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Demand Bidding and Real-Time Pricing-Based Optimal Operation of Multi-Microgrids

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Abstract

Energy management system (EMS) plays a vital role in operation of microgrids (MGs). EMS has to ensure the system stability, economic operation, and reduction of pollutant emissions. In this paper, an algorithm based on hierarchical centralized EMS has been proposed for day-ahead scheduling of multi-microgrids (MMGs) operation in the grid-connected mode. The proposed hierarchical EMS has two levels of EMSs, which are microgrid EMS (MG-EMS) and community EMS (C-EMS). Due to the utilization of hierarchical centralized EMS, privacy of each MG will be preserved. In order to reduce the load demand in peak hours and reshape the load profile, demand response (DR) programs such as real-time pricing (RTP) and demand bidding programs have been integrated in the optimization strategy. The mathematical model of the proposed algorithm is based on a mixed integer linear programming (MILP) and has been implemented through Java/CPLEX.

***Keywords**: Demand bidding, demand response, energy management system, mixed integer linear programming, optimal multi-microgrids optimization, real-time pricing*

1. Introduction

A microgrid (MG) is a set of controllable distributed generators (CDGs), renewable distributed generators (RDGs), battery energy storage systems (BESSs), and load demand in low voltage network, which can be operated in both grid-connected and islanded modes [1], [2]. In the grid-connected mode, shortage power can be bought from the utility grid, as well as surplus power can be sold to utility grid. In islanded mode, if the load demand cannot be fulfilled by local sources, load shedding has to be carried out to assure the power balance of the system. To solve this problem, microgrids are commonly connected together to form a multi-microgrid (MMG) system [3-4]. In a multi-microgrid system, the surplus/shortage power of each MG can be exchanged with other MGs for sharing cheaper sources and reducing load shedding in the whole system. Nowadays, MG/MMGs operation has been investigated by several researches for improving system reliability, minimization of total operation cost, as well as reducing air pollutant emissions [5]. In the grid-connected mode, MMG system can trade power with utility grid. However, the trading prices are usually high in the peak-hours. Therefore, in order to economically operator the MMG system, load demands in the peak hours have to be decreased. Nowadays, demand response (DR) programs have been integrated by several studies to reshape the load profiles, as well as to reduce load demand at peak intervals. The two major types of DR programs are price-based and incentive-based DR programs [6].

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In [7-8], a DR model based on real time pricing (RTP) program has been developed and optimal MG operation based on electricity distribution market has been used. In [8], a stochastic programming method has been also developed to model uncertainties in the system. The optimization model of MG operation has been investigated by [9] with multi-energy resources considering price-based DR programs. Moreover, the incentive-based demand response programs have also been applied by several studies. The role of incentive-based programs in an MG has been introduced in [10]. In [11], demand bidding program has been developed and applied for hotel energy management. Energy management system (EMS) is used for implementing DR programs for MG/MMGs operation. The architecture of an EMS could be centralized or decentralized.

A decentralized architecture has been developed for decision making and communication between each component of MG/MMG system based on a multiagent system (MAS) [12]. The decentralized EMS makes it easier to extend the size of MG/MMG system. However, each component in the decentralized EMS can make its decision for its goal. Therefore, the operation cost of the whole system could be increased. In [13], a decentralized EMS has been developed based on MAS and employed fuzzy logic for its implementation. Short-term operation of MGs based on MAS was proposed in [14]. While, MMG operation based on decentralized control architecture, which consists of four control levels has been proposed by [15]. On the other hand, in the centralized EMS, scheduling is performed by a centralized unit and all information of the loads, generators, and BESSs will be gathered, so the total operation cost of day-ahead scheduling can be reduced [12]. A centralized EMS has been developed in [16] for isolated MGs. The EMS has been formulated using a model predictive control approach. A brief review of EMS architectures for MGs operation has been discussed in [17]. This research has also proposed a centralized EMS for standard-alone operation based on a multi-stage economic load dispatch. While, a centralized controller has been suggested by [18] for optimal MGs operation in a real-time market following difference policies.

Several studies in the literature have been conducted to solve the day-ahead scheduling of the MG/MMG operation problem. The common optimization techniques used in the literature are either based on deterministic optimization or stochastic optimization. A brief introduction of computational optimization techniques have been presented in [19]. Mixed integer linear programming (MILP) is known to be one of the most common programming technique for optimal scheduling of MMGs operation [20].

Most of the researches in the literature have implemented their algorithms based on either centralized or decentralized architecture. However, as mentioned in previous paragraph, each of the centralized and decentralized architecture have their own disadvantages. Therefore, hierarchical architectures have evolved in the literature for day-ahead scheduling of MMGs. These hybrid architectures not only minimize the total operation cost but also ensure the privacy of individual MGs. Therefore, the hierarchical centralized EMS architecture has been used in this paper for scheduling of MMGs.

In this paper, we propose an algorithm to develop a hierarchical centralized EMS for day-ahead scheduling of MMGs in the grid-connected mode. The hierarchical EMS has two levels of EMS systems, which are microgrid EMS (MG-EMS) and community EMS (C-EMS). Each individual MG has a MG-EMS (level 2) for local optimization and communication with C-EMS. Additionally, C-EMS (level 1) has to communicate with all MG-EMSs and distributed network operator (DNO). The C-EMS is also responsible for performing global optimization. In the proposed algorithm, the privacy of each MG will be increased. In order to reduce the load demand in peak hours and reshape the load profile, demand response (DR) programs such as real-time pricing (RTP) and demand bidding programs have been integrated in the proposed optimization strategy. In the proposed algorithm, load demand could be shifted from peak intervals to off-peak intervals by participating in real-time pricing (RTP) program by each MG. Moreover, demand bidding strategy is applied by C-EMS for bidding load demand in the bidding time (from DNO). The load demand could be reduced in the bidding intervals by curtailing the non-critical loads. This will result in incentives for the participating MGs and reduction in the total operation cost of the MMG system. A mathematical model for the proposed algorithm has been developed based on an MILP method and has been evaluated through Java/CPLEX [21].

