

Mathematical Modeling of Real-Time Scheduling for Microgrid Considering Uncertainties of Renewable Energy Sources

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Abstract

This paper deals with the real-time scheduling of a microgrid considering uncertainties of renewable energy sources (RESs). A two-step mathematical model based on real-time scheduling and demand responses (DRs) is proposed. DR programs, time of use (TOU) and emergency demand response programs (EDRP), are used to minimize the operation cost of microgrid. The proposed real-time scheduling is based on spinning and load reserves to deal with uncertainties of RESs. In the first step, the day-ahead scheduling is run for 24 hours with forecasted RESs. The second step deals with the actual RESs and the microgrid operation is rescheduled in the real time. The effectiveness of DR programs on the electrical demand for each interval is also shown in this study. The mixed-integer linear programming (MILP) method using CPLEX optimization program is used to solve the proposed two-step mathematical model.

Keywords: *Microgrid operation, demand response, TOU, EDRP, mixed-integer linear programming (MILP), day-ahead scheduling, real-time scheduling*

1. Introduction

A microgrid is the electricity distribution system, which usually consists of local loads, distributed energy resources including renewable energy sources (RESs), energy storage systems (ESSs). The use of RESs such as wind and solar power can bring economic benefits as well as improve environmental quality. However, it is difficult to forecast the exact amounts of the wind or solar power generations. The microgrid operation will be affected due to the uncertainties of wind or solar power generators. Therefore, it is necessary to consider the uncertainties of RESs in the microgrid operation [1-3]. Generally, a microgrid can be operated in grid-connected or islanded modes [4-6]. Grid-connected mode is considered in this study.

The uncertainties of wind or solar power generators can be solved by using the spinning and load reserves in microgrids. The difference between the forecasted and actual outputs of RESs is compensated by these reserves. The real-time scheduling is used not only to minimize the total operation cost but also to ensure the stability of a microgrid system [7, 8]. The mathematical model of the real-time scheduling was proposed such as a two-stage model for real-time scheduling in [1, 3, 9] or short-term scheduling in [2].

Demand response (DR) programs are widely applied with real-time scheduling for the microgrid operation. While real-time scheduling can handle the problems introduced by uncertainties of RESs, DR programs can be implemented to reduce power demand during peak-interval as giving customers incentives or time-varying rates [10]. DR programs decide the amounts of shedding or shifting loads based on the market price and customers' incentives for each time period [9, 11]. DR programs are divided into two categories: price-based programs and incentive-based programs. Time of use (TOU)

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program is one of the price-based programs, which present rates with different unit prices for usage during different period. Emergency demand response program (EDRP) is a type of incentive-based DR program, which provides incentive payment to customers for reducing their loads during reliability-triggered events, but curtailment is voluntary [12]. Two DR programs, TOU and EDRP programs are considered for the microgrid operation in this study.

The two step mathematical model of real-time scheduling based on the DR programs is proposed to solve the problems introduced by uncertainties of wind or solar power generators. The proposed model of real-time scheduling determines day-ahead generation scheduling and minimize the total operation cost of the microgrid with electrical and heat loads. In the first step, the day-ahead scheduling with the forecasted output amounts of RESs is performed by microgrid central controller (MGCC). In the second step, the real-time scheduling is run with the actual output amounts of RESs. The impact of DR programs on electrical loads and optimal microgrid operation is also shown in this study. The mixed-integer linear programming (MILP) method is used to solve the proposed two-step mathematical model using CPLEX optimization program under the C++ environment.

The paper is organized as follows. In Section 2, the two steps mathematical model of real-time scheduling are proposed based on two demand responses, TOU and EDRP. Case study is presented in Section 3. Finally, conclusions and future works are summarized in Section 4.

2. Real-Time Scheduling for Microgrid Operation

A microgrid consists of RESs such as wind or solar power generations. In practical, it is difficult to forecast the exact amounts of the RESs. Therefore, the uncertainties of wind or solar power generators need to consider in the microgrid operation. In this study, the two step mathematical model of the real-time scheduling is proposed to deal with the uncertainties of RESs, as shown in Figure 1. Step 1 is the day-ahead scheduling that considers the forecasted output amounts of RESs. Besides, Step 2 deals with the actual output amounts of RESs, and the uncertainties of RESs are compensated by spinning and load reserves. The real-time scheduling is run in Step 2 based on the difference of the forecasted and actual outputs of RESs. Additionally, in order to improve the stability of the microgrid, DR programs, which consist of TOU and EDRP programs, are applied to Step 1 to reduce the power demand during peak-interval.

