterns is equal to the sum of base load when the DRP is applied. In addition, equation (26) provides the minimum/maximum flexibility of electricity demand.

3.1.9. Multi- objective algorithm

In this section, the optimization of the objective functions is addressed through the ε-constraint method in order to detect the best compromise solution through the pareto front and fuzzy satisfying methods. To solve the multi-objective problem, the problem is converted to single-objective [26] one. An objective function is minimized or maximized, and the other objective functions are formulated as inequality constraints by using proper parameters, known as control factors. In the HOEM problem, f_2^{low} is optimized while f_1^{low} and f_3^{low} are considered as the constraints, as follows:

$$OF_{low} = min\left(f_2^{low}\right) \tag{26}$$

s.t

$$f_1^{low}\leqslant\varepsilon_2 \tag{27}$$

$$f_3^{low}\leqslant\varepsilon_1 \tag{28}$$

3.2. Mathematical formulation for the upper level

The upper-level optimization is mathematically modelled in this subsection.

3.2.1. Generation cost

The first objective function in the upper level indicates the various components of the microgrid costs, including cost of power transaction to the upstream network, and generation cost of power transaction between MGs and network, as follows:

$$f_1^{up} = GC_{up} = \sum_{t\in\Omega_t}\sum_{i\in\Omega_b} P^{Sub^{up}}_{i,t}\times\lambda_t + \sum_{t\in\Omega_t}\sum_{i\in\Omega_{MG}} P^{MG}_{i,t}\times\lambda_t \tag{29}$$

3.2.2. Emission cost

The second objective in the upper level is the emission costs of MGs and network, as follows:

$$f_2^{up} = EC_{up} = \sum_{t\in\Omega_t}\sum_{i\in\Omega_{Sub}} P^{Sub^{up}}_{i,t}\times\ (N_{CO_2}+N_{SO_2}+N_{NO_x}) \tag{30}$$

3.2.3. Active power losses

The third objective in the upper level indicates the losses of active power, including distribution system losses, as follows:

$$f_3^{up} = P^{Total}_{Loss_{up}} = \sum_{t\in\Omega_t}\sum_{i,j\in\Omega_b}\left(R^L_{ij}\times\left|I^L_{ij}\right|^2\right) \tag{31}$$

3.2.4. Power flow constraints in the upper level

The proposed model in the upper level considers the optimal power flow. Using the AC load flow leads to a nonlinearity. However, the DC load flow causes the technical constraints of voltage and reactive power to be omitted, and in some cases, it leads to voltage instability problems. Hence, the power flow constraints in the upper level are determined as follows:

$$P^{Sub^{upper}}_{i,t} + \sum_{i\in\Omega_{MG}} P^{MG}_{i,t} - P^D_{i,t} = V_{i,t}\sum_{j\in\Omega_b} V_{j,t}\times(G_{ij}cos\theta_{ij,t}+B_{ij}sin\theta_{ij,t}) \tag{32}$$

$$Q^{Sub^{up}}_{i,t} + \sum_{i\in\Omega_{MG}} Q^{MG}_{i,t} - Q^D_{i,t} = V_{i,t}\sum_{j\in\Omega_b} V_{j,t}\times(G_{ij}sin\theta_{ij,t}-B_{ij}cos\theta_{ij,t}) \tag{33}$$

$$V_i^{min}\leqslant V_{i,t}\leqslant V_i^{max} \tag{34}$$

$$\left(I^2_{R_{ijt}}+I^2_{M_{ijt}}\right)\leqslant I^2_{MAX_{ij}} \tag{35}$$

$$I_{R_{ijt}} = G_{ij}\left(V_{i,t}cos\theta_{i,t}-V_{j,t}cos\theta_{j,t}\right) - B_{ij}\left(V_{j,t}sin\theta_{i,t}-V_{j,t}sin\theta_{j,t}\right) \tag{36}$$

$$I_{M_{ijt}} = G_{ij}\left(V_{i,t}sin\theta_{i,t}-V_{j,t}sin\theta_{j,t}\right) + B_{ij}\left(V_{j,t}cos\theta_{i,t}-V_{j,t}cos\theta_{j,t}\right) \tag{37}$$

3.2.5. Objective function

The objective function in the upper level is given as follows:

$$F^{up} = \zeta_1 f_1^{up}+\zeta_2 f_2^{up}+\zeta_3 f_3^{up}\, where \sum_{i=1}^{3}\zeta_i = 1 \tag{38}$$

$$OF_{up} = min(F^{up}) \tag{39}$$

where the penalty factors of f_1^{up}, f_2^{up} and f_3^{up} are denoted as ζ_1, ζ_2 and ζ_3 respectively.