2. System Model

2.1. Multi-Microgrids Architecture

Figure 1 depicts the proposed architecture for optimal multi-microgrids (MMGs) operation. The multi-microgrid (MMG) system is considered as a small-scale power system where several MGs are connected and can exchange power between them. The MMG system can be operated in both inter-connected and islanded modes. Each MG also contains several units such as: controllable distributed generator (CDG), renewable distributed generator (RDG), battery energy storage system (BESS), and loads. The load can be classified into three kinds of loads, which are fixed loads, shiftable loads, and controllable loads for implementing demand response programs. The BESS has been used in this system for improving the reliability of the supply, as well as enhancing the economical operation of the system.

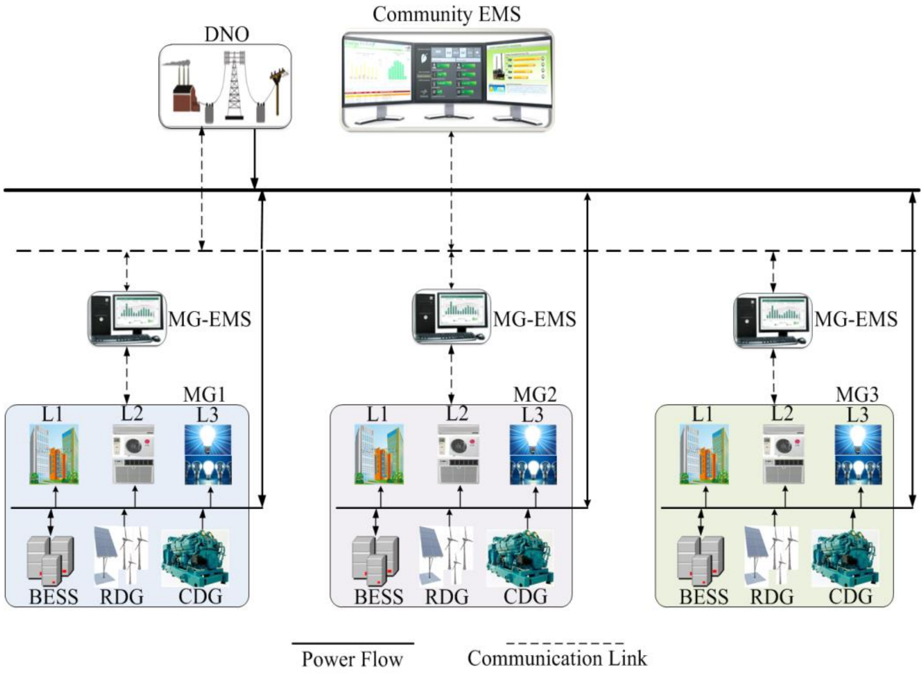

Figure 1. Multi-Microgrids Configuration

It can be observed from figure 1 that each MG has an MG-EMS that gathers all information of all the local components. Each MG-EMS performs local optimization and is also responsible for communicating with C-EMS. Each MG-EMS informs the C-EMS about surplus, shortage powers and amount of load available for bidding. Moreover, whole system can communicate with the distributed network operator (DNO) via C-EMS which is also responsible for global optimization of the MMG system.

2.2. Proposed Method for Multi-Microgrids Operation

The algorithm of optimal MMGs operation is formulated as a three-step MILP problem and is illustrated in Figure 2. In step 1 (local optimization), each MG-EMS performs local optimization considering RTP program and trading prices. The amount of surplus and shortage power is proposed to C-EMS. In step 2, C-EMS performs global optimization considering bidding times from DNO. There are two cases for processing which are as follows:

In non-bidding time, C-EMS receives all information from individual MGs and performs global optimization. In this case, C-EMS only runs global optimization based on the MG-EMSs' information and informs each MG-EMS about its schedule.