In order to apply DR programs, three types of loads depending on the types of the loads are assumed in this study, which are: fixed load, shiftable load, and controllable load as follows [13, 14]:

- Fixed load (or non-controllable load): a demand that must be supplied to avoid user's dissatisfaction.
- Shiftable load: the load profile for these devices can be shifted from one period to another period for reducing demand load at peak hours.
- Controllable load: loads cannot move to an interval from another and they must be on or off.

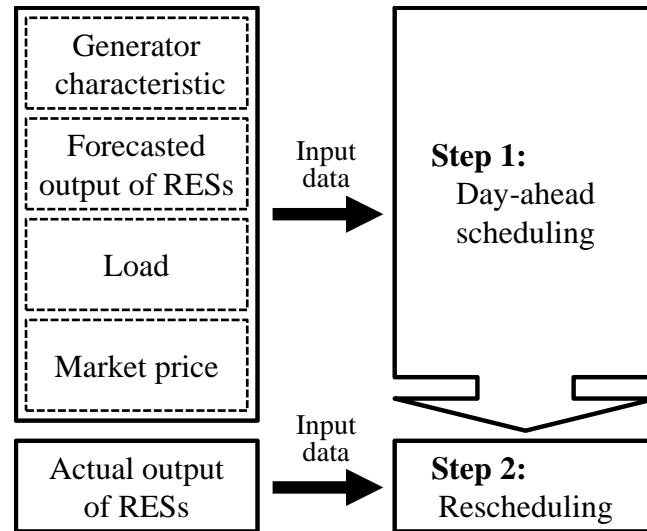


Figure 1. Operation Process for Real-Time Scheduling

2.1. Nomenclature

Before presenting the mathematical model of the microgrid operation, mathematical notations for the model are defined as follows:

t = the identifier of operation interval

T = the number of operation intervals

i = the identifier of diesel

I = the number of the diesel

j = the identifier of CHP

J = the number of the CHP

k = the identifier of HOB

K = the number of the HOB

L_{charge} = losses for charging

L_{dis} = losses for discharging

η_j = the ratio of the heat and electric power of the j^{th} CHP

$u_i(t)$ = on or off mode of the i^{th} diesel at t^{th} interval

C^{Diesel_i} = the production cost of the i^{th} diesel [won/kWh]

C^{CHP_j} = the production cost of the j^{th} CHP [won/kWh]

C^{HOB_k} = the production cost of the k^{th} HOB [won/kWh]

$SU^{Diesel_i}(t)$ = startup cost of the i^{th} diesel at t^{th} interval [won]

$C_{start}^{Diesel_i}$ = startup cost of the i^{th} diesel [won]

$Inc_{shed}^{Control}(t)$ = the incentive for load reduction at t^{th} interval [won/kWh]

$PR^{Buy}(t)$ = the buying price from the power grid at t^{th} interval [won/kWh]

$PR^{Sell}(t)$ = the selling price to the power grid at t^{th} interval [won/kWh]

- $pen(t_{from}, t_{to})$ = penalty of shifting power from t_{from}^{th} interval to t_{to}^{th} interval [won/kWh]
- $P_{adj}^{Load}(t)$ = the total amount of adjusted power load at t^{th} interval [kWh]
- $P^{Fix}(t)$ = the amount of power consumed by the fixed load at t^{th} interval [kWh]
- $P_{ini}^{Shift}(t)$ = the amount of power consumed by the shiftable load at t^{th} interval [kWh]
- $P_{adj}^{Shift}(t)$ = the amount of adjusted power consumed by the shiftable load at t^{th} interval after the load shifting [kWh]
- $P(t_{from}, t_{to})$ = the amount of power shifted from t_{from}^{th} interval to t_{to}^{th} interval [kWh]
- $P_{ini}^{Control}(t)$ = the amount of power consumed by the controllable load at t^{th} interval [kWh]
- $P_{adj}^{Control}(t)$ = the amount of adjusted power consumed by the controllable load at t^{th} interval after the load shedding [kWh]
- $P_{shed}^{Control}(t)$ = the amount of load shedding at t^{th} interval [kWh]
- $P^{RESs}(t)$ = the output produced from renewable energy resources (RESs) at t^{th} interval [kWh]
- $P^{Diesel_i}(t)$ = the output produced from the i^{th} diesel at t^{th} interval [kWh]
- $P^{CHP_j}(t)$ = the electrical output produced from the j^{th} CHP at t^{th} interval [kWh]
- $H^{CHP_j}(t)$ = the heat output produced from the j^{th} CHP at t^{th} interval [kWh]
- $H^{HOB_k}(t)$ = the output produced from the i^{th} HOB at t^{th} interval [kWh]
- $H^{Load}(t)$ = the amount of heat demand at t^{th} interval [kWh]
- $H^{Waste}(t)$ = the amount of heat waste at t^{th} interval [kWh]
- $P^{Buy}(t)$ = the amount of power purchased from the power grid at t^{th} interval [kWh]
- $P^{Sell}(t)$ = the amount of power sold to the power grid at t^{th} interval [kWh]
- $P_{charge}^{BESS}(t)$ = the amount of power charged at t^{th} interval [kWh]
- $P_{dis}^{BESS}(t)$ = the amount of power discharged at t^{th} interval [kWh]
- P_{max}^{BESS} = maximum power capacity of the BESS [kWh]
- P_{ini}^{BESS} = initial power capacity of the BESS [kWh]
- $P_{SoC}^{BESS}(t)$ = state of charge (SoC) of BESS at t^{th} interval [kWh]
- $P_{max}^{IF}(t)$ = maximum total amount of power shifting from another interval to interval t [kWh]
- $P_{max}^{OF}(t)$ = maximum total amount of power shifting from interval t to another interval [kWh]
- $P_{min}^{Diesel_i}$ = minimum production capacity of the i^{th} diesel [kWh]