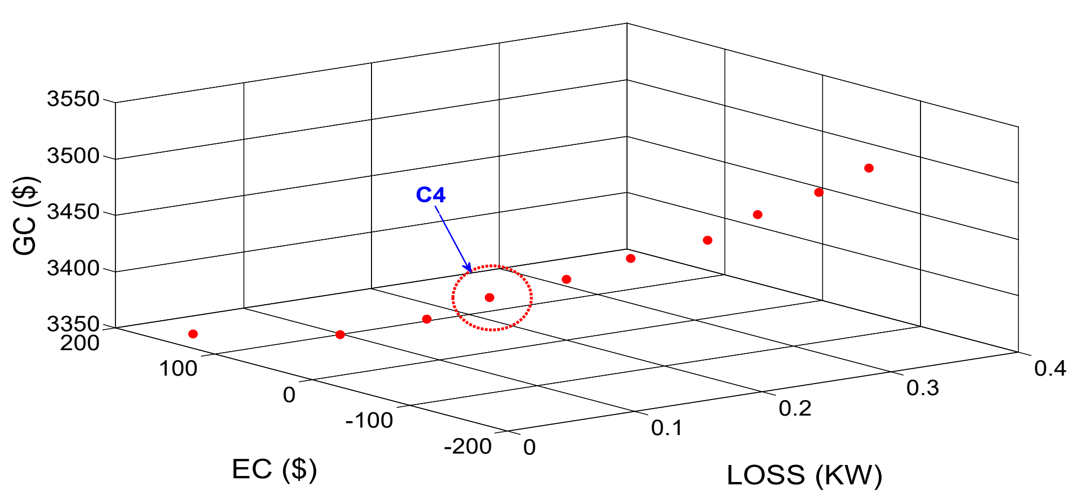

Fig. 3. Description of the Pareto front in the ε-constraint method.

Table 2
Pareto optimal solutions of the hoem.

Number of the solution	$f_1^{low} = GC^{low}$ (\$)	$f_1^{low} = EC^{low}$ (\$)	$f_1^{low} = P_{Loss_{low}}^{Total}$ (kW)	$\frac{GC^{low^{max}} - GC^{low}}{GC^{low^{max}} - GC^{low^{min}}}$	$\frac{EC^{low^{max}} - EC^{low}}{EC^{low^{max}} - EC^{low^{min}}}$	$\frac{P_{Loss_{low}}^{Total^{max}} - P_{Loss_{low}}^{Total}}{P_{Loss_{low}}^{Total^{max}} - P_{Loss_{low}}^{Total^{min}}}$	*Min*
1	3362.821	120.907	0	1	0	1	0
2	3380.424	15.178	0.034	0.888	0.370	0.890	0.370
3	3398.027	−27.489	0.069	0.777	0.520	0.777	0.520
4*	**3415.631**	**−47.337**	**0.103**	**0.666**	**0.589**	**0.667**	**0.589**
5	3433.234	−80.409	0.138	0.555	0.705	0.554	0.554
6	3450.837	−101.464	0.172	0.444	0.779	0.445	0.444
7	3468.44	−134.323	0.207	0.219	0.894	0.332	0.219
8	3486.044	−140.519	0.241	0.222	0.916	0.222	0.222
9	3503.647	−157.785	0.276	0.111	0.976	0.109	0.109
10	3521.25	−164.402	0.31	0	1	0	0