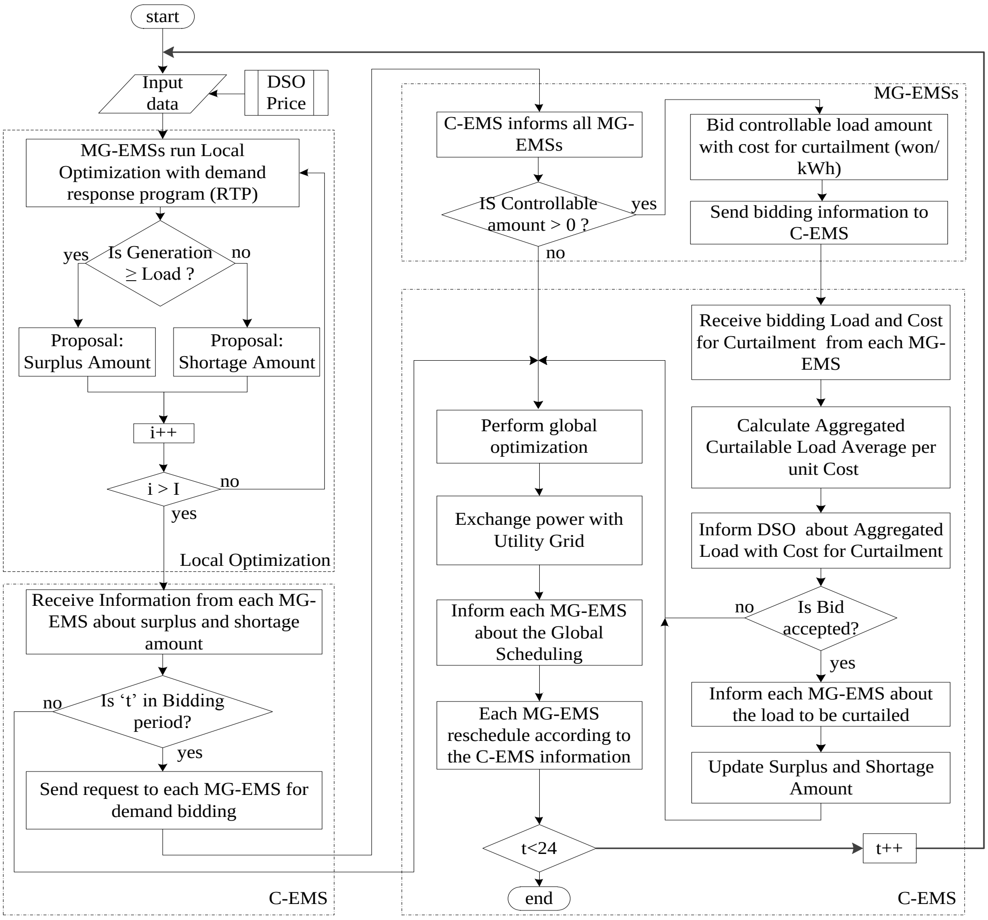

Figure 2. Algorithm for Optimal MMGs Operation

In bidding time, C-EMS informs each MG-EMS about bidding time and waits for MG-EMS response (reject/accept). If accepted, MG-EMS has to inform the C-EMS about the amount of load available for curtailment along with its cost. C-EMS calculates and decides total load to be bid for whole system with its expected cost based on the MG-EMS's proposals. When the bidding is rejected from DNO, the C-EMS performs global optimization that is similar with non-bidding time. Otherwise, the amount of load to be curtailed leads to increase/decrease in amount of surplus/shortage power. Therefore, the amount of surplus/shortage has to be updated by C-EMS in each interval. Finally, C-EMS runs global optimization and informs each MG-EMS. All the MG-EMSs have to run local optimization again (rescheduling) by using the updated information from C-EMS.

3. Problem Formulation

3.1. Nomenclature

The parameters, constants, and variables used in the problem formulation of the proposed MMG scheduling method are listed below.

Indices

$(.)_{.,t,n}$	At time t in microgrid n; where $t \in \{t_1, t_2, \ldots, 24\}$ and $n \in \{n_1, n_2, \ldots, N\}$
i	Indices of controllable distributed generators in microgrid n; $i \in \{i_1, i_2, \ldots, I_n\}$
t, n	Indices of time slots and microgrids

Parameters and Constants

$C_{n,i}^{CDG}$	Operating cost of unit i.
$C_{n,i}^{SU}$	Start-up cost of unit i.
$C_{n,i}^{SD}$	Shut-down cost of unit i.
$P_{n,i}^{\min}$	Minimum generation limits of unit i.
$P_{n,i}^{\max}$	Maximum generation limits of unit i.
$P_{n,t}^{RDG}$	Renewable distributed generation output.
$PR_{Buy,t}^{Grid}$	Buying price from utility grid.
$PR_{Sell,t}^{Grid}$	Selling prices to utility grid.
$P_{n,t}^{L\_\mathrm{fix}}$,	Amount of fixed load.
$P_{n,t}^{L\_\mathrm{con}}$	Amount of controllable load.
$P_{n,t}^{L\_shift}$	Amount of shiftable load.
$v_{n,t,t'}$	Penalty of shifting load from t to t'.
$IF_{n,t}^{\max}$	Maximum inflow of load from interval t.
$OF_{n,t}^{\max}$	Maximum outflow of load to interval t.
L_n^{Char}	Charging losses of BESS.
L_n^{Dis}	Discharging losses of BESS.
$P_{BESS,n}^{Cap}$	Capacity of BESS.
$u_{Bid,t}$	Bidding status [1= Bidding times; 0= Otherwise].
$v_{Bid,t}$	Accepted status [1= Accept; 0= Reject].
$P_{Cur,t}^{\min}$	Minimum of proposal bidding load amount to DNO.

Variables

$u_{n,i,t}$	Commitment status of unit i [1= ON; 0= OFF].
$y_{n,i,t}$	Start-up decision of unit i [1= Start-up; 0= Otherwise].
$z_{n,i,t}$	Shut-down decision of unit i [1= Shut-down; 0= Otherwise].

$P^{CDG}_{n,i,t}$	Generation output of unit i.
$P_{Short,n,t}$	Amount of shortage power in nth MG.
$P_{Sur,n,t}$	Amount of surplus power in nth MG.
$P^{Char}_{n,t}$	Amount of charging power of BESS.
$P^{Dis}_{n,t}$	Amount of discharging power of BESS.
$P^{L\_adj}_{n,t}$	Amount of adjusted load.
$P^{Shift}_{n,t,t'}$	Amount of shifted load from time t to time t'.
$SOC^{BESS}_{n,t}$	State of charge for BESS.
$C_{Cur,n,t}$	Proposal cost of bidding load for curtailment to C-EMS.
$P_{Cur,n,t}$	Proposal bidding load amount to C-EMS.
$C_{Cur,t}$	Proposal cost of bidding load for curtailment to DNO.
$P_{Cur,t}$	Proposal bidding load amount to DNO.
$P^{Buy}_{n,t}$	Amount of power bought from utility grid.
$P^{Sell}_{n,t}$	Amount of power sold to utility grid.
$P^{\mathrm{Re}c}_{n,t}$	Amount of power received from other MGs.
$P^{Send}_{n,t}$	Amount of power sent to other MGs.

3.2. Mathematical Model

This section describes day-ahead scheduling for optimal operation of MMGs considering demand response programs, which are demand bidding and real-time pricing (RTP) programs. The MG-EMS and C-EMS perform local optimization and global optimization to determine the optimal production schedules for each CDG, purchasing/selling from/to utility grid, as well as charging/discharging schedules for BESSs. In order to reduce the load amount of MMG system in peak hours, demand bidding and RTP programs are also applied. In the proposed method, RTP program is implemented by MG-EMS and demand bidding is implemented by C-EMS. An MILP-based cost minimization model has been developed for the proposed MMG system operation.