$P_{\max}^{Diesel_i}$ = maximum production capacity of the i^{th} diesel [kWh]

$P_{\min}^{CHP_j}$ = minimum production capacity of the j^{th} CHP [kWh]

$P_{\max}^{CHP_j}$ = maximum production capacity of the j^{th} CHP [kWh]

$P_{\min}^{HOB_k}$ = minimum production capacity of the k^{th} HOB [kWh]

$P_{\max}^{HOB_k}$ = maximum production capacity of the k^{th} HOB [kWh]

$\Delta P^{RESs}(t)$ = the difference of the RESs between forecasted and actual output at t^{th} interval [kWh]

$\Delta P^{Diesel_i}(t)$ = the difference of the i^{th} diesel after rescheduling at t^{th} interval [kWh]

$\Delta P^{CHP_j}(t)$ = the difference of the j^{th} CHP after rescheduling at t^{th} interval [kWh]

$\Delta P^{Buy}(t)$ = the difference of buying after rescheduling at t^{th} interval [kWh]

$\Delta P^{Sell}(t)$ = the difference of selling after rescheduling at t^{th} interval [kWh]

$\Delta P_{dis}^{BESS}(t)$ = the difference of BESS's discharging after rescheduling at t^{th} interval [kWh]

$\Delta P_{charge}^{BESS}(t)$ = the difference of BESS's charging after rescheduling at t^{th} interval [kWh]

$\Delta P_{adj}^{Load}(t)$ = the difference of adjustable load after rescheduling at t^{th} interval [kWh]

2.2. Mathematical Model of Real-Time Scheduling

The operation processes of MGCC consist of two steps, where the day-ahead scheduling and the real-time scheduling are dealt with. The day-ahead scheduling, which considers the forecasted output amounts of RESs, is run in Step 1. The real-time scheduling is run in Step 2 with the actual output amounts of RESs.

2.2.1. Step 1: day-ahead Scheduling

Step 1 is the day-ahead scheduling of the microgrid with the forecasted output amounts of RESs. The spinning and load reserves are calculated based on the difference of forecasted and actual outputs of RESs. DR programs (TOU and EDRP programs) are applied in this step, which decide the amounts of loads shifting and shedding for reducing total cost objective function. The cost function of the microgrid in Step 1 is the total expenses occurred by the electric and heat energies for the microgrid as follows:

$$\begin{aligned}
 Min C = & \sum_{t=1}^T \sum_{i=1}^I (C^{Diesel_i} \cdot P^{Diesel_i}(t) + C_{start}^{Diesel_i} \cdot SU^{Diesel_i}(t)) \\
 & + \sum_{t=1}^T \left(\sum_{j=1}^J C^{CHP_j} \cdot P^{CHP_j}(t) + \sum_{k=1}^K C^{HOB_k} \cdot P^{HOB_k}(t) \right) \\
 & + \sum_{t=1}^T [PR^{Buy}(t) \cdot P^{Buy}(t) - PR^{Sell}(t) \cdot P^{Sell}(t)] \quad (1)
 \end{aligned}$$

$$\begin{aligned}
 & - \sum_{t=a}^{t=b} Inc_{shed}^{Control}(t) \cdot P_{shed}^{Control}(t) + \sum_{t_{from}=1}^T \sum_{t_{to}=1}^T [pen(t_{from}, t_{to}) \cdot P(t_{from}, t_{to})] \\
 & + \sum_{t=1}^T [C_{reserve}^{Load}(t) \cdot P_{reserve}^{Load}(t) + \sum_{i=1}^I C_{reserve}^{Diesel_i}(t) \cdot P_{reserve}^{Diesel_i}(t)]
 \end{aligned}$$

