Interactive Model for Energy Management of Clustered Microgrids

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Abstract—**With the large scale integration of distributed renewable energy resources, the control strategy of hybrid WT-PV-battery microgrid clusters are playing an important role for the success of the development. This paper proposes a two-level optimization model for the coordinated energy management between distribution systems and clustered WT-PV-battery microgrids (MGs). The upper level of the model is for the operation of the distribution network. The lower level is for the coordinated operation of multiple MGs. An interactive game matrix (IGM) is applied to coordinate the power exchange among multiple MGs and between the distribution network and MGs. The model is solved by a modified hierarchical genetic algorithm. Case studies on a distribution system with multiple MGs demonstrate the effectiveness of the proposed method in improving power quality, reliability, and environmental benefits.**

Index Terms—power distribution systems; renewable energy integration; microgrids; energy management optimization; responsive reserve

NOMENCLATURE

Sets

I	set of distribution network nodes
I^{g}	set of distribution network nodes with micro turbines (MTs) and static VAR compensations (SVGs)
I^{M}	set of distribution network nodes with MGs
T	set of every operation period
F_{N}	set of MGs needing power or power storage support
F	set of MGs
S_f	set of DGs and storage battery (SB) in MG$_f$, f=1, 2, 3, and 4 denote MT, SB, photovoltaic generator (PV) and wind turbine (WT), respectively
H_f	set of MGs supporting MG$_f$
S^{D}	set of MG$_i$ needing power support in S
S^{P}	set of MG$_j$ providing power support in S

Variables

$R_{f,t}^{EX}$	variable of interactive game matrix (IGM)
$C_{f,t}$	cost of $R_{f,t}^{EX}$
$V_{i,t}$	voltage
P_t^{LS}	power loss of distribution network
$P_{i,t}^{PED}/Q_{i,t}^{PED}$	active/reactive power exchange between MG and distribution network at upper level
$P_{f,t}^{PE}/Q_{f,t}^{PE}$	active/reactive power exchange between MG$_f$ and distribution network at lower level
$P_{i,t}^{g}/Q_{i,t}^{g}$	active/reactive power of MT and static VAR compensation (SVC)
$\theta_{i,j,t}$	phase angle difference between i and j
g_1/g_2	dispatchable capacity of MT/SB in other MGs
k_i	binary variable of g_i
k_n^1	binary variable of g_n^1
k_m^2	binary variable of g_m^2
$P_{s,f,t}^{G}/Q_{s,f,t}^{G}$	active/reactive power of DG$_s$ and SB in MG$_f$
$x_{h,t}/y_{h,t}$	binary variable of $P_{h,t}^{MTEX}/P_{h,t}^{SBEX}$ to determine whether it is carried out
$P_{h,t}^{MTEX}/P_{h,t}^{SBEX}$	remaining dispatchable capacity of MT/SB in MG$_h$ supporting MG$_f$
$a_{f,t}/b_{f,t}$	binary variables of $P_{f,t}^{MTEX}/P_{f,t}^{SBEX}$ to determine whether it is carried out
$E_{f,t}^{T}$	transition state of charge (SOC) of SB in MG$_f$
$E_{f,t}$	SOC of SB in MG$_f$
$\alpha_{h,t}/\beta_{h,t}$	maximum permissible remaining dispatchable capacity in $P_{h,t}^{MTEX}/P_{h,t}^{SBEX}$

Parameters

$P_{i,t}^{L}/Q_{i,t}^{L}$	active/reactive load of node$_i$
η	power exchange degree
$G_{i,j}/B_{i,j}$	conductance/susceptance of line i-j
P^{PEmax}/P^{PEmin}	maximum/minimum power exchange
P_i^{gmax}/P_i^{gmin}	maximum/minimum output of MT and SVC in upper level
Q^{PEman}/Q^{PEmin}	maximum/minimum reactive power exchange
Q_i^{gmax}/Q_i^{gmin}	maximum/minimum reactive output of MT and SVC in upper level
P_h^{MTmax}/P_h^{MTmin}	maximum/minimum output of MT in MG$_h$
Q_h^{MTmax}/Q_h^{MTmin}	maximum/minimum reactive output of MT in MG$_h$
P_h^{SBmax}/P_h^{SBmin}	maximum/minimum output of SB in MG$_h$
Q_h^{SBmax}/Q_h^{SBmin}	maximum/minimum reactive output of SB in MG$_h$
V_i^{man}/V_i^{min}	maximum/minimum voltage at node$_i$
q	sale/purchase price of grid
K_s^{FUEL}	fuel cost
K_s^{OM}	operation & maintenance cost
$P_{f,t}^{ML}/Q_{f,t}^{ML}$	active/reactive load in MG$_f$
R_t	original responsive reserve of distribution network
R_t^{MC}	responsive reserve of MG cluster
R_t^{OMC}	original spare capacity of MG cluster
E_f^{max}/E_f^{min}	maximum/minimum capacity of SB in MG$_f$
R^{up}/R^{down}	ramp up/down coefficient of MT
p_x	emission fine
$N_{x,s}$	DG emissions
α	limit parameter of $P_{h,t}^{MTEX}$
ε	coefficient of reserve support degree from MG cluster to distribution network

I. INTRODUCTION

The integration of distributed energy resources (DERs) is a promising solution to restructure the current distribution network and increase the reliability of energy supply [1-3]. Microgrids (MGs) are smart clusters of distributed generators

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(DGs), loads and energy storage system (ESS) [4-5]. MGs can facilitate the integration and operation of DERs [6-8]. Multiple microgrids can be connected to a modern distribution system to further improve the operation, reliability, economic benefits, and environmental friendliness [9-10]. However, the integration of clustered MGs also poses new challenges on the energy management of the system [11].

The operation and control of a distribution system with MGs has been studied in the existing literature. An energy management unit based on amulti-agent system was presented in [14] to improve economic benefits and system operations of a stand-alone microgrid. Reference [15] introduced a modified concept of multi-carrier energy hub and integrated it with the modeling of a microgrid. The above mentioned work considered the energy management of a single microgrid. The authors in[16] proposed leader-follower strategies for the energy management of multiple MGs. The study in[17] developed a stochastic model to regulate the power exchange between a utility grid and the connected MGs. An intelligent energy and thermal comfort management was established in [18] for grid-connected microgrids with a heterogeneous occupancy schedule. These studies focused on the single-period dispatch without ESS. Reference [19] established a method of demand side management to reduce the peak demand and maximize customers' benefits in a smart distribution system with multiple MGs. Reference [20] explained a statistical cooperative dispatch method to minimize the operation cost of a distribution system with multiple MGs. The authors in [21] proposed a stochastic game theory-based method for the coordinated energy management of networked MGs. All of the above mentioned studies used economic benefits as the objective in performing the optimal energy management. In addition to economic benefits, to achieve an versatilely improved system operation, such as a flattened voltage profile and an increased reliability, is of great importance for a modern distribution system with clustered MGs.