3.2.1. Local Optimization: The objective function minimizes the total operation cost of each microgrid in the system. It is given by equation (1):

$$\begin{aligned}\min \sum_{i\in I_n}\sum_{t\in T}&\left(C^{CDG}_{n,i}\cdot P^{CDG}_{n,i,t}+y_{n,i,t}\cdot C^{SU}_{n,i}+z_{n,i,t}\cdot C^{SD}_{n,i}\right)\\ &+\sum_{t\in T}\left(PR^{Grid}_{Buy,t}\cdot P_{Short,n,t}-PR^{Grid}_{Sell,t}\cdot P_{Sur,n,t}\right)+\sum_{\substack{t,t'\in T\\ t\neq t'}} v_{n,t,t'}\cdot P^{Shift}_{n,t,t'}\end{aligned} \tag{1}$$

In the above formulation, the cost objective function comprises of cost of CDG units (including start-up, shut-down and operation costs), price for buying electricity from utility grid, profit for selling electricity to utility grid, and penalty for shifting load, respectively.

The objective function is subjected to the constraints (2)-(13):

$$u_{n,i,t} \cdot P_{n,i}^{\min} \le P_{n,i,t}^{CDG} \le u_{n,i,t} \cdot P_{n,i}^{\max} \qquad \forall i \in I_n, n \in N, t \in T \tag{2}$$

$$y_{n,i,t} = \max\left\{\left(u_{n,i,t} - u_{n,i,t-1}\right), 0\right\},\ u_{n,i,t} \in \{0,1\} \qquad \forall i \in I_n, n \in N, t \in T \tag{3}$$

$$z_{n,i,t} = \max\left\{\left(u_{n,i,t-1} - u_{n,i,t}\right), 0\right\} \qquad \forall i \in I_n, n \in N, t \in T \tag{4}$$

$$P_{n,i,t}^{RDG} + \sum_{i \in I_n} P_{n,i,t}^{CDG} + P_{n,t}^{Short} + P_{n,t}^{Dis} = P_{n,t}^{L\_adj} + P_{n,t}^{Sur} + P_{n,t}^{Char} \qquad \forall n \in N, t \in T \tag{5}$$

$$0 \le P_{n,t}^{Char} \le P_{BESS,n}^{Cap} \cdot \left(1 - SOC_{n,t-1}^{BESS}\right) \cdot \frac{1}{1 - L_n^{Char}} \qquad \forall n \in N, t \in T \tag{6}$$

$$0 \le P_{n,t}^{Dis} \le P_{BESS,n}^{Cap} \cdot SOC_{n,t-1}^{BESS} \cdot (1 - L_n^{Dis}) \qquad \forall n \in N, t \in T \tag{7}$$

$$SOC_{n,t}^{BESS} = SOC_{n,t-1}^{BESS} - \frac{1}{P_{BESS,n}^{Cap}} \cdot \left(\frac{1}{1 - L_n^{Dis}} \cdot P_{n,t}^{Dis} - P_{n,t}^{Char} \cdot (1 - L_n^{Char}) \right) \tag{8}$$

$$0 \le SOC_{n,t}^{BESS} \le 1 \qquad \forall n \in N, t \in T \tag{9}$$

$$v_{n,t,t'} = \begin{cases} 0 & if\ shifting\ is\ allowed \\ \infty & otherwise \end{cases} \qquad \forall n \in N, t \in T, t' \in T \tag{10}$$

$$\sum_{\substack{t' \in T \\ t' \ne t}} P_{n,t',t}^{Shift} \le IF_{n,t}^{\max},\ \sum_{\substack{t' \in T \\ t' \ne t}} P_{n,t,t'}^{Shift} \le OF_{n,t}^{\max} \qquad \forall n \in N, t \in T \tag{11}$$

$$OF_{n,t}^{\max} = P_{n,t}^{L\_shift} \qquad \forall n \in N, t \in T \tag{12}$$

$$P_{n,t}^{L\_adj} = P_{n,t}^{L\_fix} + P_{n,t}^{L\_shift} + P_{n,t}^{L\_con} + \sum_{\substack{t' \in T \\ t' \ne t}} P_{n,t',t}^{Shift} - \sum_{\substack{t' \in T \\ t' \ne t}} P_{n,t,t'}^{Shift} \qquad \forall n \in N, t \in T \tag{13}$$

Constraint (2) limits minimum and maximum outputs of CDG units. The constraints related to start-up and shut-down costs of CDGs are given by (3) and (4) based on commitment of CDG units. Constraint (5) represents the power balance between the supply and demand in each interval of time. The amount of charging and discharging of BESSs are given by constraints (6) and (7), respectively. The stage of charge (SOC) is updated based on charging and discharging amounts at each interval by (8). Constraint (9) limits the SOC of BESS operation. Finally, demand response model (as RTP program - load shifting model) is presented by (10)-(13). The penalty for shifting load is given by (10). Constraints (11) and (12) limit maximum load demand that can be sent/received to/from other intervals. After implementing demand response, the load demand is updated by (13).

3.2.2. Global Optimization: After finishing local optimization, the information of surplus/shortage amount is proposed to C-EMS by each MG-EMS. In the proposed algorithm, bidding strategy is implemented in this step for curtailing load in the peak-hours by performing global optimization. The objective function for global optimization contains price for buying electricity from other MGs and profit for selling electricity to other MGs, respectively. It is given by equation (14).

$$\min \sum_{t \in T} \left(PR_{Buy,t}^{Grid} \cdot P_{\mathrm{Buy},t} - PR_{Sell,t}^{Grid} \cdot P_{Sell,t} \right) \tag{14}$$

The objective function is subjected to the constraints (15)-(24).

