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A Bi-Level Optimization Approach for Optimal Operation of Distribution Networks with Retailers and Micro-grids

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Abstract- *Distributed energy resources (DERs) including distributed generators (DGs) and controllable loads (CLs) are managed in the form of several microgrids (MGs) in active distributions networks (ADNs) to meet the demand locally. On the other hand, some loads of distribution networks (DNs) can be supplied by retailers which participate in wholesale energy markets. Therefore, there are several decision makers in DNs which their cooperation should be modeled for optimal operation of the network. For this purpose, a bi-level optimization approach is proposed in this paper to model the cooperation between retailers and MGs in DNs. In the proposed model, the aim of the upper level (leader) and lower level (follower) problems are to maximize the profit of retailers and to minimize the cost of MGs, respectively. To solve the proposed multi-objective bi-level optimization model, multi-objective Particle Swarm Optimization (MOPSO) algorithm is employed. The effectiveness of the proposed bi-level model and its solution methodology is investigated in the numerical results.*

Keyword: Bi-level Optimization, Micro-grids, Particle Swarm Optimization, Retailer

1. INTRODUCTION

1.1. Motivation and Aim

In traditional distribution networks, distribution company (Disco) is responsible to meet demand with minimum power losses in Ref. [1]. Supplying the increasing demand with this approach is not economic regarding high power losses of the network and the low reliability [2]. With restructuring in power systems, new energy players named as retailers are emerged. These players purchase energy from wholesale energy markets and sell it with different price tariffs to various consumers. In distribution networks with various retailers, consumers have different options to select the best retailers for their energy consumptions with the aim of minimizing the energy costs.

On the other hand, to meet the demand of distribution network in an optimal way, distributed energy resources (DERs) are emerged in the network in Ref. [3]. To better management of them, they are integrated as micro-grids (MGs) [4]. Therefore, there are several MGs with various resources and specifications in distribution networks. MG operator (MGO) can meet the demand with optimal scheduling of resources and optimal trading energy with other decision makers in distribution network such as retailers and other MGs. For this purpose, a new decision making framework is required to model the cooperation between retailers and MGs in distribution network which is the aim of this paper.

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1.2. Literature review and contributions

The operation problem of distribution networks in the presence of DERs and MGs has been investigated from different viewpoints in the literature. In Ref. [5], a two-stage hierarchical framework is utilized to model the decision making problem of a Disco in wholesale energy markets. In Ref. [6], the previous study is extended considering the uncertainties of real-time electricity prices and demands. The authors of Ref. [7] proposed one-leader multi-follower bi-level approach to model the trading strategies of a proactive Disco in the markets. Widespread installation of DERs in distribution networks causes that Discos have the option of supplying loads from these resources besides the wholesale markets considering the guaranteed energy purchase price of DERs for a specified future period [8]. A bi-level framework is suggested in Ref. [9] to support a Disco's operational decisions with DERs and interruptible loads in a competitive market. In order to optimize the Disco's day-ahead acquisition, a bi-level problem [10] is presented to supply electrical energy from the wholesale market, interruptible loads and DERs.

The economic, technical and environmental influence of MGs penetration in the operational problems of distribution networks are studied using multi-criteria decision techniques [11]. In Ref. [12], three economic operation criteria, active power losses, and environmental advantages are introduced to present the performance of MGs in the distribution networks. The utilization of MGs and a Disco is modeled using a hierarchical framework in Ref. [13]. A methodology is introduced in Ref. [14] to present such framework as a bi-level problem in which the fitness function of the upper-level problem is to maximize the profit of the Disco and the fitness function of the lower-level problem is to minimize the MGs cost. In Ref. [15], optimal operation of a Disco and MGs is modeled using a hierarchical decision-making framework.

Ref. [16] is devoted to risk modeling and the optimization of portfolios of the retailers' performance in the markets. The authors presented a framework composed by end-use costumers using the Markowitz theory. The short-term scheduling of retailer is introduced in Ref. [17] considering its trading strategies with markets and consumers. In Ref. [18], the selling prices of retailers to consumers are considered under fixed, time-of-use, and real-time pricing. In Ref. [19], a two-stage two-level approach is proposed to model the retailers' decisions in the markets considering demand response management. The decision-making framework of retailers under the market environment is formulated as a bi-level optimization problem in Ref. [20] where retailers and consumers are supposed as leaders and followers, respectively.