This paper proposes a two-level energy management model for the interactive operation of a distribution network with clustered MGs. An interactive game matrix (IGM) is developed to model the interactions among MGs. The IGM can take full advantage of remaining dispatchable capacity in ESS (i.e.,storage battery (SB) in this paper) and DGs. The objectives of the upper level energy managment are to minimize power exchange fluctuation, voltage deviation and power loss. The objectives of the lower level energy management are to minimize operation costs and the pollution emission. The lower level also offers responsive reserve support to the upper level. The two-level optimization problem is solved using a modified hierarchical genetic algorithm. Case studies are performed on an IEEE 14-bus test system with three MGs.

The main contributions are listed as follows:

1) A multi-period optimal dispatch model is proposed for a clustered MGs -based distribution network.
2) Responsive reserve of DGs and remaining dispatchable capacity of ESS and controllable DGs are introduced to the model to improve the system operation.
3) Interactive game matrix (IGM) is defined to mathematically model coordinated operations of clustered MGs and the distribution network using the game theory.

This paper is organized as follows. Section II presents the concept of clustered MGs-based distribution systems. The two-level energy management model is presented in Section III. Section IV introduces the behavior analysis and interactive game matrix that is used for modelling the interactions among MGs. The solution algorithm is introduced in Section V. In Section VI, case studies on a distribution system with three MGs are provided. Section VII concludes the paper with major findings.

II. DISTRIBUTION SYSTEMWITH CLUSTERED MICROGRIDS

A. *Distribution system with clustered MGs*

Fig. 1 shows a distribution system with clustered MGs. The proposed model in this paper is integrated into a local energy management system (EMS). The EMS makes the dispatch strategy through the proposed model according to the forecasting data. The objective of the proposed two-level model is to coordinate the energy management of the distribution grid and MGs to achieve the system-wide efficiency [22].

In this paper, MGs are connected to different nodes in a distribution system. For example, if MG1 needs to send power to MG3, MG 1 should firstly exchange the power with the distribution grid. Then MG3 receives the same amount of power with transmission loss from the distribution grid. The distribution grid acts as a channel for the power exchange among the connected MGs.

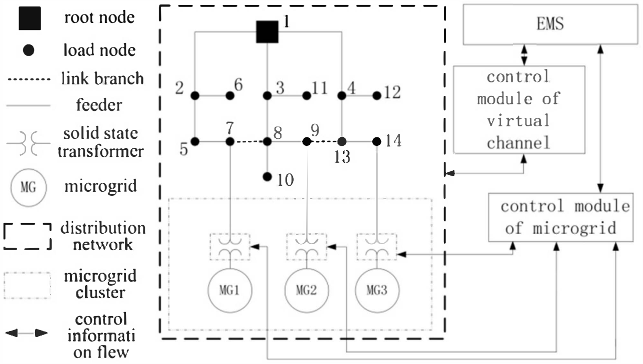


Fig. 1. The modified IEEE 14-bus distributionsystem with clustered MGs

B. *Power reserve mechanism*

In this paper, the available power reserve includes the responsive reserve and the remaining dispatchable capacity.

Some DGs such as Micro Turbines (MTs) and Wind Turbines (WTs) are spinning generators. Hence their reserve can be scheduled. In our model, these DGs in a MG cluster contribute to the system responsive reverse through the interaction between their hosting MGs and the distribution network to improve the system reliability.

The remaining dispatchable capacity comes from ESS and controllable DGs (e.g.,MTs in this paper). For instance, if the SB in MG1 has stored energy, or the MT in MG1 does not reach its generation limit, the stored power or the remaining generation capacity can be sent to MG2 or MG3. Meanwhile, MG2 or MG3 can also store energy in the SB in MG1.

C. *Two-level Coordinated Energy Management*

The energy management model is formulated as a two-level optimization problem [23]. The upper level represents the interaction between clustered MGs and the distribution network. The lower level models the interaction among MGs. Both levels have multiple objectives. Exchanging variables between the upper and lower levels are $P_{\mathrm{PED}i,t}$,$Q_{\mathrm{PED}i,t}$, $P_{\mathrm{PE}f,t}$, $Q_{\mathrm{PE}f,t}$ and the responsive reserve. Different MGs interact with each other by exchanging the remaining dispatchable capacity. The structure of the two-level model is shown in Fig. 2.

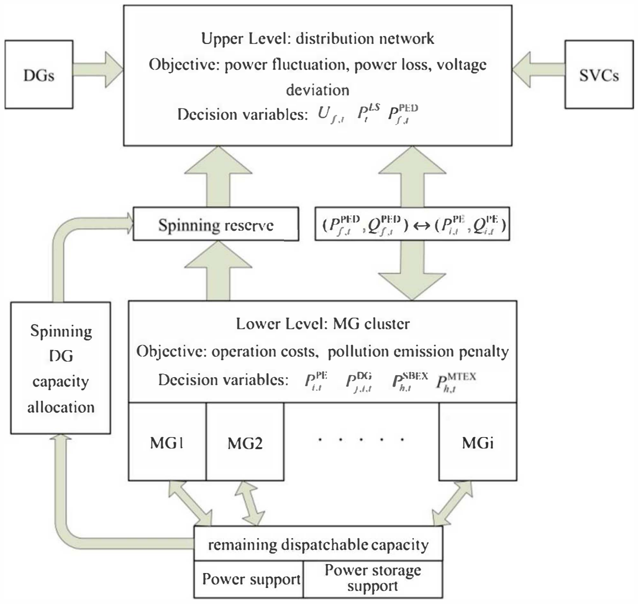


Fig. 2. Structure of the two-level model

III. OPTIMIZATION MODEL OF DISTRIBUTIONSYSTEM

A. Mathematical formulation for upper level

The mathematical formulation of the upper-level model is described as follows:

$$\min F^{\mathrm{up}} = \mu_1 F_1 + \mu_2 F_2 + \mu_3 F_3 \tag{1}$$

$$F_1 = \sum_{t=1}^{T} \sqrt{\sum_{i \in I} (V_{i,t} - 1)^2 / I} \tag{2}$$

$$F_2 = \sqrt{\sum_{t=1}^{T} \Big(\sum_{i \in I^{\mathrm{M}}} P_{i,t}^{\mathrm{PED}} - \eta \Big)^2 / T} \tag{3}$$

$$F_3 = \sum_{t=1}^{T} P_t^{LS} \tag{4}$$

s. t.