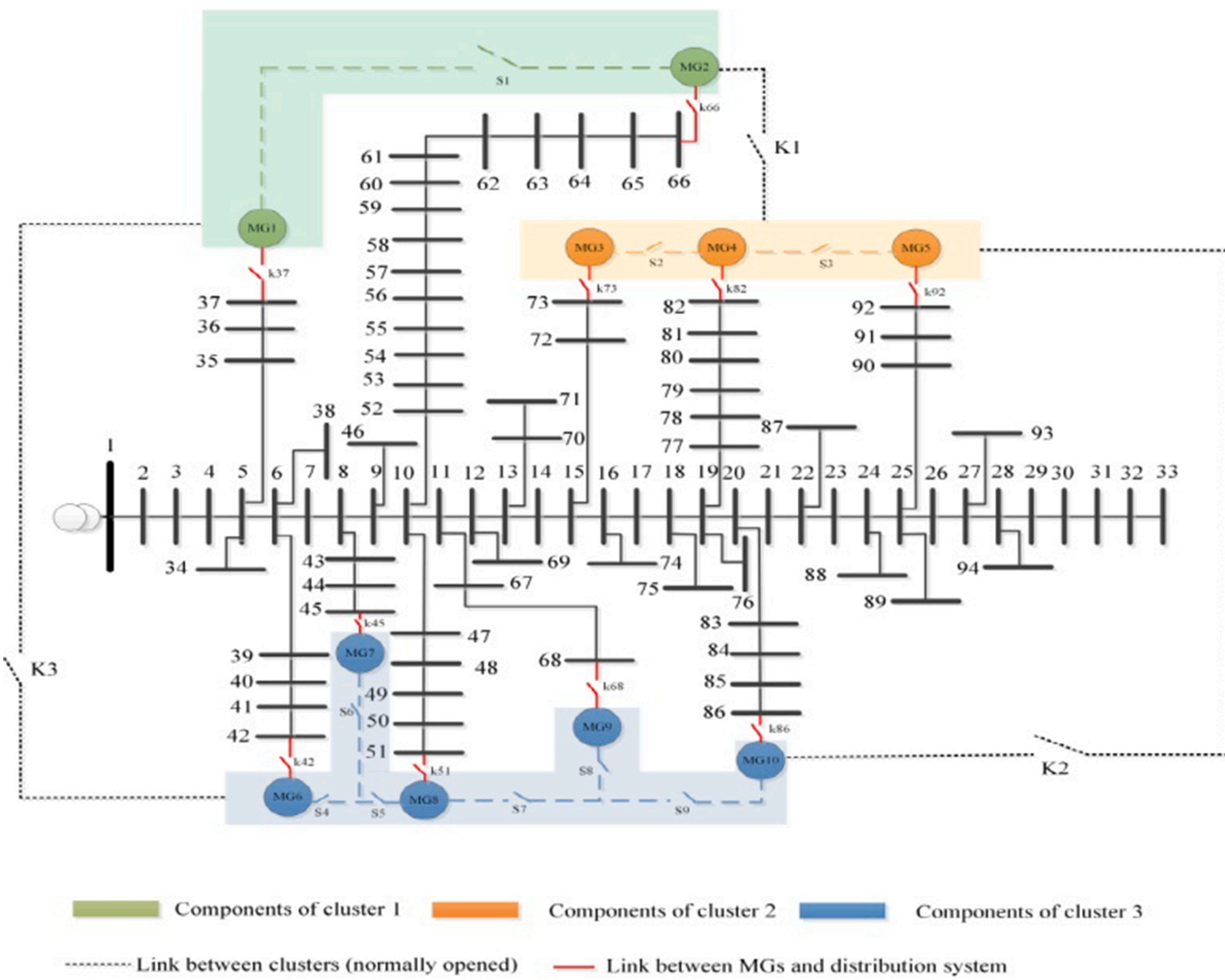

Fig. 4. Single line diagram of the 94-bus distribution test system.

The choice of these coefficients is quite optional. In fact, in the upper level the optimization is carried out from a network perspective, so the penalty factors of the objective function in this level are chosen by the network agent. The proposed model in the upper level, corresponding to a non-linear programming problem, is coded in GAMS [32] environment.

3.3. Fuzzy min–max decision maker

A Pareto-front is obtained when the HOEM problem in the lower level is solved. Then, the best solution should be selected from the obtained results in the Pareto front set. For this aim, in this study, a fuzzy decision-maker is utilized. In this approach, the obtained solutions in the Pareto front are assigned by fuzzy membership functions.

The degree of each membership function in the designated fuzzy sets is specified using values between 0 and 1 [33]. While a membership value of ‘1′ represents the compatibility with the fuzzy sets, a value of ‘0′ represents conflict. The best solution of the Pareto front sets is obtained using the degree of satisfaction assigned by the fuzzy membership functions.