The DNO informs C-EMS about bidding time, and then C-EMS informs each MG-EMS about bidding time and receives proposals for bidding from all MGs. The bidding information contains the amount of load to be curtailed with its cost. After receiving all information for bidding, the total amount of load to be curtailed with its cost is calculated by (17)-(18). C-EMS bids total amount of load to be curtailed with average cost to DNO. The profit can be calculated by using (15) when the bidding is accepted. The amount of surplus power can be updated by (16).

$$\Pr ofit: u_{Bid,t} \cdot C_{\mathrm{Cur},t} \cdot P_{Cur,t} \cdot v_{Bid,t} \qquad \forall t \in T \qquad (15)$$

$$P_t^{Sur} := P_t^{Sur} + P_{Cur,t} \qquad \forall t \in T \qquad (16)$$

Where:

$$C_{Bid,t} = average(C_{cur,n,t}) \qquad \forall n \in N, t \in T \qquad (17)$$

$$P_{Cur,t} = \sum_{n \in N} P_{cur,n,t} \qquad \forall t \in T \qquad (18)$$

$$P_{Cur,n,t} \le P_t^{L\_con} \qquad \forall n \in N, t \in T \qquad (19)$$

$$P_{Cur,t} \ge P_{Cur,t}^{\min} \qquad \forall t \in T \qquad (20)$$

$$\sum_{n \in N} \left(P_{n,t}^{Sur}\right) + P_t^{Buy} + \sum_{\substack{m,n \in N \\ m \ne n}} \left(P_{m-n,t}^{\mathrm{Rec}}\right) = \sum_{n \in N} \left(P_{n,t}^{Short}\right) + P_t^{Sell} + \sum_{\substack{m,n \in N \\ m \ne n}} \left(P_{n-m,t}^{Send}\right) \qquad \forall t \in T \qquad (21)$$

$$\sum_{n \in N} \sum_{\substack{m \in N \\ m \ne n}} \left(P_{n-m,t}^{Send}\right) = \sum_{n \in N} \sum_{\substack{m \in N \\ m \ne n}} \left(P_{m-n,t}^{\mathrm{Rec}}\right) \qquad \forall n \in N, t \in T \qquad (22)$$

$$0 \le \sum_{\substack{m \in N \\ m \ne n}} \left(P_{n-m,t}^{Send}\right) \le P_{n,t}^{Sur} \qquad \forall n \in N, \forall t \in T \qquad (23)$$

$$0 \le \sum_{\substack{m \in N \\ m \ne n}} \left(P_{m-n,t}^{\mathrm{Rec}}\right) \le P_{n,t}^{Short} \qquad \forall n \in N, \forall t \in T \qquad (24)$$

The amount of load to be curtailed is proposed by each MG-EMS, which has to be less than the amount of controllable load in that interval and is expressed by (19). While, constraint (20) represents the minimum amount of load available for bidding to DNO. The power balance can be written by using (21) where the total supply contains surplus amount of each MG, buying power from utility grid, and receiving power from other MGs, which has to be balanced with the total of the shortage power, selling power to utility grid, and sending power to other MGs. Constraint (22) ensures that the balance between total amount of power traded between the MGs of the MMG system. Constraints (23) and (24) limit sending power and receiving power in each MG.

3.2.3. Local Optimization (Rescheduling): After finishing global optimization, each MG-EMS receives its schedule from C-EMS. Each MG-EMS performs local optimization again based on global optimization schedule. Equation (25) expresses cost objective function for rescheduling, which contains CDGs generation cost (including start-up, shut-down, and operation costs), the price of buying/receiving power from utility grid/other MGs, the profit of selling/sending power to utility grid/other MGs, and the incentive from DNO for curtailing loads, respectively.

$$
\begin{aligned}
\min \sum_{i\in I_n}\sum_{t\in T}&\left(C^{CDG}_{n,i}\cdot P^{CDG}_{n,i,t} + y_{n,i,t}\cdot C^{SU}_{n,i} + z_{n,i,t}\cdot C^{SD}_{n,i}\right)\\
&+ \sum_{t\in T}\left(PR^{\mathrm{Rec}}_{n,t}\cdot P^{\mathrm{Rec}}_{n,t} - PR^{Send}_{n,t}\cdot P^{Send}_{n,t}\right) + \sum_{t\in T}\left(PR^{Grid}_{Buy,t}\cdot P^{Buy}_{n,t} - PR^{Grid}_{Sell,t}\cdot P^{Sell}_{n,t}\right)\\
&- \sum_{t\in T}\left(C_{cur,n,t}\cdot P_{cur,n,t}\right) \qquad (25)
\end{aligned}
$$

Subject to

$$
P^{RDG}_{n,i,t} + \sum_{i\in I_n}\left(P^{CDG}_{n,i,t}\right) + P^{\mathrm{Rec}}_{n,t} + P^{Buy}_{n,t} = P^{L\_adj}_{n,t} + P^{Send}_{n,t} - P_{Cur,n,t} + P^{Sell}_{n,t} \qquad \forall n\in N, t\in T \qquad (26)
$$

Similarly, equation (26) represents the power balancing constraint considering load curtailment after global optimization. Furthermore, the objective function is also subjected to the CDGs constraints (generation limits, start-up, and shut-down conditions) as given by (2)-(4) and BESS constraints (charging/discharging, SOC limits) as shown in (6)-(9).

4. Numerical Results

In this study, an MMG system has been developed. The system has three MGs that can exchange power among themselves, as well as can trade with the utility grid (grid-connected mode). Each MG contains a CDG, RDG, BESS, and load demand. The loads have been classified into three types i.e. fixed, shiftable and controllable loads for applying demand response programs. The proposed model has been simulated in Java by using IBM ILOG CPLEX v12.3.

Before simulating the proposal model, input data has been defined for the simulations. The trading prices and CDG costs are shown in Figure 3. The CDG and BESS parameters are given by Table 1. Finally, the load classifications of individual MGs are presented in Table 2.