There is an increased tendency for using metaheuristic algorithms for solving optimization problems in recent years. A swarm intelligence method based multi-period gravitational search algorithm is applied in Ref. [21] for real-time energy management of MGs in island mode. In the model, the multi-objective optimization method is introduced to minimize the production cost to increase the efficiency. In Ref. [22], a multi-objective bi-level optimal operation model for distribution network with grid-connected MGs is investigated. To solve the multi-objective problem, a combination technique based on self-adaptive genetic algorithm and nonlinear programming is used. An improved harmony search algorithm is used [23, 24] in optimal planning of distribution networks in the presence of distributed generations (DGs).

Modeling the interactions between Disco and MGs are investigated in many studies. On the other hand, the decision making problem of retailers is investigated in several papers. However, since in future active distribution networks (ADNs) there are several retailers and MGs, a new decision making framework between these energy players is required which it is proposed in this paper. In such framework, different retailers and MGs can cooperate with each other to maximize the total social welfare of the whole system. To model such framework, a bi-level multi-objective optimization technique is employed in which the price and trading power among retailers and MGs are considered as the two decision variables couple retailers and MGs to each other. Multi-objective particle swarm optimization (MOPSO) algorithm [25, 26] is used to solve the proposed bi-level model. Therefore, the main contributions of this paper are threefold as follows:

- Proposing a new decision-making framework for distribution networks in the presence of retailers and MGs.
- Proposing a bi-level optimization model which provides a hierarchical framework where retailers and MGs optimize their related objectives independently and in cooperation with each other.
- The MOPSO algorithm is used to determine the equilibrium points between retailers and MGs in which the local electricity prices and the amount of power exchanges between retailers and MGs are determined.

1.3. Paper Organization

The rest of the paper is organized as follows. Problem description is presented in section 2. The problem is mathematically formulated in section 3. Solution methodologies employed to solve the proposed model are described in section 4. Numerical results are given in section 5 and conclusion is done in section 6.

2. PROBLEM DESCRIPTION

This The interaction between retailers and MGs in a distribution network is shown in Figure 1. MGs are include DGs and interruptible loads (ILs) which decide about optimal scheduling of them regarding their characteristics as well as prices offered by retailers. In such framework, retailers can purchase energy from wholesale markets such as pool or future markets. Retailers, which are considered as the upper level decision maker in the proposed model, offers the local electricity prices to the MGs. MGs receives these prices and schedule their resources and decide about the power exchange with retailers. Therefore, each MG offers the amount of power exchange to the retailers. This iterative process, which is illustrated in Fig. 2, is continued until the equilibrium point between decision makers is obtained.

In this paper, MOPSO is used to determine the equilibrium points. In equilibrium points, the local electricity prices and the amount of power exchanges between retailers and MGs are determined. Also, retailers decide about the purchased power from wholesale electricity market and each MG schedules its power generation of DGs and the amount of load curtailment. MGs based on the amount of their demand and the characteristics of their resources, can act as a consumer or producer in local electricity market. This framework is mathematically modeled in the next section.