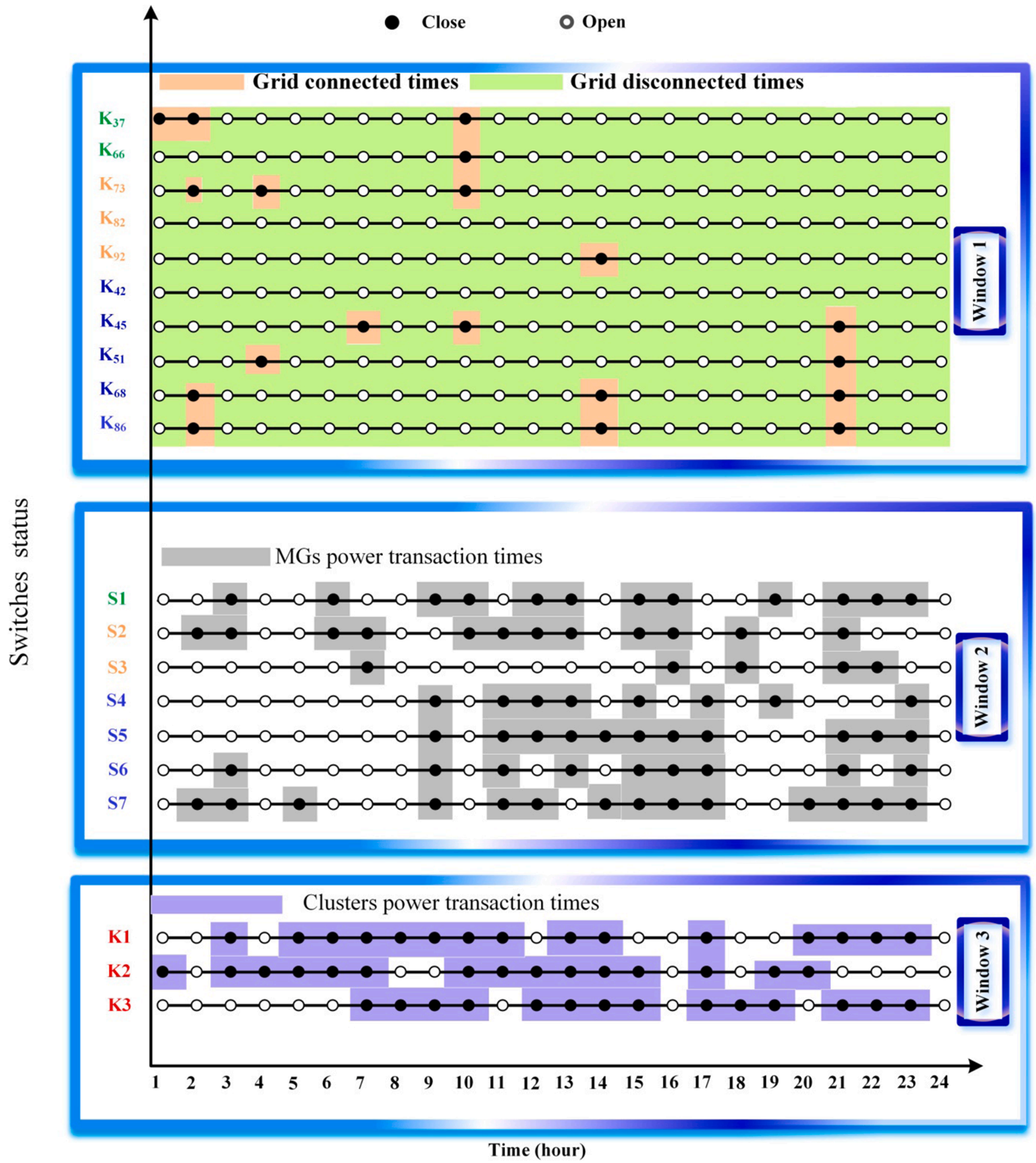

Fig. 5. The status of the switches in the lower level.

The best solution is selected using the min–max approach [30]. In this approach, for each solution in the Pareto front, the minimum value of f_1^{low},f_2^{low} and f_3^{low} needs to be determined. Then, the best compromise solution is selected as the solution with the maximum value of $min(f_1^{low}, f_2^{low}, f_3^{low})$. The membership functions are calculated as (41).

$$\tilde{\mu}_q\left(f_i^{low}\right) = \left\{ \begin{array}{cc} 1 & f_i^{low} \leqslant f_i^{low^{min}} \\ \dfrac{f_i^{low^{max}} - f_i^{low}}{f_i^{low^{max}} - f_i^{low^{min}}} & f_i^{low^{min}} \leqslant f_i^{low} \leqslant f_i^{low^{max}} \\ 0 & f_i^{low} \leqslant f_i^{low^{max}} \end{array} \right\}, \forall q \in \Upsilon, i \in \Psi \quad (40)$$

where q represents the qth solution of the ith objective function, Υ in this study has 10 members, $f_i^{low^{max}}$ indicates the membership of each objective function for the fuzzy decision, with the maximum value of f_i^{low} being calculated for the minimum value of $f_{i'}^{low}$ (i.e., $i' = \Psi - q$). This denotes that the maximum f_i^{low} is achieved when the $f_{i'}^{low}$ is minimized. On the other hand, the minimum membership value of the objective function f_i^{low} is assigned by $f_i^{low^{min}}$. The best solution is chosen using the proposition of fuzzy min–max:

$$\Im = \max_{q \in \Upsilon}\left\{ \min_{i \in \Psi}\left\{ \tilde{\mu}_q\left(f_i^{low}\right) \right\} \right\} \quad (41)$$

The proposed model in the lower level, a mixed integer non-linear programming problem, is coded in GAMS environment [33].