Constraints:

The limited power of the diesel generator, CHP, and HOB are expressed by (2)–(5):

$$P_{min}^{Diesel_i} \cdot u_i(t) \leq P^{Diesel_i}(t) \quad (2)$$

$$P^{Diesel_i}(t) + P_{reserve}^{Diesel_i}(t) \leq P_{max}^{Diesel_i} \cdot u_i(t) \quad (3)$$

$$P_{min}^{CHP_j} \leq P^{CHP_j}(t) \leq P_{max}^{CHP_j} \quad (4)$$

$$P_{min}^{HOB_k} \leq P^{HOB_k}(t) \leq P_{max}^{HOB_k} \quad (5)$$

The ratio of the heat and electric power of CHP as following:

$$H^{CHP_j}(t) = \eta_j \cdot P^{CHP_j}(t) \quad (6)$$

On–off mode binary constraint:

$$u_i(t) = \begin{cases} 1 & \text{if } P^{Diesel_i} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

The startup cost of a diesel unit is calculated as in (8) and (9):

$$SU^{Diesel_i}(t) = C_{start}^{Diesel_i} \cdot [u_i(t) - u_i(t-1)] \quad (8)$$

$$SU^{Diesel_i}(t) \geq 0 \quad (9)$$

The balance between the power supply and the power demand in the microgrid is expressed as in (10). When the BESS is discharged, it can be considered as the power supply in the microgrid. On the other hand, the BESS can be considered as the load when it is charged. The heat balance in the microgrid is given in (11).

$$P_{forecast}^{RESs}(t) + \sum_{i=1}^I P^{Diesel_i}(t) + \sum_{j=1}^J P^{CHP_j}(t) + P^{Buy}(t) - P^{Sell}(t) + P_{dis}^{BESS}(t) - P_{charge}^{BESS}(t) = P_{adj}^{Load}(t) \quad (10)$$

where $P_{adj}^{Load}(t) = P^{Fix}(t) + P_{adj}^{Shift}(t) + P_{adj}^{Control}(t)$

$$\sum_{j=1}^J H^{CHP_j}(t) + \sum_{k=1}^K H^{HOB_k}(t) \geq H^{Load}(t) \quad (11)$$

The amounts of charging and discharging of BESS are shown in (12) and (13), respectively. Equations (14) and (15) show the SoC of BESS for each interval. It means that the BESS should be operated in the allowable range. SoC in the first interval (P_{SoC}^{BESS}) is the initial value of the BESS ($P_{SoC}^{BESS}(t-1) = P_{ini}^{BESS}$).

$$0 \leq P_{charge}^{BESS}(t) \cdot (1 - L_{charge}) \leq P_{max}^{BESS} - P_{SoC}^{BESS}(t-1) \quad (12)$$

$$0 \leq P_{dis}^{BESS}(t) \leq P_{SoC}^{BESS}(t-1) \cdot (1 - L_{dis}) \quad (13)$$

$$P_{SoC}^{BESS}(t) = P_{SoC}^{BESS}(t-1) - P_{dis}^{BESS}(t) / (1 - L_{dis}) + P_{charge}^{BESS}(t) \cdot (1 - L_{charge}) \quad (14)$$

$$0 \leq P_{SoC}^{BESS}(t) \leq P_{max}^{BESS} \quad (15)$$

The shiftable load can be shifted from peak intervals to off-peak intervals. It depends on the trading prices and generation costs. Equations (16)–(17) express the constraints of the inflow power and the outflow power for shifting power from t_{from}^{th} interval to t_{to}^{th} interval.