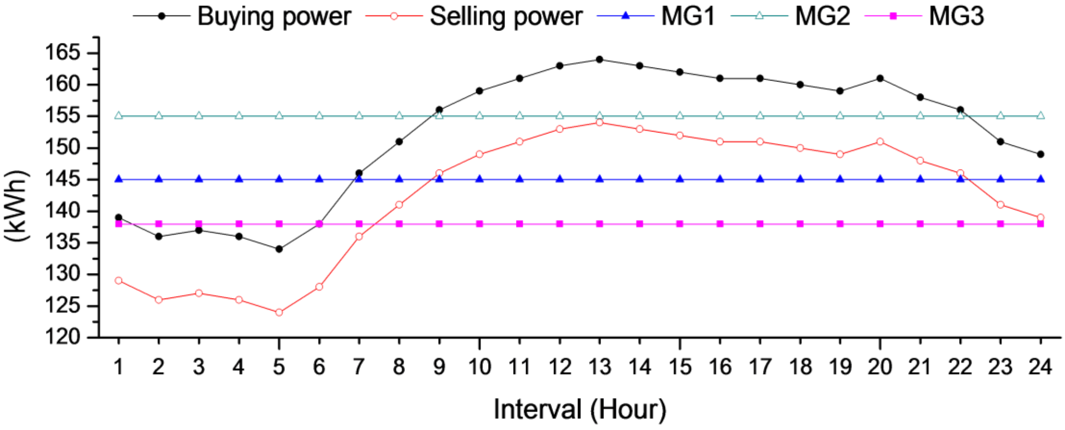

Figure 3. Trading Prices and Generation Costs of Individual MGs.

Table 1: Parameters for CDG and BESS Units of Individual MGs.

Parameters / MGs	CDG					BESS			
	Cost (KRW)	**Min. (kWh)**	**Max. (kWh)**	**Startup Cost (KRW)**	**Shutdown Cost (KRW)**	**Initial (KRW)**	**Cap. (kWh)**	**Charging Loss**	**Discharging Loss**
MG1	145	0	500	200	100	50	200	0.05	0.05
MG2	155	0	500	250	100	50	200	0.05	0.05
MG3	138	0	550	200	100	50	200	0.05	0.05

Table 2: Load Classification in Each MG.

Time	MG1			MG2			MG3		
	$P_t^{L\_fix}$	$P_t^{L\_shift}$	$P_t^{L\_con}$	$P_t^{L\_fix}$	$P_t^{L\_shift}$	$P_t^{L\_con}$	$P_t^{L\_fix}$	$P_t^{L\_shift}$	$P_t^{L\_con}$
1	283	31	22	364	48	36	309	37	26
2	258	28	19	355	47	35	309	35	24
3	245	27	18	355	47	35	302	35	24
4	265	28	19	360	47	35	316	35	24
5	299	32	23	362	48	36	333	38	27
6	310	33	24	351	46	34	333	38	27
7	287	30	21	346	46	34	319	36	25
8	337	37	28	356	46	34	412	39	28
9	396	43	34	386	51	39	437	44	33
10	446	48	40	404	53	41	443	48	37
11	504	54	42	452	60	48	480	54	43
12	530	57	45	452	60	48	496	55	44
13	456	50	45	479	63	51	498	53	42
14	487	50	20	505	67	55	489	55	44
15	466	49	23	501	66	54	479	54	43
16	467	47	10	510	67	55	478	54	43
17	458	48	24	523	69	57	487	55	44
18	485	50	20	529	70	58	500	57	46
19	513	53	21	530	71	59	515	59	48
20	490	50	10	540	72	60	503	58	47
21	470	51	42	500	67	55	489	56	45
22	390	42	33	478	64	52	437	50	39
23	357	38	29	403	53	41	383	43	32
24	327	35	26	403	53	41	369	42	31

4.1. Optimized Results of Step 1: Local Optimization

As mentioned previously for local optimization, RTP program as a shifting load method is implemented by MG-EMS for reducing load demand at peak-hours. The load curves after implementing RTP program for each MG are given by Figure 4. The use of the program leads to shifting load demand from peak hours to off-peak hours. In Figure 4, the load demands of individual MGs are shifted from peak interval (interval 10-20) with

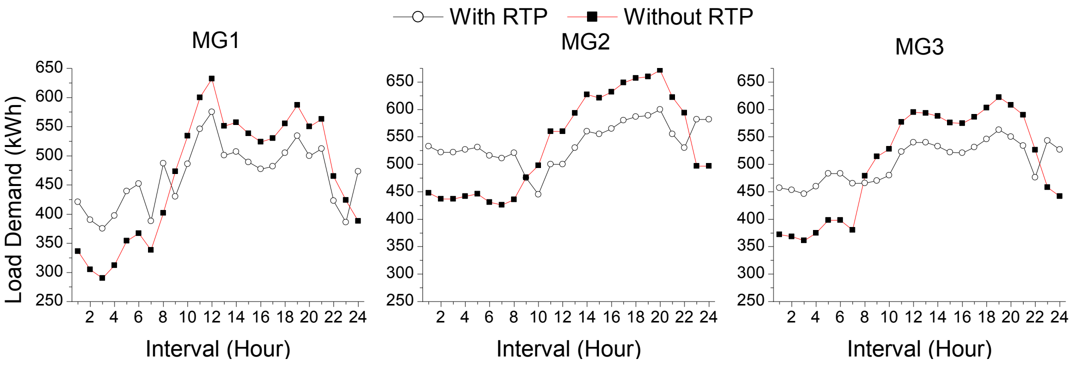

Figure 4. The Effect of RTP Program to Load Demand

high trading prices to other intervals with lower trading prices. Therefore, the total operation cost of the MMG system can be reduced. This may also result in increase of surplus power at peak hours which could be sent to other MGs having shortage at that interval.

4.2. Optimized Results of Step 2: Global Optimization

In this step, C-EMS performs global optimization for whole system considering demand bidding strategy. After receiving bidding time from DNO, C-EMS informs all individual MGs to bid the amount of load available for curtailment with its cost. In this study, the bidding time has been assumed for intervals 10-20 only. The amount of bidding load is shown in Figure 5. Each MG-EMS decides the amount of bidding load independently with expected incentive based on the amount of controllable load for reducing its operation cost.