$$\begin{cases} P_{i,t}^{\mathrm{g}} - P_{i,t}^{\mathrm{L}} - P_{i,t}^{\mathrm{PED}} = \\ V_{i,t} \sum V_{j,t} (\mathrm{G}_{i,j} \cos\theta_{i,j,t} + \mathrm{B}_{i,j} \sin\theta_{i,j,t}) \\ Q_{i,t}^{\mathrm{g}} - Q_{i,t}^{\mathrm{L}} - Q_{i,t}^{\mathrm{PED}} = \\ V_{i,t} \sum V_{j,t} (\mathrm{G}_{i,j} \sin\theta_{i,j,t} + \mathrm{B}_{i,j} \cos\theta_{i,j,t}) \end{cases} \tag{5}$$

$$\begin{cases} P_{i,t}^{\mathrm{g}} - P_{i,t-1}^{\mathrm{g}} \le R^{\mathrm{up}} \\ P_{i,t-1}^{\mathrm{g}} - P_{i,t}^{\mathrm{g}} \le R^{\mathrm{down}} \end{cases} \tag{6}$$

$$\begin{cases} P^{\mathrm{PE\,min}} \le P_{i,t}^{\mathrm{PED}} \le P^{\mathrm{PE\,max}} \\ P_i^{\mathrm{g\,min}} \le P_{i,t}^{\mathrm{g}} \le P_i^{\mathrm{g\,max}} \\ Q^{\mathrm{PE\,min}} \le Q_{i,t}^{\mathrm{PED}} \le Q^{\mathrm{PE\,max}} \\ Q_i^{\mathrm{g\,min}} \le Q_{i,t}^{\mathrm{g}} \le Q_i^{\mathrm{g\,max}} \\ V_i^{\min} \le V_{i,t} \le V_i^{\max} \end{cases} \tag{7}$$

$$\sum_{i \in I^g} (P^{\mathrm{gm\,ax}} - P_{i,t}^{\mathrm{g}}) \ge R_t - R_t^{\mathrm{MG}} \tag{8}$$

In the above formulation, F_1 represents the voltage deviations of all nodes. F_2 describes the level of total power exchange fluctuations between distribution network and MGs, and it is important to reduce the power exchange fluctuation since it may affect the power quality of customers and lead to voltage/frequency deviations [24]. The reliability and operation costs of the distribution system may also be adversely affected in certain cases [25]. F_3 indicates the total power loss of the distribution network. Penalty factors of F_1, F_2, and F_3 are denoted as μ_1, μ_2, and μ_3, respectively. Constraints on power flows, outputs, voltages, and the original spare capacity of the distribution network are shown in (5)-(8).

B. Mathematical formulation for lower level

When the power generation and demand are not balanced in a MG, it can import power from or export to other MGs through the channels in the distribution system. The allocation of the support from other MGs is based on their remaining dispatchable capacities. The lower level model is formulated as follows:

$$\min f^{down} = f_1 + f_2 \tag{9}$$

$$f_1 = \sum_{f \in F} \Big\{ \sum_{t=1}^{T} \Big[q P_{f,t}^{\mathrm{PE}} + \sum_{s \in S_f} (K_s^{\mathrm{FUEL}} + K_s^{\mathrm{OM}}) P_{s,f,t}^{\mathrm{G}} + C_{f,t} R_{f,t}^{\mathrm{EX}} \Big] \Big\} \tag{10}$$

$$f_2 = \sum_{t=1}^{T} \sum_{f \in F} \sum_{s \in S_f} (p_{\mathrm{CO_2}} \cdot N_{\mathrm{CO_2},s} + p_{\mathrm{NO}_x} \cdot N_{\mathrm{NO}_x,s} + p_{\mathrm{SO_2}} \cdot N_{\mathrm{SO_2},s}) \cdot P_{s,f,t}^{\mathrm{G}} \tag{11}$$

s. t.

$$\begin{cases} P_{f,t}^{\mathrm{ML}} - \sum_{s \in S_f} P_{s,j,t}^{\mathrm{G}} - P_{f,t}^{\mathrm{PE}} = 0 \\ Q_{f,t}^{\mathrm{ML}} - \sum_{s \in S_f} Q_{s,j,t}^{\mathrm{G}} - Q_{f,t}^{\mathrm{PE}} = 0 \end{cases} \tag{12}$$

$$\begin{cases} E_{f,t}^{\mathrm{T}} = E_{f,t-1}^{\mathrm{T}} - P_{2,f,t}^{\mathrm{G}} \\ E_{f,t} = E_{f,t}^{\mathrm{T}} - y_{f,t} P_{f,t}^{\mathrm{SBEX}} \\ E_f^{\min} \le E_{f,t} \le E_f^{\max} \end{cases} \tag{13}$$

$$\begin{cases} P_f^{\mathrm{MTmin}} \le P_{1,f,t}^{\mathrm{G}} + x_{f,t} P_{f,t}^{\mathrm{MTEX}} \le P_f^{\mathrm{MTmax}} \\ -P_f^{\mathrm{SBmax}} \le P_{2,f,t}^{\mathrm{G}} + y_{f,t} P_{f,t}^{\mathrm{SBEX}} \le P_f^{\mathrm{SBmax}} \\ Q_f^{\mathrm{MTmin}} \le Q_{1,f,t}^{\mathrm{G}} \le Q_f^{\mathrm{MTmax}} \\ -Q_f^{\mathrm{SBmax}} \le Q_{1,f,t}^{\mathrm{G}} \le Q_f^{\mathrm{SBmax}} \end{cases} \tag{14}$$

$$\begin{cases} P_{1,f,t}^{\mathrm{G}} + x_{f,t} P_{f,t}^{\mathrm{MTEX}} - P_{1,f,t-1}^{\mathrm{G}} \le R^{\mathrm{up}} \\ P_{1,f,t-1}^{\mathrm{G}} - (P_{1,f,t}^{\mathrm{G}} + x_{f,t} P_{f,t}^{\mathrm{MTEX}}) \le R^{\mathrm{down}} \end{cases} \tag{15}$$