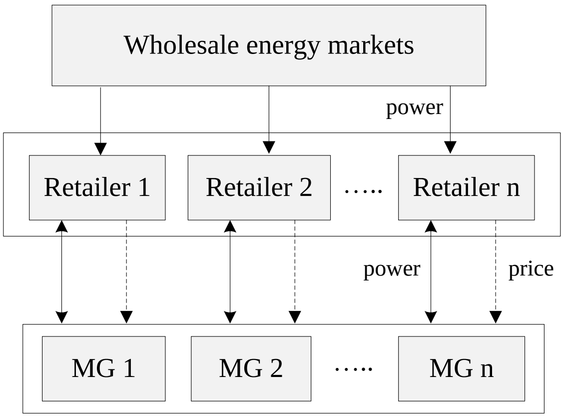


Fig. 1. The relationship between retailers and MGs in a distribution network

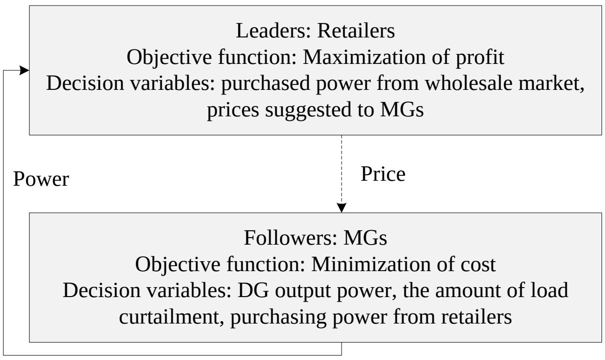


Fig. 2. Multi-objective bi-level decision-making structure

3. Mathematical Formulation

The bi-level optimization framework is a decision model with hierarchical structure and multiple participants [27]. Each level has its own objectives, constraints and decision variables. The upper-level decisions could restrict the lower-level performance. Thus, the optimal strategy of the lower-level would influence the process of the upper-level decisions [27]. The bi-level model can be expressed as follows:

$$\text{Upper level: } \begin{cases} \underset{x}{Min}\, F(x,y) \\ s.t.\, g(x,y) \le 0 \end{cases} \tag{1}$$

$$\text{Lower level: } \begin{cases} \underset{y}{Min}\, f(x,y) \\ s.t.\, h(x,y) \le 0 \end{cases} \tag{2}$$

where $x \in R^{n_x}$, $y \in R^{n_y}$ are the decision variables of the upper- and lower-level problems, respectively. $F, f: R^{n_x+n_y} \to R$ are the objective functions of the upper- and lower-level problems, respectively. $g: R^{n_x+n_y} \to R^{n_u}$ and $h: R^{n_x+n_y} \to R^{n_l}$ are the constraints of upper- and lower-level problems, respectively. In the proposed model, the upper-level problem is an optimization model of the retailers in the energy market to reduce the cost of purchased power from the wholesale market and increasing the revenue from trading energy with the MGs. The lower-level problem is the operation problem of MGs to reduce the cost of supplying demand. The lower-level problem is implemented to provide the optimal operating structure with the minimum cost and maximum energy utilization between DGs and interruptible loads in MGs.

In this paper, an economic platform is proposed for trading power between retailers and MGs which is operated and managed by distribution network operator. This problem is similar to the day-ahead energy market managed by independent system operator (ISO). Therefore, since the economic issue is very important in such problems, the distribution network in not considered in the model as proposed in several valid papers [14, 15].

3.1. Upper-level problem

The upper-level problem is modeled as follows for each j:

$$Maximize\, F(j) = \sum_{i=1}^{I} P_{ij}\, \mu^{Local} - P_j^{Market}\, \mu^{Market} \tag{3}$$

$$P_j^{Market} \le P_j^{\max} \tag{4}$$

$$0 \le \mu^{Local} \le \mu^{\max} \tag{5}$$

$$P_j^{Market} = \sum_{i=1}^{I} P_{ij} \tag{6}$$

Where, i is the index of MGs, j is the index of retailers, P_i^{Market} is purchased power from the wholesale markets (MW), μ^{Market} is the wholesale market price ($/MWh), P_{ij} is power trading between retailers and MGs (MW), μ^{Local} is the price of this trading power ($/MWh), $P_i^{\max}$ is the maximum purchased power from the market by retailers (MW), $\mu^{\max}$ is the maximum price limitations for power exchange between retailers and MGs

(\$/MWh). Eqs. (3)-(6) accordingly describe the decision-making problem of retailers (leaders) as the upper-level decision maker. In this problem, the purchased power from the market and offers to the MGs are determined as the decision variables. The objective function of the leader is maximizing profit obtained from selling/purchasing energy to/from MGs/wholesale markets which is modelled in Eq. (3). Eq. (4) is used to limit the purchasing power by retailers from the market. Eq. (5) is the limitation of upper and lower bound of the selling price of energy by retailers to MGs. The power balance of retailers is modelled as Eq. (6).