Shiftable power inflow constraint:

$$\sum_{t_{from}=1, t_{from} \neq t}^T P(t_{from}, t) \leq P_{max}^{IF}(t) \quad (16)$$

Shiftable power outflow constraint:

$$\sum_{t_{to}=1, t_{to} \neq t}^T P(t, t_{to}) \leq P_{max}^{OF}(t) = P_{ini}^{Shift}(t) \quad (17)$$

When the shiftable load is transferred from t_{from}^{th} to t_{to}^{th} interval, the penalty is given as follows:

$$pen(t_{from}, t_{to}) = \begin{cases} \infty & \text{if customer don't permit shiftable load to } t_{to}^{th} \\ 0 & \text{otherwise} \end{cases} \quad (18)$$

Equation (19) shows the amount of adjusted power after shifting load to t^{th} interval.

$$P_{adj}^{Shift}(t) = P_{ini}^{Shift}(t) + \sum_{t_{from}=1, t_{from} \neq t}^T P(t_{from}, t) - \sum_{t_{to}=1, t_{to} \neq t}^T P(t, t_{to}) \quad (19)$$

The amounts of power reduction and reserve for peak interval are shown in (20) and (21):

$$P_{shed}^{Control}(t) = P_{ini}^{Control}(t) - P_{adj}^{Control}(t) \quad (20)$$

$$P_{reserve}^{Load}(t) \leq P_{adj}^{Control}(t) \quad (21)$$

The spinning and load reserves required for t^{th} interval is given as follows:

$$P_{reserve}^{Load}(t) + \sum_{i=1}^I P_{reserve}^{Diesel_i}(t) \geq P_{reserve}^{min}(t) \quad (22)$$

2.2.2. Step 2: Real-time scheduling

In Step 2, the actual output amounts of RESs are measured, and the real-time scheduling is run based on the actual output amounts of RESs. The uncertainties of RESs are compensated by the spinning and load reserves that are determined in Step 1. The cost function of the microgrid in Step 2 is shown as follows:

$$\begin{aligned} Min C = & \sum_{t=t'}^T \sum_{i=1}^I (C^{Diesel_i} \cdot P^{Diesel_i}(t) + C_{start}^{Diesel_i} \cdot SU^{Diesel_i}(t)) \\ & + \sum_{t=t'}^T \left(\sum_{j=1}^J C^{CHP_j} \cdot P^{CHP_j}(t) + \sum_{k=1}^K C^{HOB_k} \cdot P^{HOB_k}(t) \right) \\ & + \sum_{t=t'}^T [PR^{Buy}(t) \cdot P^{Buy}(t) - PR^{Sell}(t) \cdot P^{Sell}(t)] \end{aligned} \quad (23)$$

$$- \sum_{t=i', t \geq a}^{t=b} Inc_{shed}^{Control}(t) \cdot P_{shed}^{Control}(t)$$

The constraints for Step 2 are given in (24). The amounts of the spinning and load reserves are changed, which depend on the difference of the forecasted and actual outputs of RESs. The upper limited of load shedding and the output power of diesel generator are shown in (25) and (26), respectively.

$$\Delta P^{RESs}(t) + \sum_{i=1}^I \Delta P^{Diesel_i}(t) + \sum_{j=1}^J \Delta P^{CHP_j}(t) + \Delta P^{Buy}(t) - \Delta P^{Sell}(t) + \Delta P_{dis}^{BESS}(t) - \Delta P_{charge}^{BESS}(t) = \Delta P_{adj}^{Load}(t) \quad (24)$$

$$\Delta P_{shed}^{Control}(t) \leq P_{reserve}^{Load}(t) \quad (25)$$

$$\Delta P^{Diesel_i}(t) \leq P_{reserve}^{Diesel_i}(t) \quad (26)$$

3. Case Study

In order to show the validation of the proposed mathematical models for real-time scheduling in the microgrid, a case study has been conducted and its simulation results are presented in this section.

3.1. Scenario

The microgrid in Figure 2 is used for case study of optimal microgrid operation; the microgrid consists of a photovoltaic power generator (PV), two diesel generators, two CHPs, a HOB. The BESS can be charged or discharged depending on the market price. Grid-connected operation mode of microgrid allows power trading with utility grid. The characteristics of distributed generators are presented in Table 1. While the forecasted output amounts of RESs are listed as in Table 2, the actual output amounts of RESs are in Table 3. Load data such as heat load and electrical load are shown in Table 4 and the market price is shown in Table 5.