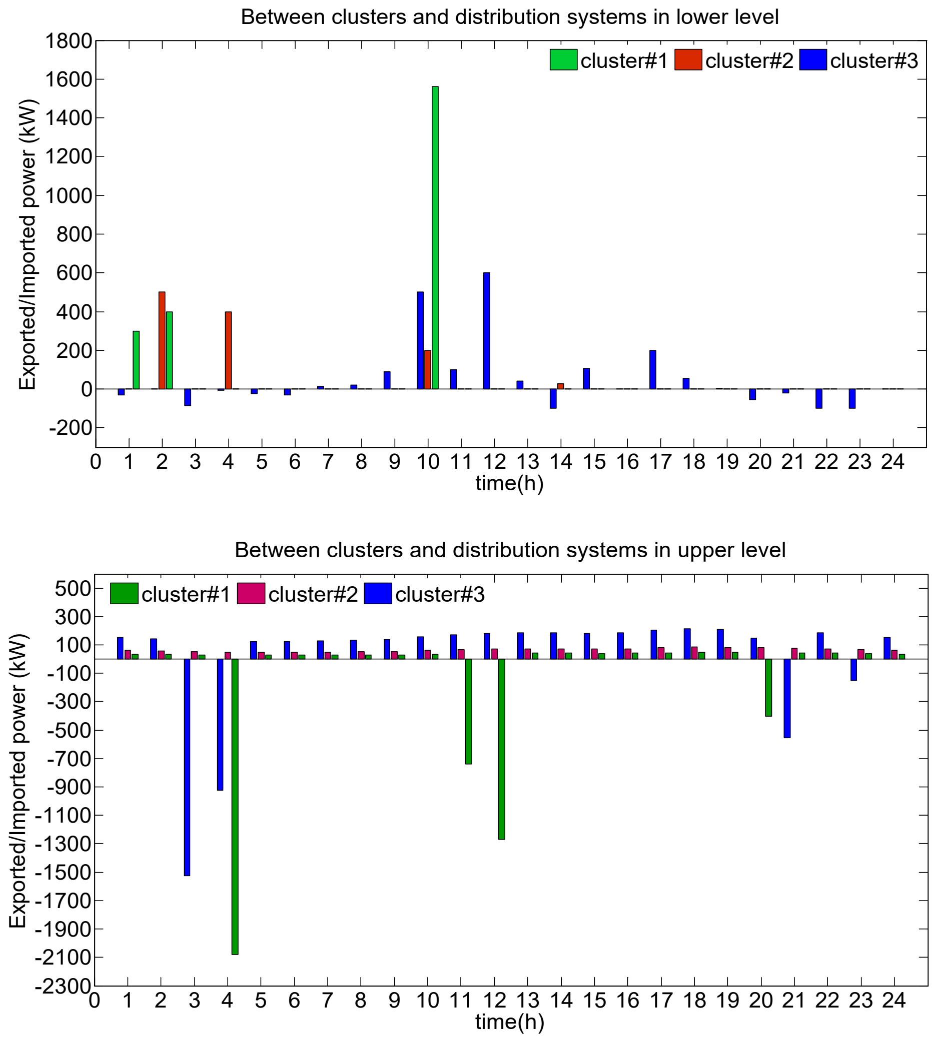

Fig. 6. Power transaction between the distribution network and the clusters in the multi-level optimization.

According to the hourly data of load, PV, and WT, by selecting 10 Pareto optimal solutions, the value of $\widetilde{\mu}_q\left(f_i^{low}\right)$ is obtained for each objective function and by applying equation (41) on $\widetilde{\mu}_q\left(f_i^{low}\right)$, the compromise solution is obtained. The optimal values of the objective functions are also shown in Table 1.

As can be seen, for example, the optimal amount of pollutant emission costs is -$47.337. This means that not only CMGs have not paid the emission cost of pollution penalties, but also CMGs has benefited by injecting power in some hours with at least the pollution emission rate to the distribution system and upstream network, according to level 4. The description of the Pareto front in the ε-constraint method is shown in Fig. 3 (see Table 2.).

4. Case study and numerical results

4.1. Case study and structure of the distribution network

The case study and simulation parameters are presented in this section. Further, the effects of CMGs and HOEM proposed method on the distribution system are also examined. In this paper, the IEEE 94-bus distribution network [30], as shown by the single line diagram in Fig. 4, is considered as the test system to implement the developed model. It is considered that there are 10 interconnected MGs in this distribution network, and three CMGs are created by the connected MGs. Hourly transaction prices among MGs are defined from system agent [34].

Fig. 4 illustrates the main structure of the distribution network with the connected MGs, the interconnection lines, and the location of each MG in the distribution network used in this paper. Please note that the developed comprehensive framework of this work can be easily adapted to any other large-scale network. The data of this system is extracted from [30].