$$\sum_{f \in F} (P_f^{\mathrm{MTmax}} - P_{1,f,t}^{\mathrm{G}}) + \sum_{f \in F} E_{f,t} \ge R_t^{\mathrm{OMC}} \tag{16}$$

$$\sum_{f \in F} R_{f,t}^{\mathrm{EX}} \le \varepsilon R_t^{\mathrm{OMC}} \tag{17}$$

$$R_t^{\mathrm{MC}} = (1 - \varepsilon) R_t^{\mathrm{OMC}} \tag{18}$$

Where f_1 represents the total operation costs of clustered MGs. The cost of power exchange between the distribution system and clustered MGs can be calculated using the grid price q. The penalty of pollution emission is modeled in f_2. Constraints on power balance, SB capacities, DG outputs, ramping rates, and interactive responsive reserves are shown in (12)-(18). In equations (17) and (18), ε represents the allocation of the original spare capacity of MGs between the distributed network and MGs.This paper assumes that every MG contains a SB and a MT.

IV. OPERATION OF CLUSTERED MICROGRIDS

A. Behavior analysis

In this section, the mechanism of interactive operation in clustered MGs is analyzed with the theory of cooperative game and priority.

In the cooperative game theory, different players (i.e, MGs in this paper) can form different coalitions (i.e., an MG clusters in this paper) in the player set based on the benefit allocation strategy to pursue the maximum benefit. Let S and N denote a coalition of MGs and the player set of clustered MGs, respectively. The allocation strategy is optimal when S and N

satisfy condition (19). This means individuals in coalitions can obtain more benefits than independent counterparts [26]:

$$\begin{cases} \mathbf{x} = (x_1,\dots,x_i) \\ \sum_{i=1}^{n} x_i = v(N) \\ \sum_{i\in S} x_i \ge v(S), \forall S \in N \end{cases} \tag{19}$$

where x_i and $v(\bullet)$ represent benefit function and characteristic function, respectively [24]. x_i: for the cooperative game theory $(N,v), N=\{1,2,\cdots,n\}$, give every player i ($i \in N$) a real parameter x_i and form $\mathbf{x} = (x_1,\dots,x_i)$, which satisfy $x_i \ge v(\{i\})$, $\cdots\sum_{i=1}^{n} x_i = v(N)$, then $\mathbf{x}$ is the allocation strategy of S, and x_i is benefit function. $v(S)$: the maximum utility of gaming between S and $N - S = \{i \mid i \in N, i \notin S\}$.

In a coalition S, there are at least a demander i ($i \in S^{\mathrm{D}}$) and a provider j ($j \in S^{\mathrm{P}}$). We define $N_i = P_i^{\mathrm{load}} - P_i$ as the power demand of i, where P_i^{load} means the load of MG$_i$, and P_i is generated by i to satisfy its load. Moreover, j only provides its remaining dispatchable capacity. Define λ as the utility parameter ($/kW), and $v(S)$ is defined as follows [27]:

$$v(S) = \lambda \textstyle\sum_{k\in S} P_k + \lambda \textstyle\sum_{i\in S_{\mathrm{D}}, j\in S_{\mathrm{P}}} P_{ij} \tag{20}$$

where P_{ij} represents the power transferred from j to i. The benefit function of MG$_i$ can be defined as:

$$x_i = \lambda\pi_i + \lambda\pi_i^{\mathrm{ex}} \tag{21}$$

where π_i describes the power generated by MG$_i$ in the coalition, and π_i^{ex} represents the total power support from other MGs in the coalition. Assume that every coalition S meets the condition $\sum_{i\in \mathrm{S}} \mathrm{N}_i = \sum_{i\in \mathrm{S_D}, j\in \mathrm{S_P}} P_{ij}$, then we know:

$$\begin{cases} x(\mathrm{N}) = \lambda\sum_{i\in\mathrm{N}}(\pi_i + \pi_i^{ex}) = \lambda(\sum_{i\in\mathrm{N}} P_i + \sum_{m\in\mathrm{S'_D}, l\in\mathrm{S'_P}} P_{ml}) \\ \qquad = v(\mathrm{N}), \quad \mathrm{S'_D} \bigcup \mathrm{S'_P} = \mathrm{N} \\ x(\mathrm{S}) = \lambda\sum_{i\in\mathrm{S}}(\pi_i + \pi_i^{ex}) = \lambda(\sum_{i\in\mathrm{S}} P_i + \sum_{i\in\mathrm{S}} \mathrm{N}_i) \\ \qquad = \lambda(\sum_{i\in\mathrm{S}} P_i + \sum_{i\in\mathrm{S_D}, j\in\mathrm{S_P}} P_{ij}) \\ \qquad = v(\mathrm{S}), \mathrm{S_D} \bigcup \mathrm{S_P} = \mathrm{S}, \quad \forall \mathrm{S} \in \mathrm{N} \end{cases} \tag{22}$$

According to condition (19), the allocation strategy of utilizing the remaining dispatchable capacity is optimal. In equation (21), π_i and λ are constants. Hence, an MG with larger π_i^{ex} obtains more benefit. It means that the remaining dispatchable capacity needs to be utilized as much as possible. However, from the dynamic point of view, the MG-wide power generation and demand in a coalition is not always at equilibrium, and λ is a variable. Therefore the remaining dispatchable capacity needs to be allocated according to priority and rules need to be set to guide its interaction with MGs.

When $N_i \neq 0$, MG$_i$ has a decision set $G = \{g_1, g_2\}$, where g_i is the decision variable. Every variable represents the remaining dispatchable capacity in other MGs available to support MG$_i$. Since SBs are more flexible than MTs and can be used for emergency, the remaining dispatchable capacity of SBs should be allocated at the last. Accordingly g_1 has a higher priority than g_2. In addition, if g_i comes from more than one MG, it also has a decision set $G_{g_i} = \{g_1^i, \dots, g_n^i\}$. Every decision variable g_n^i represents the capacity of a MG, and the one with more remaining dispatchable capacity has a higher priority. For the convenience of modeling and computing, binary variables are introduced here to mathematically describe priority levels of decision variables. Every decision variable has its own binary variable as a trigger. When trigger conditions are satisfied, the trigger is set to 1, which means that the corresponding decision variable is executed. For a decision variable, trigger conditions are: 1) the previous trigger is 1; if the present trigger has the highest priority level, this condition can be ignored; 2) MG$_i$ still needs power or power storage support after the preivous decision variable is executed. For any MG$_i$ that needs support, the allocation of the remaining dispatchable capacity is made as follows: all decision variables with their trigger are arranged from the highest to the lowest priority level, and then their trigger is set one by one in the array dependent on trigger conditions until all decision variables are allocated. The flow chat of the capacity allocation is shown in Fig. 3.