3.2. Lower level problem

The lower level problem is proposed to find the optimal operating strategy between DGs and interruptible load demand in MGs. The operation problem of each MG and its reaction to the retailers' offers is modeled as follows:

$$\{Minimize\, F(i) = \sum_{j=1}^{J} P_{ij}\, \mu^{Local} + C_{DG_i} P_{DG_i} + C_{IL_i} P_{IL_i} \quad (7)$$

$$\sum_{j=1}^{J} P_{ij} + P_{DG_i} + P_{IL_i} = P_{Demand_i} \quad (8)$$

$$0 \le P_{DG_i} \le P_{DG_i}^{\max} \quad (9)$$

$$0 \le P_{IL_i} \le P_{Demand} \times \alpha \quad (10)$$

$$P_{ij}^{\min} \le P_{ij} \le P_{ij}^{\max} \} \forall_i \quad (11)$$

Where, P_{DG_i} is the power generation of DG (MW), P_{IL_i} is the rate of load curtailment (MW), α is the weighting factor of demand, C_{DG_i} is the price of the DG power generation (\$/MWh), C_{IL_i} is the load curtailment cost (\$/MWh), P_{Demand_i} is the power demand (MW), $P_{DG_i}^{\max}$ is the maximum DG capacity limit (MW), $P_{ij}^{\max}$ is the maximum limit for buying power from market (MW) and $P_{ij}^{\min}$ is the minimum limit for purchasing power from market (MW). Eqs (7)-(11) describe the problem of decision making of MGs in the lower level problem. The objective function of MGs is to minimize the cost of operation by determining the power trading with retailers and optimal scheduling of DGs and ILs as modeled in Eq. (7). The power balance of MGs is modeled as Eq. (8) in which the purchased power from retailers, power generation of DGs, and the amount of ILs is equal to power demand of MGs. Eq. (9) is the limitation of upper and lower bound of the DGs power generation. Eq. (10) is the limitation of upper and lower bound of the load curtailments. Eq. (11) is the limitation of power exchange between retailers and MGs.

4. Optimization Techniques

4.1. Multi-objective particle swarm optimization for upper level problem

The comparison of particle swarm optimization (PSO) with other heuristic algorithms makes the concept under consideration a Pareto set ranking procedure [28, 29] could be the straight way to develop the scheme to exploit the multi-objective optimization problems. The upper level problem is a multi-objective optimization one which is considered as an effective approach to find the optimal solution between different objectives. The detailed procedures for finding the best solutions by optimal Pareto set are introduced as follows [19]:

Step 1: Initiate the parameters of the algorithm, the number of objective, number of retailers and MGs, load demand and problem restrictions.

Step 2: Population and speed initialization. The particle includes the variables of P_i^{Market}, μ^{Market}, P_{ij} and μ^{Local}. In this step, a set of particles is randomly generated within the considered restrictions.

Step 3: Evaluate each of the particles in the population. It is based on the feedback of lower level optimization. The best solution is adjusted by optimal structures of lower optimization, improving the retailers' performance.

Step 4: Keep the positions of the particles that indicate non-dominated candidates in the described external repository.

Step 5: Initialize the memory of each particle (this memory provides as a cicerone to search through the solution space. This process is also kept in the external repository as the best solution).

Step 6: To achieve the maximum number of iterations, perform the sub-sections as:

a) Calculate the speed of each particle using the following equation [20]:

$$v[i+1] = w \times v[i] + R_1 \times (Pbest[i] - Pop[i]) + R_2 \times (REP(h) - Pop[i]) \quad (12)$$

where, $Pbest[i]$ is the best position that the particle i has had, w is the inertia weight and $REP(h)$ is a value that is taken from the external repository. The h is chosen as: those repositories comprising more than one individual are established compatibility equal to the outcome of dividing any number (we used $nREP = 3$ in our experiments) by the number of individuals that they contain. $Pop[i]$ is the current value of the particle i.

b) Calculate the new positions of the particles by using the generated speed from the former step.

$$Pop[i+1] = Pop[i] + v[i+1] \quad (13)$$

c) Retain the positions of the particles between the related limitations.

d) Evaluate each of the particles in Pop.

e) Update the external repository entirely with the geographical representation of the particles within the population. This update consists of inserting all the currently non-dominated locations into the repository. Any dominated positions are removed from the repository in the process. As regards, the size of the repository is limited, whenever it gets full, a peripheral criterion is used for retention: those particles relocated in areas with less populated of the search space are given predominance over those standing in highly populated regions.

f) If the position obtained of the particle is better than the position contained in its memory, then the particle's position is updated as follows:

$$Pbest[i] = Pop[i] \tag{14}$$

g) The loop counter increases.

Step 7: End.