The developed problem in the lower level is modelled as a mixed integer non-linear programming problem, while the upper level is simulated as a non-linear programming problem in GAMS environment using the SBB solver. The number of loads in each MG, as well as the rated power of the MTs and renewable resources (WTs and PVs), are taken from [11]. The developed model is solved for a 24 h' performance horizon. The obtained results for the developed model are discussed. Then, the impacts of the multi-level optimization on the distribution network operation are also examined.

4.2. Hourly switching state results

The hourly switching state is shown in Fig. 5. Furthermore, a sensitivity analysis on the switching decision in each level is discussed in three windows, as follows:

- Window 1: This frame shows the status of the connection between the MGs and the distribution system in the lower level, so in the hours when the switches are open, each MG is separated from the

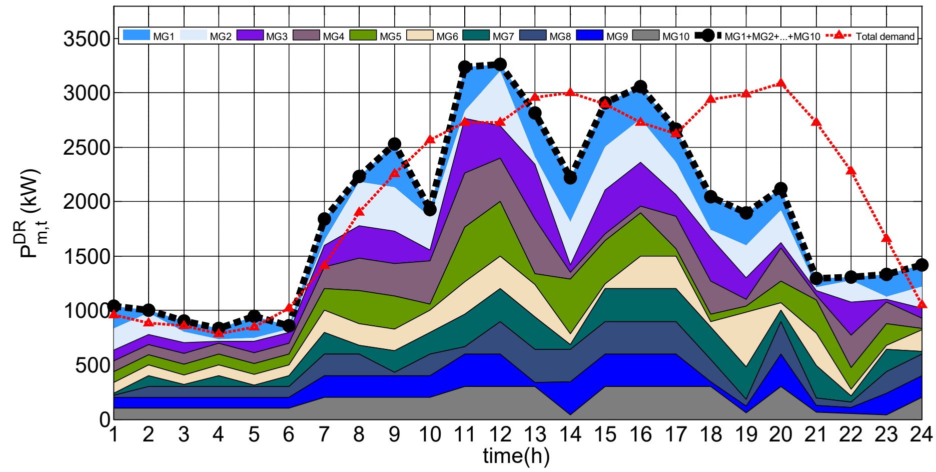

Fig. 7. DR index variation in different clusters.

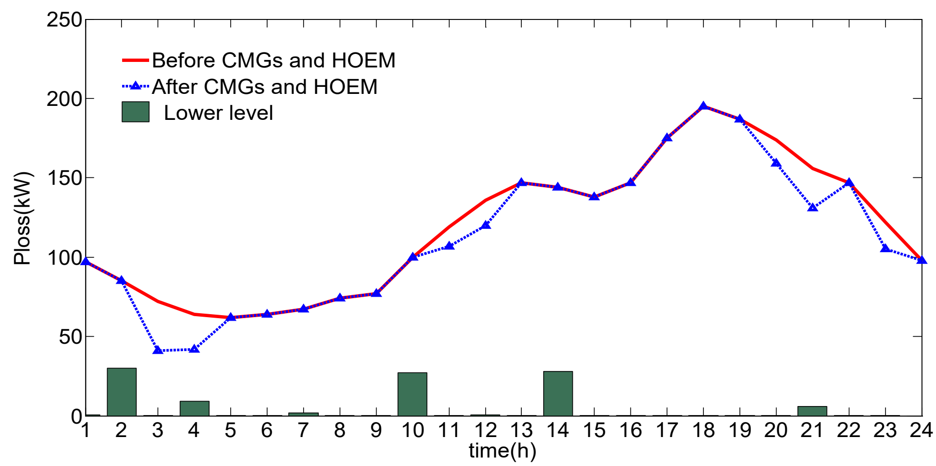

Fig. 8. Active power losses of the distribution network, with and without CMGs.

distribution system. As can be seen, not only the MGs in most times do not need to import power from the distribution system, but also in some hours, it is possible to export power to the distribution system, as shown in Fig. 6 for lower level.

- Window 2: This frame shows the hourly power transaction between the MGs, which are in the same cluster in the lower level. In fact, when the switches are close in this frame, the power transaction is only between MGs in their own clusters.
- Window 3: In this window, the power transaction planning between clusters is taken into consideration. Evident is the fact that, except in hours 2, 16 and 24, the rest of the times we have power exchanged between clusters. Therefore, it can be concluded that the HPOS strategy should increase the power transaction between the clusters to enhance the robustness in facing losses and emission pollution.