Table 1. Production Characteristics of Distributed Generators

Item	Cost (won/kWh)		Capacity (kW)	
	Variable	Startup	Minimum	Maximum
DG 1	100	200	0	100
DG 2	75	175	0	50
CHP 1	35	150	30	80
CHP 2	35	150	20	70
HOB	150	200	0	100

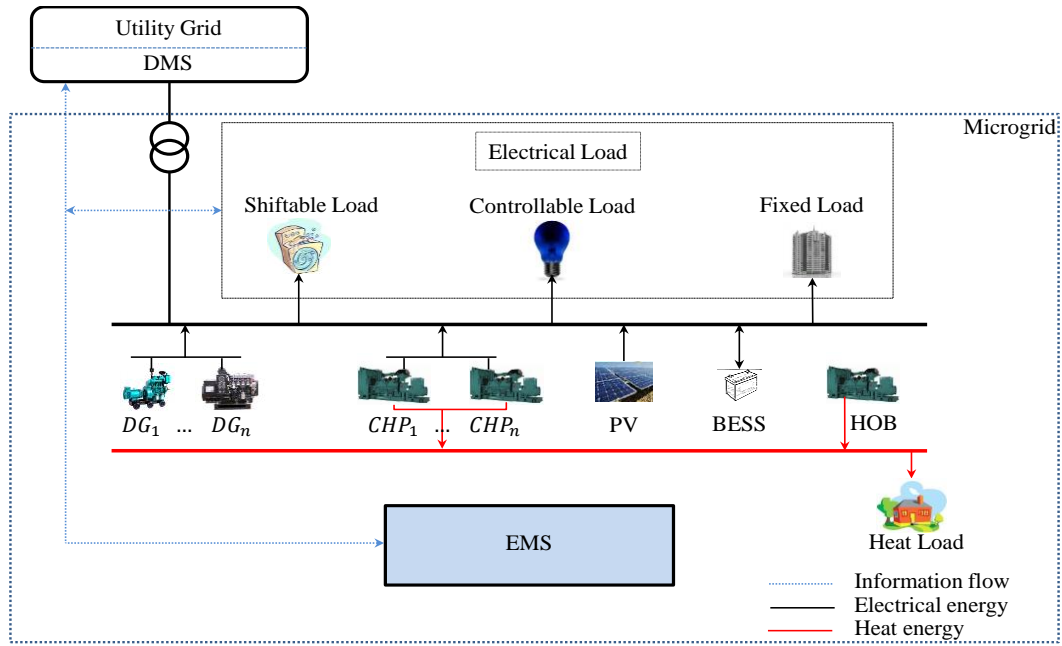


Figure 2. Test Microgrid

Table 2. Forecasted the Photovoltaic Power Generation Output

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Output (kWh)	0	0	0	0	55	75	130	150	170	200	220	250
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Output (kWh)	230	200	140	100	80	0	0	0	0	0	0	0

Table 3. Real the Photovoltaic Power Generation Output

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Output (kWh)	0	0	0	0	55	100	145	170	180	200	210	215
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Output (kWh)	210	200	175	100	60	0	0	0	0	0	0	0

Table 4. Load Data

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Electrical load (kWh)	400	400	395	397	420	455	460	475	490	510	550	600
Heat load (kWh)	100	100	120	123	125	120	130	135	135	140	140	135
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Electrical load (kWh)	600	575	560	550	550	555	540	530	500	490	450	450
Heat load (kWh)	133	130	125	130	130	127	130	130	135	130	130	120

Table 5. Market Price

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Buying price (won/kWh)	30	33	41	54	67	74	78	110	120	130	154	157
Selling price (won/kWh)	15	15	22	34	45	51	55	63	66	80	122	125

Hour	13	14	15	16	17	18	19	20	21	22	23	24
Buying price (won/kWh)	157	154	152	130	100	60	55	49	47	47	44	44
Selling price (won/kWh)	127	126	122	60	50	55	50	40	40	41	41	41

3.2. Day-ahead Scheduling

In this case, the incentive for load shedding is assumed as 160 won/kWh. The microgrid can shift or shed their loads to the off-peak interval by MDCC to minimize their electricity payment. Figure 3 shows the day-ahead scheduling of microgrid with the forecasted output of RESs. Amounts of load shedding and load shifting are dispatched based on the market price by the DR programs. After implementing the DR programs, the load curve is changed as in Figure 3 drawn as a red solid line. The load in the peak interval is shifted to off-peak interval for reducing load demand. The outputs of the distributed generators are determined for power balance with the minimum total cost. BESS is charged during off-peak interval (interval 1, 2) due to the low buying price and is discharged during peak interval because of high buying price.