The amount of bidding load from all MGs will be bid to DNO by C-EMS. If the bidding is rejected, C-EMS performs global optimization normally. Otherwise, the amount of surplus/shortage will be changed. The increase in amount of surplus power, as well as the decrease in amount of shortage power has to be updated by C-EMS in this step after performing global optimization. The optimal global scheduling is given by Figure 6. At off-peak intervals (interval 1-8 and 23, 24), the trading prices are lower than buying prices. Therefore, the total amount of shortage power in whole system can be fulfilled by buying power from utility grid. In the peak intervals (intervals 9-22), the surplus power will be either

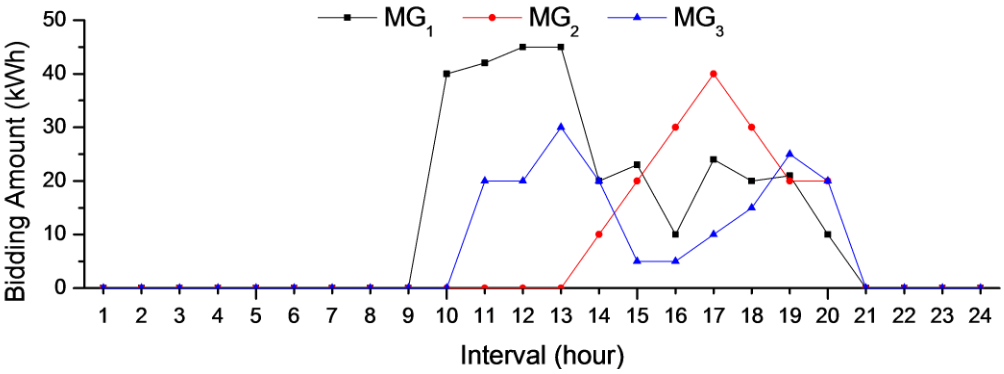

Figure 5. Bidding Amount of Individual MGs.

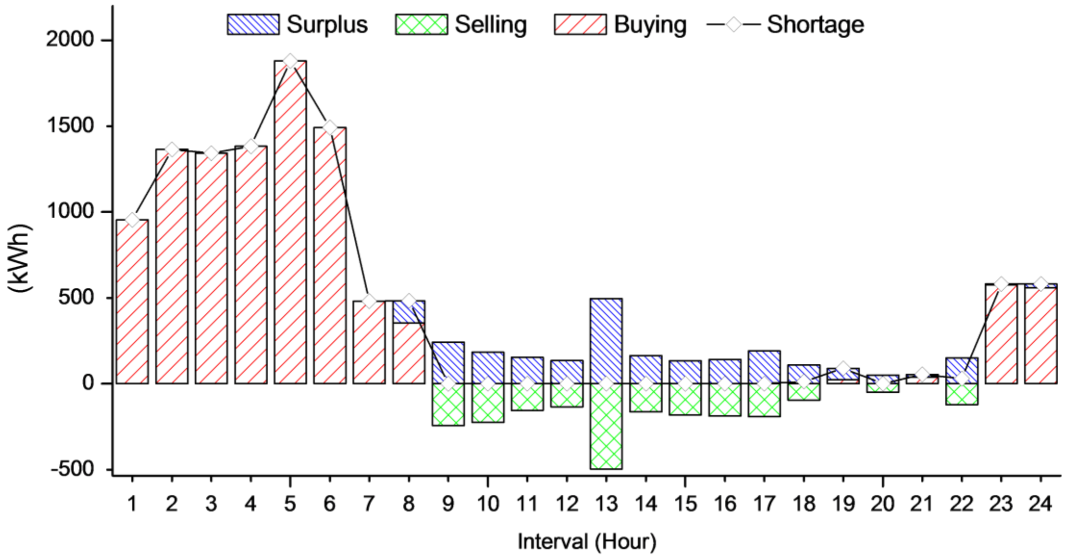

Figure 6. Global Optimization Results of MMG System.

sent to other shortage MGs, or will be sold to utility grid based on trading prices. After performing global optimization, all of information for individual MGs schedules has to be informed to each MG-EMS by C-EMS.

The effect of demand bidding strategy to the system is shown in Figure 7. Two cases have been simulated with demand bidding and without demand bidding strategy. In the peak hours (from interval 10 to interval 20), the bidding has been accepted, the amount of surplus power increases i.e. in interval 10 to interval 18. Therefore, the system can sell more power to utility grid and get more profit. At interval 19, the amount of shortage power has been reduced, so total buying power will be reduced in the peak hour.

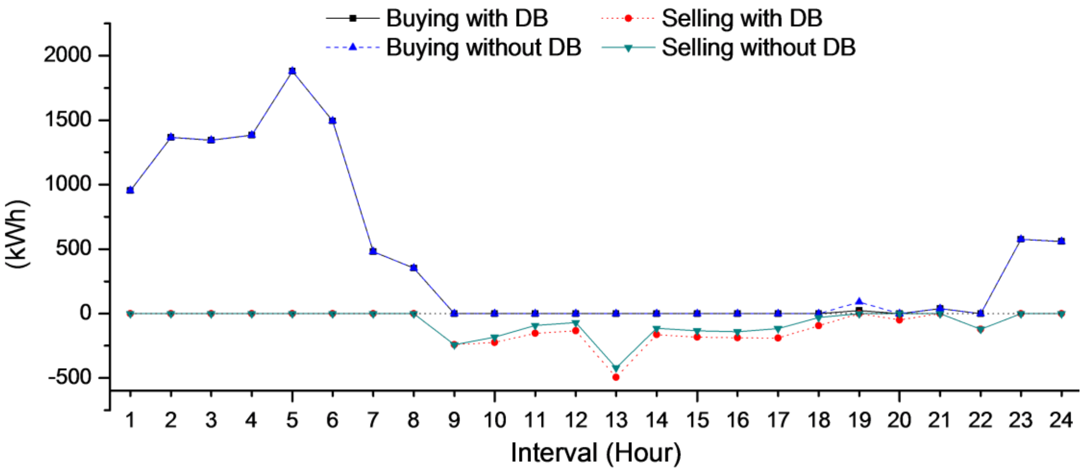

Figure 7. The Effect of Demand Bidding Strategy.

Table 3. Optimal Scheduling of Each MG After Rescheduling.