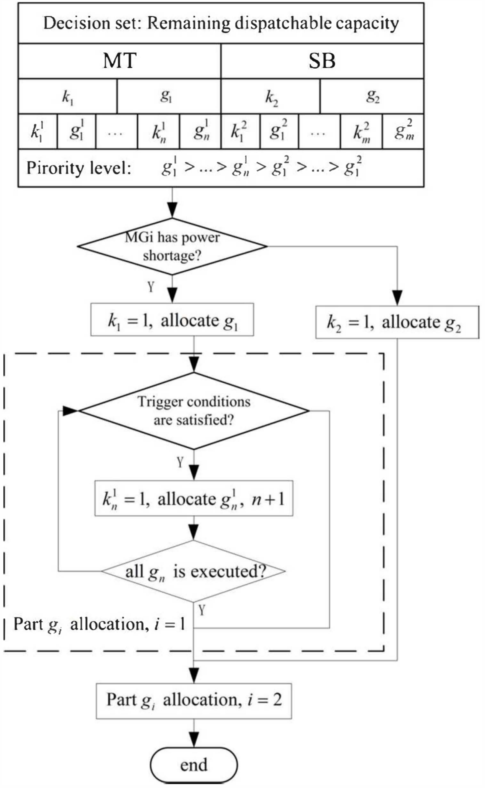


Fig.3.Flow chat of the interactive operation

B. *Interactive game matrix*

Interactive game matrix (IGM) is a mathematic model to represent and direct the allocation of the remaining dispatchable capacity in the MG cluster. Based on the behavior analysis, the variable of an IGM is described as follows:

$$R_{f,t}^{\mathrm{EX}} = a_{f,t} X_{f,t} P_{f,t}^{\mathrm{MTEX}} + b_{f,t} Y_{f,t} P_{f,t}^{\mathrm{SBEX}} \tag{23}$$

$$X_{f,t} = [x_{h,t} \dots x_{H_i,t}] \tag{24}$$

$$Y_{f,t} = [y_{h,t} \dots y_{H_i,t}] \tag{25}$$

$$P_{f,t}^{\mathrm{MTEX}} = [P_{h,t}^{\mathrm{MTEX}} \dots P_{H_i,t}^{\mathrm{MTEX}}]^{\mathrm{T}}, 0 \le P_{h,t}^{\mathrm{MTEX}} \le \alpha_{h,t} \tag{26}$$

$$\begin{gathered} P_{f,t}^{\mathrm{SBEX}} = [P_{h,t}^{\mathrm{SBEX}} \dots P_{H_i,t}^{\mathrm{SBEX}}]^{\mathrm{T}}, 0 \le P_{h,t}^{\mathrm{SBEX}} \le \beta_{h,t} (\mathit{power\ support}), \\ or\, \beta_{h,t} - E_f^{\max} \le P_{h,t}^{\mathrm{SBEX}} \le 0 (\mathit{power\ storage\ support}) \end{gathered} \tag{27}$$

$$\alpha_{h,t} = \alpha P_h^{\mathrm{MTmax}} - P_{1,h,t}^{\mathrm{G}} \tag{28}$$

$$\beta_{h,t} = E_{h,t}^{\mathrm{T}} \tag{29}$$

$$a_{f,t} = \begin{cases} 1 & when\ P_{f,t}^{\mathrm{ML}} - \sum\limits_{s \in S_f} P_{s,f,t}^{\mathrm{DG}} > 0 \\ 0 & when\ P_{f,t}^{\mathrm{ML}} - \sum\limits_{s \in S_f} P_{s,f,t}^{\mathrm{DG}} \le 0 \end{cases} \tag{30}$$

$$x_{h,t} = \begin{cases} 1 & when\ \alpha_{h,t} = \max\{\alpha_{h',t} \,|\, h' \in H_f\} \\ & or\ \alpha_{h',t} = P_{h',t}^{\mathrm{MTEX}}, \alpha_{h',t} \in \{\alpha_{h'',t} \,|\, \alpha_{h'',t} > \\ & \qquad \alpha_{h,t}, h \in H_f\} \\ 0 & other\ situations \end{cases} \tag{31}$$

$$b_{f,t} = \begin{cases} 1 & when\ P_{f,t}^{\mathrm{ML}} - \sum\limits_{s \in S_f} P_{s,f,t}^{\mathrm{DG}} < 0\ or\ \alpha_{h,t} = \\ & P_{h,t}^{\mathrm{MTEX}}, \forall \alpha_{h,t} \in \{\alpha_{h',t} \,|\, h' \in H_f\} \\ 0 & other\ situations \end{cases} \tag{32}$$

$$y_{h,t} = \begin{cases} & when\ \beta_{h,t} = \max\{\beta_{h',t} \,|\, h' \in H_f\} \\ 1 & or\ \beta_{h',t} = P_{h',t}^{\mathrm{SBEX}}, \beta_{h',t} \in \{\beta_{h'',t} \,|\, \beta_{h'',t} > \beta_{h,t}, h \in H_f\} \\ & or\ P_{h,t}^{\mathrm{SBEX}} < 0 \\ 0 & other\ situations \end{cases} \tag{33}$$

$$C_{f,t} = \frac{\sum\limits_{h \in H_f} [(K_1^{\mathrm{FUEL}} + K_1^{\mathrm{OM}}) P_{h,t}^{\mathrm{MTEX}} + K_2^{\mathrm{OM}} P_{h,t}^{\mathrm{SBEX}}]}{\sum\limits_{h \in H_f} (P_{h,t}^{\mathrm{MTEX}} + P_{h,t}^{\mathrm{SBEX}})} \tag{34}$$

where $i \in I_{\mathrm{N}}$ and $h \in H_f$, $P_{f,t}^{\mathrm{MTEX}}$ and $P_{f,t}^{\mathrm{SBEX}}$ are $1 \times H_f$ matrices, $X_{f,t}$ and $Y_{f,t}$ are $H_f \times 1$ matrices. $a_{f,t}$, $b_{f,t}$, $x_{h,t}$, and $y_{h,t}$ are the triggers. Trigger conditions are equations (30)-(33).In equation (28), α limits an MT's output within its generation capacity. The flow chart of IGM is shown in Fig. 4.