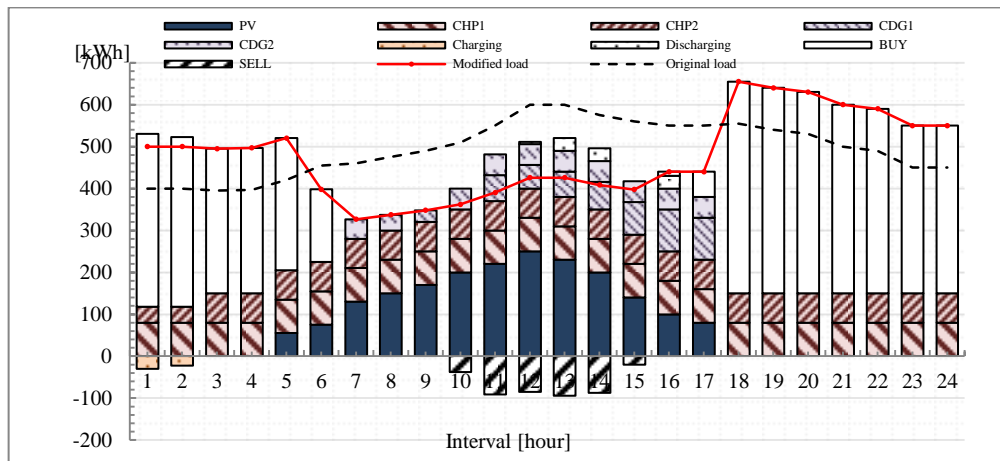


Figure 3. Electric Part in Day-Ahead Scheduling

In this step, the amounts of the reserves are calculated based on the difference between the forecasted and actual outputs of RESs. The minimum amounts of the reserves are determined for each interval based on historical data as shown in Figure 4. In this paper, diesel generators are used for spinning reserves as well as load reserves. The amounts of the reserves will be determined by the real-time scheduling for the stability of systems.

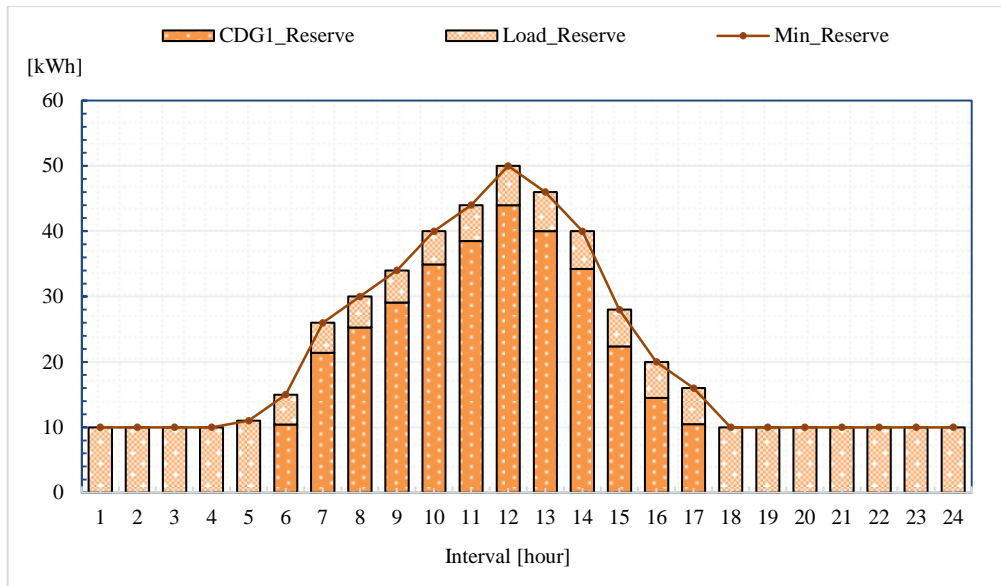


Figure 4. Reserve Part in Day-Ahead Scheduling

Figure 5 shows the amount of CHP and HOB outputs and heat load. It is always ensured that the balance between heat source and heat load for each period of time. Owing to the higher cost of HOB than the cost of CHP, HOB is used in case of the CHP cannot provide the heat load for peak interval. The amount of HOB output is usually small due to its high generation cost. The remaining heat is used to charge the heat energy storage system (HESS) which can be discharged for other intervals. However, in this case, the HESS is not useful because the amount of the remaining heat is small.