4.2. PSO for lower level problem

The PSO algorithm reaches on the optimization problem with a set of practical constraints. It starts with random solutions and then searches the optimal value of the objective function. Judge whether there are solved points in the feasible region of the lower level model, if yes, then use the new solutions to update corresponding P_i^{Market} and μ^{Market} in upper level, if not, then the generated particles are not passed. For better understanding, the implementation of bi-level optimization is shown in the Fig. 3.

5. NUMERICAL RESULTS

In this section, the numerical results are presented for a hypothetical distribution network in the presence of three retailers and four MGs. The specification of MGs and retailers are given in Tables 1 and 2. The maximum amount of load curtailment is 5 percent of the MG's load. The minimum and maximum amount of price between retailers and MGs is 34 and 80 \$/MWh, respectively. This range of price is determined by the distribution network operator, which is responsible for supervision and enforcing rules in the distribution network. The simulations are done in MATLAB environment and the parameters of MPSO algorithm are given in Table 3. The numerical results in this section are given in the Tables 4 and 5. Also, Fig. 4 indicates the operation result for the retailers and the MGs in the proposed bi-level model. Since retailer 1 suggests the minimum price to MGs, they purchase the maximum power from this retailer in comparison with other ones.

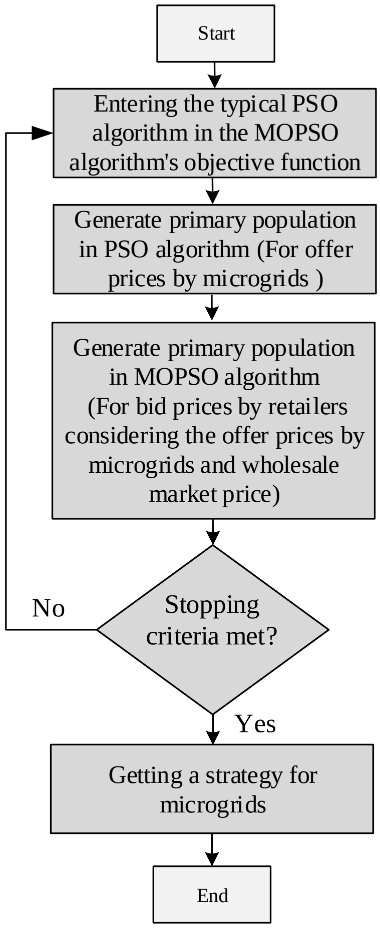


Fig. 3. Implementation of bi-level optimization

Therefore, this retailer sells the whole capacity to the MGs regarding which the operation costs of the whole system including retailers and MGs reduces. This behavior shows the ability of the proposed bi-level approach in this paper and its solution methodology to describe the operation problem of distribution networks. The results show that the competition between retailers depend on the prices of purchased power from the market since the retailers 1, 2, and 3 sells the maximum power to the MGs, respectively.

Each MGO clears a local energy market to decide on optimal scheduling of resources and optimal purchasing power from retailers. In fact, MGO receives the bids of DGs and ILs as well as the price suggested by retailers regarding which it solves the operation problem. This behavior of MGOs is shown in Table 4 and Figure 4. Since the price suggested by retailer 1 is lower than other market players, all MGOs purchase the maximum amount of power from this retailer regarding its maximum capacity. On the other hand, regarding the low amount of generation cost of DGs and the price of load curtailment, MGOs decide to schedule of these resources with maximum capacity to obtain minimum cost.

Table 1. Input data of MGs

Sources	MG1	MG2	MG3	MG4
DGs maximum power (MW)	4	5	5.5	7
generation cost of DGs ($/MWh)	37	40	35	45
Contracting price of load curtailment ($/MWh)	41	41	41	41
Demand (MW)	15	30	20	20

Table 2. Input data of retailers (MW)

	Retailer 1	Retailer 2	Retailer 3
Maximum purchased power from market(MW)	40	30	30
Price of purchasing power from market ($/MWh)	20	25	30