Interesting results can be obtained by considering the three windows

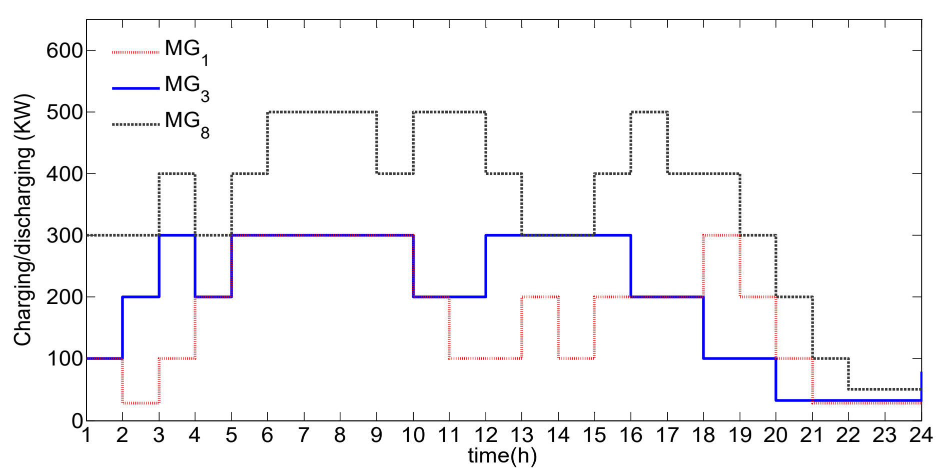

Fig. 9. The state of charge of ESSs for a MG in each cluster in the lower level.

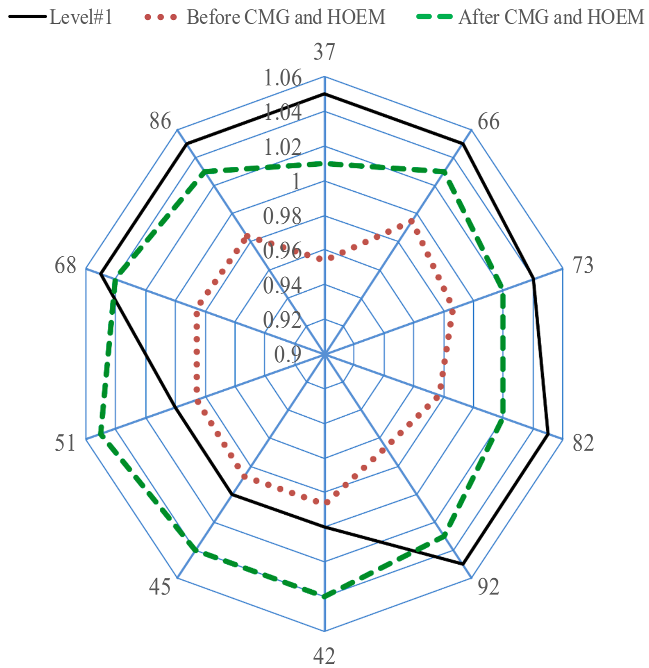

Fig. 10. Voltage magnitude of the CMGs buses for different cases in the peak loading hours.

at the same time. For example, in open switches states, islanding MGs is obtained by applying $\{window_1 \cap window_2 \cap window_3\}$ for each hour. To show this, for example in $t = 2$, MG_5, MG_6, MG_7 and MG_8 are operated in islanding mode.

4.3. Numerical results analysis

In addition, Fig. 6 demonstrates the exchange power pattern among the clusters, between clusters and the distribution network in the lower level and the upper level. It is observed that sometimes the robustness of HOEM and HPOS criteria enforce the system agent to make more power injection to the system clusters in order to strengthen the robustness of the whole system. It should be noted that in the upper level the power transaction between the distribution network and CMGs is negligible. This power increases system robustness against uncertainty, and these MGs only supply the local loads, and in some CMGs, they export power to the distribution system.

Different CMGs have various variations of the DR index for the lower level, which is illustrated in Fig. 7. It can be seen that the responsive loads have a different behavior in each MG. In this study, 20% of each MGs load is assumed to be controllable. Besides, it can be observed that the electricity consumers have increased the rate of consumption in off-peak hours according to the hourly energy price [31], while the electricity consumption is lower in on-peak hours. For example, in hours $t =$ 18 until $t = 23$, the total demand of approximately 1 MW has been reduced and the participation of customers is increased where the network agent can benefit from the DRP of CMGs in the system.

Fig. 8 illustrates the active power losses of the distribution system in these three scenarios. In the lower level, losses are insignificant during the hours of power transaction between clusters, but in total the losses during the 24 h represent 411 kW, which is because of the hours where CMGs are connected to the network. According to Fig. 8, the total active power losses of the distribution network by applying CMGs and HOEM in the upper level are 138 kW lower than without these technologies in the 24 h, which indicates the significance of CMGs in decreasing the active power losses.