In summary, equations (1)-(18) and (23)-(34) represent the proposed interactive model for the coordinated energy management.

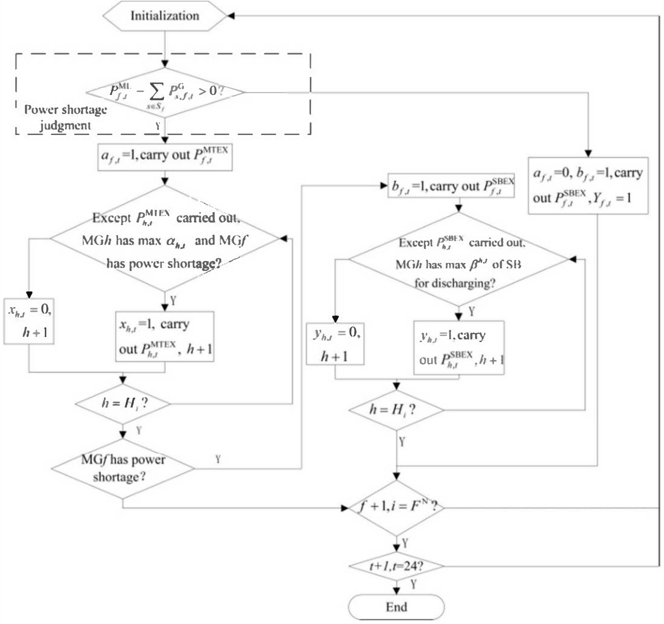


Fig. 4. Flow chart of interactive game matrix

V. PROPOSED SOLUTION ALGORITHM

In this paper, a modified hierarchical genetic algorithm (HGA) [28] is utilized to solve the proposed mixed-integer program. In HGA, the chromosome coding has two layers: the control gene layer and the parameter gene layer. Control genes are encoded by binaries to control parameter genes. Parameter genes are encoded by real numbers to represent decision variables. When a control gene is set as 1, the corresponding parameter gene is activated. Ordinary genes are also in chromosome coding encoded by real numbers and they are independent of those two kinds of genes. To better solve the problem, a modified HGA is presented by adding a superior control gene layer upon the control gene layer to control the control genes. When a superior control gene is set as 1, the corresponding control gene is activated.

In the proposed model, $a_{f,t}$ and $b_{f,t}$ are superior control genes. Control genes are $x_{h,t}$ and $y_{h,t}$. $P_{h,t}^{\mathrm{MTEX}}$ and $P_{h,t}^{\mathrm{SBEX}}$ are parameter genes. $Q_{s,f,t}^{\mathrm{G}}$ and $P_{s,f,t}^{\mathrm{G}}$ are ordinary genes. The modified HGA chromosome coding is shown in Fig. 5.

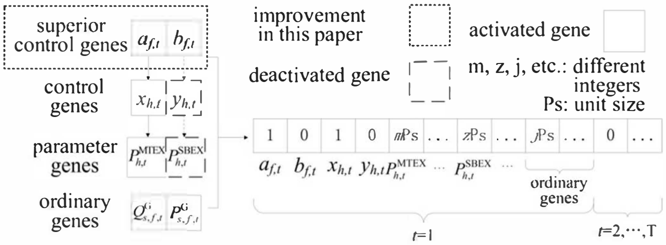


Fig. 5 Chromosome coding of modified hierarchical genetic algorithm

In each period, the algorithm resets superior control genes and control genes according to equations(30)-(33).

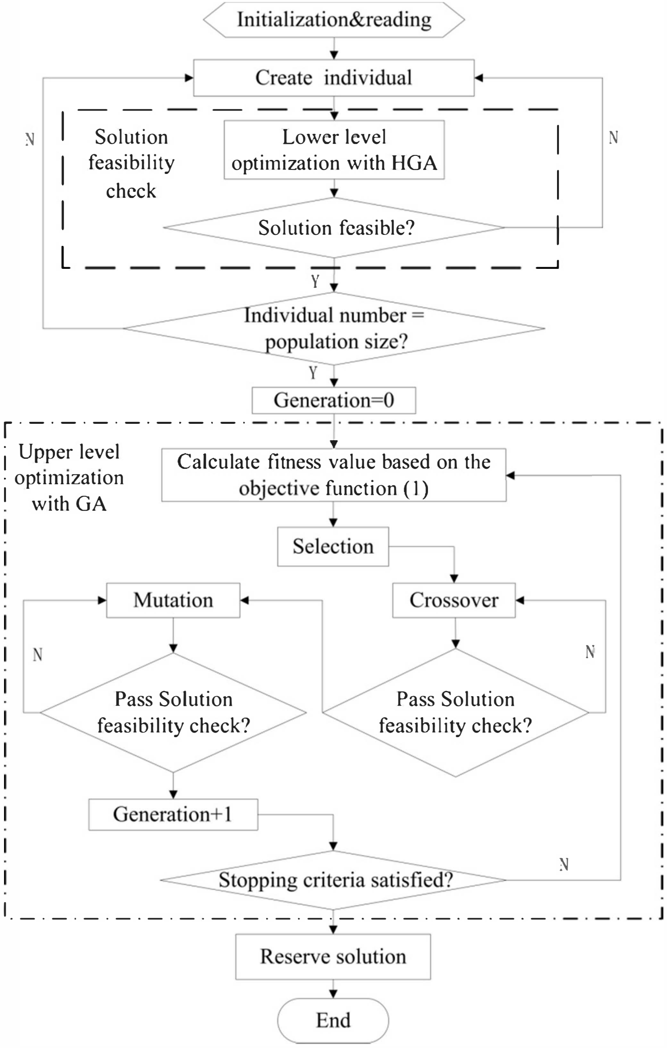


Fig. 6. Flow chat of the proposed algorithm

Details of the algorithm are described as follows:

Solution feasibility check: 1) Substitute every exchange variable (i.e., $P_{i,t}^{\text{PED}}$ and $Q_{i,t}^{\text{PED}}$) of an individual in the upper level into the lower level and calculate the lower model with the modified HGA. 2) Check whether there is a solution of the optimization problem in the lower level.