Table 3. The parameters of MPSO algorithm

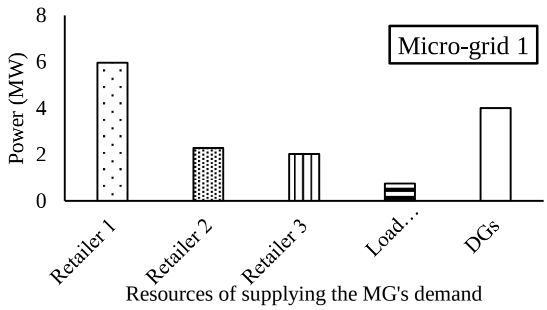
Parameter	Value
number of particle	10
number of repository	3
Maximum iteration	5
C_1	2
C_2	2
W (for linearization)	1
W_{damp} (for linearization)	0.95
Number of retailers	3
Number of MGs	4
β (parameters related to the convergence)	10
λ (parameters related to the convergence)	10

Table 4. The operation results of retailers and MGs

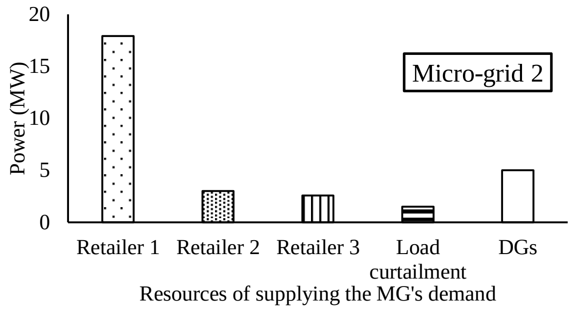
MGs	Purchased power from retailers (MW)			The amount of load curtailment (MW)	DG power generation (MW)
	Retailer 1	Retailer 2	Retailer 3		
MG1	5.96	2.27	2.02	0.75	4
MG2	17.9	3.02	2.58	1.5	5
MG3	8.75	2.52	2.23	1	5.5
MG4	7.39	2.45	2.16	1	7

Table 5. Suggested price of retailers to MGs

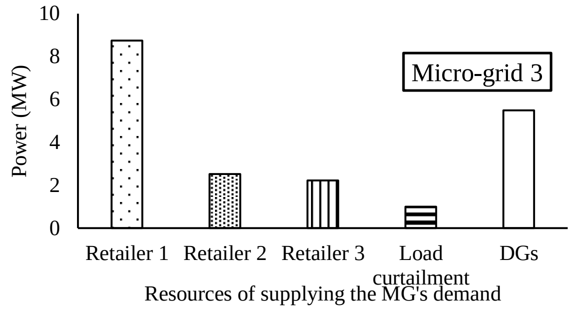
	Retailer 1	Retailer 2	Retailer 3
Suggested price ($/MWh)	34	57.37	60.63



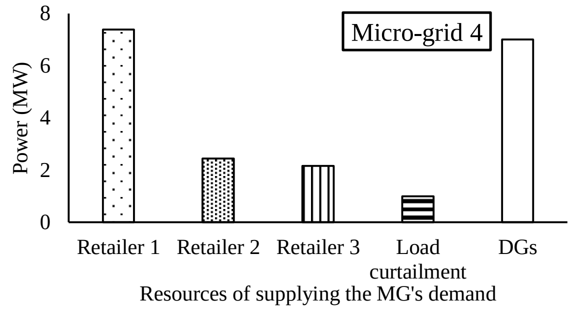
(a)



(b)



(c)



(d)

Fig. 4. Optimal operation results for retailers and MGs in the bi-level model

6. CONCLUSION

In this paper a hierarchical decision making framework is proposed to describe the operation problem of distribution networks with retailers and MGs. To model this framework, a bi-level optimization approach is proposed in which the decision problem of retailers and MGs are considered as the leaders and followers, respectively. To solve this problem, MOPSO algorithm is used. The proposed model is applied on a hypothetical distribution network with three retailers and four MGs. The results confirm the effectiveness of the proposed model to model the operation problem of distribution network with retailers and MGs. Retailer with minimum price of purchasing power from the wholesale market proposes the minimum offer to MGs regarding which sells the maximum energy to them. On the other hand, since MGO receives offers from retailers, DG, and IL to decide on optimal scheduling of resources to meet demand, a local energy market is cleared by each MGO. Regarding this local market, MGO decides on optimal generation of DGs, optimal load curtailment as well as optimal purchasing power from retailers. The results show that the retailers can obtain more profit from selling energy to MGs and also the MGs can reduce their operation costs by purchasing power from retailers with minimum prices. Therefore, these behavior of retailers and MGs increase the social welfare of the whole system which lead to better management of the distribution network.

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