Time	MG1							MG2							MG3						
	P_{CDG}	P_{Buy}	P_{Sell}	P_{RDG}	P_{BESS}^{dis}	P_{BESS}^{Char}	P_{Load}^{DR}	P_{CDG}	P_{Buy}	P_{Sell}	P_{RDG}	P_{BESS}^{dis}	P_{BESS}^{Char}	P_{Load}^{DR}	P_{CDG}	P_{Buy}	P_{Sell}	P_{RDG}	P_{BESS}^{dis}	P_{BESS}^{Char}	P_{Load}^{DR}
1	0	421	0	0	0	0	421	0	533	0	0	0	0	533	457	0	0	0	0	0	457
2	0	390	0	0	0	0	390	0	522	0	0	0	0	522	0	453	0	0	0	0	453
3	0	375	0	0	0	0	375	0	522	0	0	0	0	522	0	446	0	0	0	0	446
4	0	397	0	0	0	0	397	0	527	0	0	0	0	527	0	460	0	0	0	0	460
5	0	581.5	0	0	0	142.5	439	0	673.5	0	0	0	142.5	531	0	625.5	0	0	0	142.5	483
6	0	465.9	0	0	0	13.9	452	0	529.9	0	0	0	13.9	516	0	496.9	0	0	0	13.9	483
7	388	0	0	0	0	0	388	0	481	0	30	0	0	511	428.4	0	0	38	0	1.3	465
8	467	0	0	20	0	0	487	0	484	0	37	0	0	521	550	0	131	47	0	0	466
9	500	0	113	43	0	0	430	432	0	0	43	0	0	475	550	0	130	50	0	0	470
10	500	0	102	48	0	0	446	397	0	0	48	0	0	445	550	0	122	52	0	0	480
11	500	0	50	54	0	0	504	446	0	0	54	0	0	500	550	0	104	57	0	0	503
12	500	0	45	57	18	0	530	443	0	0	57	0	0	500	550	0	90	60	0	0	520
13	500	0	219	50	124.6	0	456	480	0	0	50	0	0	530	550	0	276.9	60	176.9	0	510
14	500	0	58	45	0	0	487	500	0	10	50	10	0	550	550	0	95	58	0	0	513
15	500	0	74	40	0	0	466	500	0	20	49	6	0	535	550	0	88	55	0	0	517
16	500	0	68	35	0	0	467	500	0	30	47	18	0	535	550	0	89	55	0	0	516
17	500	0	72	30	0	0	458	500	0	40	48	32	0	540	550	0	79	50	0	0	521
18	500	0	40	25	0	0	485	500	0	15.7	50	22.7	0	557	550	0	39	20	0	0	531
19	500	0	21	0	34	0	513	500	69	0	0	0	0	569	550	0	25	0	13	0	538
20	500	0	10	0	0	0	490	500	0	20	0	100	0	580	550	0	20	0	0	0	530
21	500	0	0	0	12	0	512	500	55	0	0	0	0	555	550	0	16	0	0	0	534
22	500	0	77	0	0	0	423	500	30	0	0	0	0	530	550	0	74	0	0	0	476
23	386	0	0	0	0	0	386	0	582	0	0	0	0	582	550	0	7	0	0	0	543
24	473	0	0	0	0	0	473	0	582	0	0	0	0	582	550	0	23	0	0	0	527

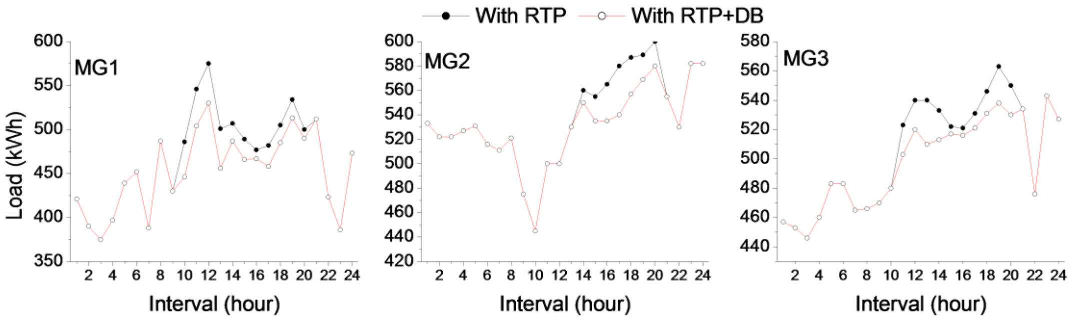

Figure 8. The Effect of DR Programs to Load Demand.

4.3. Optimized Results of Step 3: Rescheduling

The amount of load to be curtailed has been implemented in this step. Each MG can receive the incentive from DNO according to the amount of load accepted for bidding. The effect of demand response programs is given by (8). When both the RTP and demand bidding programs are applied, the amount of load demand is decreased more as compared to the RTP only case. This effect can be observed in the bidding time intervals *i.e*. intervals 10-20. Additionally, applying demand bidding strategy in the system can further reduce the operation cost by curtailing some controllable loads (the load is less important) and receives some incentives from DNO.

The day-ahead scheduling for all individual MGs is given by table 3 by implementing the proposed strategy for MMG system. The output power of CDG, RDG, charging/discharging power of BESS, exchange power among other MGs, and trading power with utility grid have been tabulated.

5. Conclusion

In this paper, an algorithm for optimal MMGs operation considering real-time pricing (RTP) program and demand bidding strategy is presented. Compared to previous studies, our model can improve the privacy of individual MGs by developing a three-step optimization model. Demand response (DR) programs have been integrated in the proposed model. In step 1, each MG-EMS performs local optimization independently for minimizing its cost with RTP program by shifting load demand in response to trading prices. Moreover, the proposed demand bidding strategy has been applied in the C-EMS. The C-EMS serves as a communication link between MG-EMS and the DNO. C-EMS makes bidding to DNO for curtailing load along with its cost based on the proposals from MG-EMSs. The effect of DR programs on load shapes in each MG has been presented by shifting and/or curtailing loads.

Furthermore, the models have been developed based on MILP and a hierarchical centralized EMS system. A hierarchical centralized EMS is made up of MG-EMSs and C-EMS instead of a big centralized EMS. It is an easy to implement method with higher flexibility, plug-and-play features, and distribution of computational burden.

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