Step 0: Initialization. Set the chromosome, population size and generation=1. Read forecasting data.

Step 1: Create initial population randomly. Check individuals with solution feasibility check. Update individuals not passing the check with new individuals until all individuals in the population pass the judgment.

Step 2: Calculate fitness values based on F^{up}.

Step 3: Let the generation of population do selection.

Step 4: Let the generation of population do crossover and mutation. Check the solution feasibility of the generated individuals. Eliminate individuals that lead to infeasible solutions, and continue crossover and mutation until the next generation of population is formed.

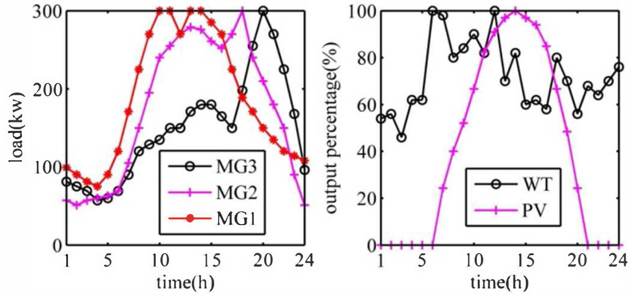
Step 5: If the condition of convergence is satisfied, return the optimal solution and the algorithm ends; otherwise go to step 2.

The above algorithm is established to solve the proposed model. Fig. 6. indicates the flow chat of the proposed algorithm.

VI. CASE STUDIES

A. Description of test system

As depicted in Fig. 1, a modified IEEE 14-bus distribution system with three MGs is used in this paper for the purposes of illustration. For this test system, the voltage base is 10.5kV, the total active load is 2870 kW, and the total reactive load is 775 kVAR. 230-kW MTs are connected at nodes 6, 11, and 12. -100~300 kVAR static VAR compensations (SVCs) are connected at nodes 7 and 13. η is set to 8kW. Fig. 7(a) shows the forecasted daily load curves and Fig. 7(b) shows the forecasted daily output curves of PVs and WTs [29]. Table I summarizes the parameters of MGs. Operating cost parameters and pollution emission penalty of DGs are obtained in [30]. q is set to be 0.61€/kWh.



(a) (b)

Fig. 7. Forecastedcurves: (a) daily load and (b) daily output percentage

Table I.Parameters of Microgrids

micro-grid	WT max output/ kW	PV max output/ kW	SB max output/ kW	SB capacity/ (kW • h)	MT max output/ kW	FC max output/ kW
MG1	--	210	80	280	--	185
MG2	250	--	70	320	195	--
MG3	200	160	80	500	100	100

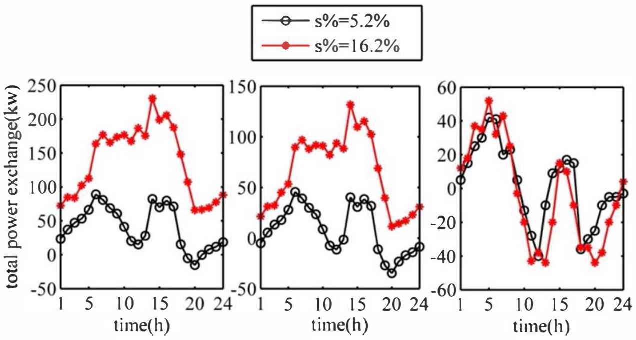
To demonstrate the proposed strategy, the following dispatch strategies and cases are considered in this paper.

- Strategy 1: the proposed dispatch strategy
- Strategy 2: the proposed dispatch strategy without the interaction among clustered MGs
- Strategy 3: traditional dispatch strategy whose objective is to minimize total operation costs of the distribution network and MGs

- Case 1: strategy 1 is applied to the distribution system connected with one MG (MG1)
- Case 2: strategy 1 is applied to the distribution system connected with three MGs (MG1, MG2 and MG3)
- Case 3: strategy 2 is applied to the system in case 1
- Case 4: strategy 2 is applied to the system in case 2
- Case 5: strategy 3 is applied to the system in case 1
- Case 6: strategy 3 is applied to the system in case 2
- Case7: strategy 3 is applied to the distribution system with no MG

B. Penetration level and power fluctuation of distribution network

The penetration level of intermittent distributed generation (IDG) and the power fluctuation of total power exchange between MGs and distribution network are important indices to evaluate the reliability of a distribution system. Define s% as the penetration level of IDG, and $0.01s$ is the proportion of IDG capacity to annual load peak. If the number of MGs including IDGs increases, s increases.



(a) (b)(c)

Fig.8. Total power exchanges in different cases: (a) case 5 (s%=5.2%) and case 6 (s%=16.2%) (b) case 3 (s%=5.2%) and case 4 (s%=16.2%) (c) case 1 (s%=5.2%) and case 2 (s%=16.2%)

Fig. 8(a) illustrates total power exchanges in cases 5 and 6. As the grid price q is less than the operation cost of a SB, the fluctuation of IDGs and loads in MGs is firstly absorbed by the power exchange with the distribution network. When s increases, the total power exchange increases significantly between 240kW and -45kW.

As depicted in Fig.8(b), the total power exchange is optimized by objective function (3) under the condition of a low penetration level (s%=5.2%). When s=16.2%, since the ability of a single MG to compensate its intermittent power is limited without supports from other MGs, the total power exchange becomes higher.

As described in Fig.8(c), due to the cooperative interaction among MGs, the growth of s has smaller impact on the distribution network. The total power exchange is thus within a smaller range between 60kW and -60kW.

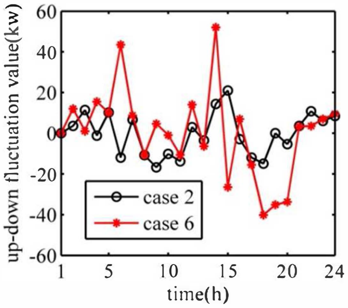


Fig. 9. Comparisons of the effect of smoothing power fluctuation in two cases

In addition, to quantify the effect of smoothing the power fluctuations, the up-down fluctuation value of total power exchange is definedas follows[31]:

$$P_t^{\text{up-down}} = \sum_{i \in I^{\text{M}}} P_{i,t+1}^{\text{PED}} - \sum_{i \in I^{\text{M}}} P_{i,t}^{\text{PED}} \tag{35}$$

As shown in Fig. 9, the power fluctuation is better smoothed in the proposed method compared to the traditional dispatch strategy.