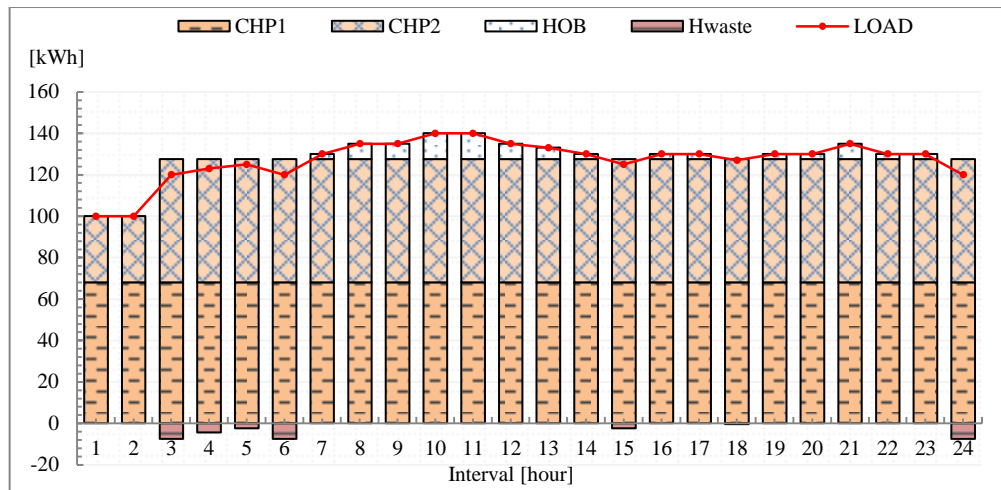


Figure 5. Heat Part in Day-Ahead Scheduling

3.3. Real-time Scheduling

In this step, MGCC can measure the actual RESs output. The microgrid operation is rescheduled based on difference of the forecasted and actual outputs of RESs, as shown in Figure 6. When the amounts of actual outputs are greater than the forecasted outputs of RESs (at interval 6, 7, 8, 9, 15), the amounts of spinning and load reserves, external trading of electric energy with the power grid, the output power of generators, and charging or discharging of BESS are changed. In this case, the amounts of buying and the output power of generators are reduced to achieve the power balance. The spinning and

loads reserves are used to compensate the difference of the forecasted and actual outputs of RESs. Additionally, these reserves can be used for the purpose of minimizing the operation cost based on the market price. For example, during peak interval, the selling price is greater than generator's cost; therefore, the spinning reserves are sold to power grid to maximize the profits. Besides, when the amounts of the actual outputs of RESs are smaller than the forecasted outputs of RESs (at interval 11, 12, 13, 17), the amounts of buying power, load shedding, spinning reserves or the BESS power are changed to achieve the power balance as well as minimize the operation cost of the microgrid.

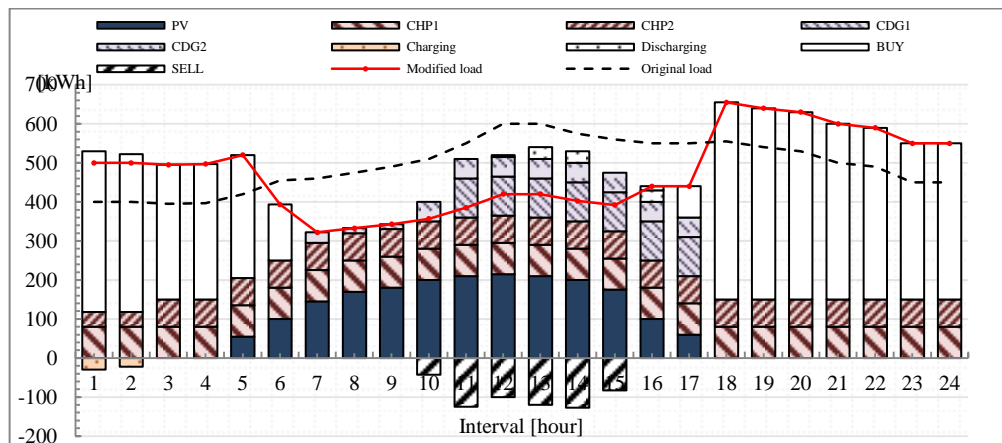


Figure 6. Real-time Scheduling (Rescheduling)

4. Conclusions

In this paper, a two-step mathematical model is proposed for real-time scheduling and demand response based on TOU and EDRP considering uncertainties. The differences between the forecasted and actual outputs of RESs are compensated by spinning and load reserves. Day-ahead scheduling is run in the first step based on the DR programs with the forecasted outputs of RESs and then the real-time scheduling is run in the second step with the actual outputs of RESs. The case study showed that the uncertainties of RESs are handled effectively by the two-step mathematical model and the economic operation of microgrid are achieved by the DR programs based on TOU and EDRP.

As future works, the load forecasting model and the uncertainties of market price will be considered.

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