Fig. 9 illustrates the ESS's charging/discharging pattern with the used driving pattern for a MG in each cluster in the lower level. It can be inferred from Fig. 9 that the uncertainty and DRP can affect the SOC of ESSs. Accordingly, a dramatic drop happened in the discharging rate of ESS for the peak hours, which indicates the role of ESSs in decreasing the negative effects of uncertainty and DRP.

Fig. 10 provides the voltage performance for the peak loading hours. It is vividly evident that by applying the CMGs and HOEM, the voltage level is closer to the maximum voltage limit. In addition, it can be observed that the simultaneous consideration of the HOEM and CMGs enhances the voltage profile of the system. Finally, the imported/exported active power from the upstream grid to the distribution network for both cases is illustrated in Fig. 11. It is indicated that, by applying CMGs and HOEM, the injected power from the upstream grid to the distribution network decreased, especially relevant at $t = 4$ where the distribution system exported 200 kW to the upstream network.

5. Conclusion

In this paper, an interactive model was proposed for addressing the energy management of CMGs in a distribution system. This study developed an innovative multi-level optimization model for the coordinated energy management between MGs and CMGs in the lower level, and between clusters and distribution systems, and finally between

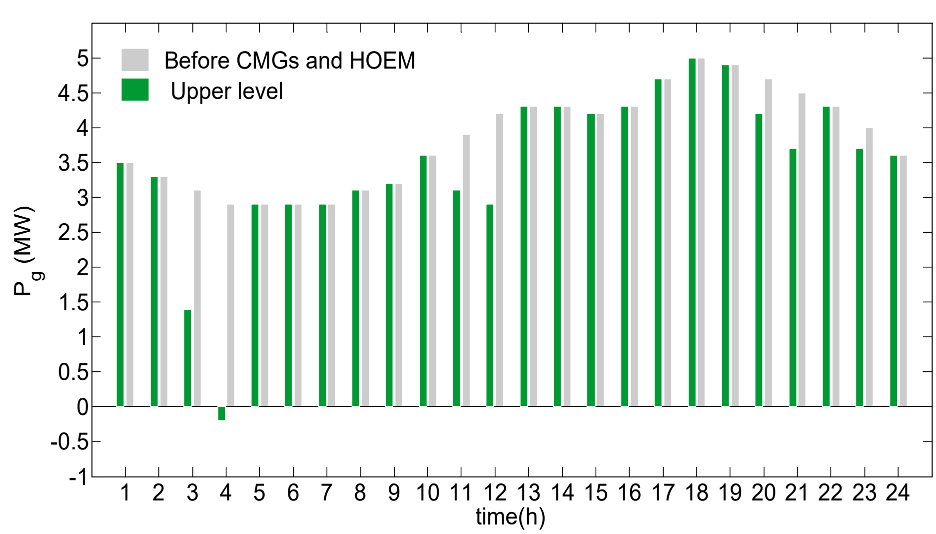

Fig. 11. Import/export power from the upstream grid to the distribution network in different cases.

distribution systems and upstream networks in the upper level. The HOEM strategy was proposed for CMGs in the distribution system. To enhance the techno-economic factors of the distribution network, each MG was equipped with various components like ESSs, WTs, MTs, PVs, and even responsive loads, while the MGs and clusters are interconnected via switches links. The proposed model aimed at minimizing the operation cost, losses, and emission cost in lower level, and by using information of the lower level in the upper level to support the distribution system loads and improve the performance of CMGs. Finally, the CMGs via distribution network can import/export power to the upstream network in the upper level. The simulation result demonstrated that the distribution system can benefit from the CMGs.

In summary, the important conclusions are as follows:

- The microgrid clustering issue as well as the interactions between the distribution network and clusters can be affected by the uncertainties of renewable energy resources.
- The robustness of HOEM and HPOS criteria enforced the system agent for a higher power injection to the clusters in order to strengthen the robustness of the whole system.
- In addition, the contribution of responsive loads to improve the characteristics of the system can be beneficial for the distribution system agent and can increase the robustness of the system against uncertainties.
- CMGs can enhance the techno-economic factors of the distribution network. In addition, load curtailment can be prevented by CMGs participation.
- Hourly scheduling switches can manage the power distribution to improve the techno-economic characteristics.
- Multi-level optimization model can coordinate the energy management between MGs and CMGs in the lower level and between clusters and distribution systems and finally between distribution systems and upstream networks in the upper level.

CRediT authorship contribution statement

Reza Saki: Conceptualization, Methodology. **Ehsan Kianmehr:** Validation, Investigation, Writing – review & editing. **Esmaeel Rokrok:** Investigation, Writing – review & editing. **Meysam Doostizadeh:** Methodology, Investigation. **Rahmat Khezri:** Methodology, Investigation. **Miadreza Shafie-khah:** Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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