C. Peak load shaving

The ability of peak load shaving can help the distribution system to reduce power generation costs and to relieve generation stress during peak periods.

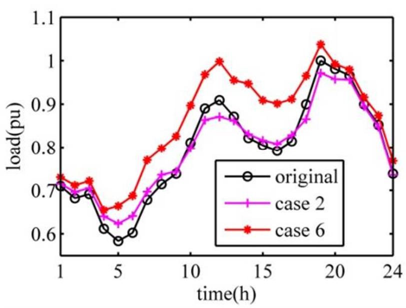
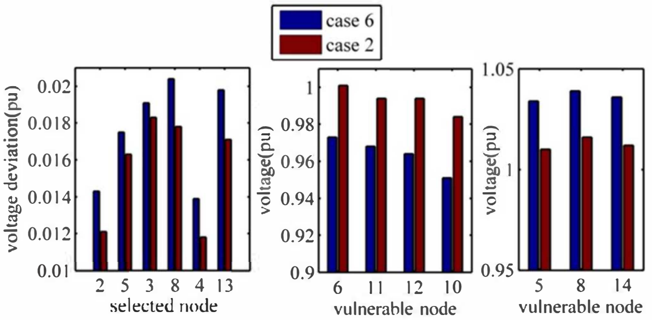


Fig. 10. Loadprofiles of the distribution network

As depicted in Fig. 10, the load difference between peak and valley is 0.3481pu in case 2, which is smaller than 0.3831pu in case 6. Compared to strategy 3, strategy 1 improves the load profile of the distribution network.

D. Voltage profile of distribution network

The optimization and regulation of voltages in a distribution network is of great importance for the system operation. When MGs with a high s% are integrated, they may cause voltage deviations of the distribution network.



(a) (b) (c)

Fig.11.Comparisons of voltage regulation data in two cases: (a) voltage deviations at selected nodes(b) voltage at vulnerable nodes under heavy loading conditionsand (c) voltage at vulnerable nodes under light loading condition

Fig. 11 (a) reveals the difference between the minimum and maximum voltages for selected nodes during the 24-hour dispatching period. It can be seen that voltage deviations in case 2 are smaller than case 6.

As presented in Fig. 11(b), under heavy load condition, voltages are low in case 6, which is especially true at ending nodes. In case 2, voltages at vulnerable nodes are increased effectively by optimizing reactive power.

In Fig. 11(c), voltages of light load are high in case 6. Since the generation of MGs can be more than load consumptions,the reverse power flow results in higher voltages at the terminal of power lines. Case 6 shows that these voltages are kept lower.

Above all, the proposed model improves the voltage profile of the distribution network.

E. Power loss of distribution network

As shown in Fig. 12, when there is no MG in the system, the power loss is high. When MGs are connected and the proposed model is applied, the power loss is reduced effectively.

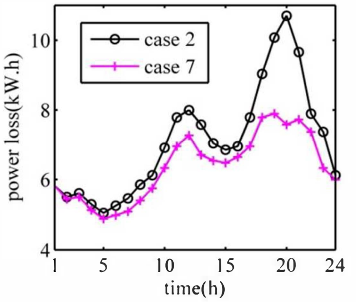


Fig. 12. Comparison of power losses in two cases

F. Responsive reservesupport from microgrid cluster

In the proposed model, R_t^{MC} is used for sharing the responsive reserve of the distribution network to enhance the system reliability. We use two indices, the expected demand not supplied (EDNS) [32] and the loss of load probability (LOLP) [33] to evaluate the system reliability. Table II is formed by the evaluation method in [32] and [33].

TableII. Distribution System Reliabilities with Different ε

ε	saved responsive reserve of distribution system /kW	LOLP	EDNS/kW
0	0	0.0321	7.25
0.2	24.8	0.0278	4.73
0.4	49.6	0.0271	3.52
0.6	74.4	0.0316	5.94
0.8	99.2	0.0516	10.27
--	--	0.0307	8.97

Table II shows reliability indices and the saved reserve from the distribution system with respect to different ε. When MGs do not provide reserve support (ε=0), the system reliability decreases. The system reliability increases as ε increases. When ε exceeds a certain threshold (near 0.4), the system reliability decreases. Therefore, the system reliabilityis improved if an appropriate value of ε is selected.

G. Environmental costs

The 24-hour environmental cost f_2 is €6370 in case 2, and €10690 in case 6. By applying the proposed method, the environmental cost has been reduced by 40.4%. On the other hand, SB utilization ratio during the entire operation period is 92.6% in case 2, higher than 71.3% in case 6. It means that the decrease of environmental cost actually represents the decrease of MT output which produces pollution. Due to IGM, if there is surplus IDG output which cannot be stored by the local MG at a certain time, this power can be stored by the SB of other MGs rather than consumed by the distribution network. When there is a power shortage, this stored power can compensate the shortage. Therefore the renewable energy utilization can also be improved.

H. Simulation time

Table III reveals the simulation time. Compared to cases 4 and 6, case 2 takes more time to complete the lower-level optimization because the IGM needs to be calculated and some genes are shared variables between the lower and upper levels. Although the computation time for the proposed method slightly increases, it is still within an acceptable range .

Table III.Simulation Time in Matlab

case	Time for upper optimization (s)	Average time for lower optimization for each MG (s)	Totaltime (s)
2	5.6	1.2	9.2
4	4.3	0.9	7
6	-	-	5.4

VII. CONCLUSIONS

In this paper, an interactive model for coordinated energy management of a distribution system with clustered MGs is proposed. There are two levels in the proposed optimization model. The upper level is to reduce power loss, improve voltage profile, and smooth power fluctuation for distribution network operation. The lower level is to reduce operation costs and pollution emission for MGs operation. A power reserve mechanism and a game theory-based strategy are introduced to coordinate the interaction between MGs and the distribution network. A modified HGA is used for solving the proposed hierarchical model. Simulations on a modified IEEE 14-buse distribution system with 3 MGs demonstrate the effectives of the proposed approach. The proposed method considers benefits and operation performances of each entity. Furthermore, it has reduced power losses by 12.7%, average power fluctuations by 56.8%, average voltage deviations by 9.1%, and environmental costs by 40.4%. Last but not least, with a proper allocation of responsive reserve from MGs to support the distribution system, the system reliability has increased.

VIII. ACKNOWLEDGEMENT

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