

Hierarchical Operation Strategies for Grid Connected Building Microgrid with Energy Storage and Photovoltaic Source

Seon-Ho Yoon, Jin-Young Choi, Dong-Jun Won

Abstract—This paper presents hierarchical operation strategies which are minimizing operation error between day ahead operation plan and real time operation. Operating power systems between centralized and decentralized approaches can be represented as hierarchical control scheme, featured as primary control, secondary control and tertiary control. Primary control is known as local control, featuring fast response. Secondary control is referred to as microgrid Energy Management System (EMS). Tertiary control is responsible of coordinating the operations of multi-microgrids. In this paper, we formulated 3 stage microgrid operation strategies which are similar to hierarchical control scheme. First stage is to set a day ahead scheduled output power of Battery Energy Storage System (BESS) which is only controllable source in microgrid and it is optimized to minimize cost of exchanged power with main grid using Particle Swarm Optimization (PSO) method. Second stage is to control the active and reactive power of BESS to be operated in day ahead scheduled plan in case that State of Charge (SOC) error occurs between real time and scheduled plan. The third is rescheduling the system when the predicted error is over the limited value. The first stage can be compared with the secondary control in that it adjusts the active power. The second stage is comparable to the primary control in that it controls the error in local manner. The third stage is compared with the secondary control in that it manages power balancing. The proposed strategies will be applied to one of the buildings in Electronics and Telecommunication Research Institute (ETRI). The building microgrid is composed of Photovoltaic (PV) generation, BESS and load and it will be interconnected with the main grid. Main purpose of that is minimizing operation cost and to be operated in scheduled plan. Simulation results support validation of proposed strategies.

Keywords—Battery energy storage system, energy management system, microgrid, particle swarm optimization.

I. INTRODUCTION

DEPLETION of fossil fuel and needs of reduction of carbon emission make renewable energy generation increased in power system these days. But because of uncertainty and intermittent characteristic of renewable resources, the more increased renewable resources, the more uncertainty in power system is. Recently, introduction of the BESS in microgrid is increased to minimized uncertainty of microgrid. The microgrid normally consists of distributed generation, energy storage system, load, and renewable generation and it is normally grid-

connected, and which is operated isolated in emergency situation. Then, each component is operated by EMS command signal according to its purpose [1], [2]. Grid-connected microgrid normally utilizes energy management techniques that minimize the sum of grid costs at the point of common coupling and internal generation costs [3].

The study on the operation and the grid-connected microgrid is proceeding steadily through thesis or demonstration site. References [3]-[9] introduce a study on microgrid operation. Microgrid is normally operated in grid-connected and isolated modes in emergency case. And it can be operated optimally in each mode [4]. Reference [5] introduces microgrid EMS that shows how to operate microgrid when predicted data differs at actual operation. The energy management system that divides it into two stages and performs the scheduling of each microgrid and the overall optimization is introduced in [6], [7]. The lower EMS and the upper EMS are divided and technique it reduces the amount of centralized EMS computation burden is introduced in [8]. In [9], a method for operating a microgrid with various purposes is introduced.

Compared to existing paper, we present a stepwise algorithm that can reduce the uncertainty and intermittent characteristics of PV in the microgrid and reduce the prediction error of load and PV. We formulate 3 steps to operate microgrid. The first step is a day ahead scheduling of BESS using PSO, which is a heuristic method using predicted PV and load data. Second step is an algorithm that performs real time control compensating the error of the data between the scheduled BESS and the real time value. The third step is to apply rescheduling data instead of day ahead scheduling data when a certain predicted data error occurs.

The rest of paper is organized as: System model and formulation are introduced in Section II. In Section III, case studies and simulation results are given and simulation results are reviewed. Finally, Section IV concludes the study.

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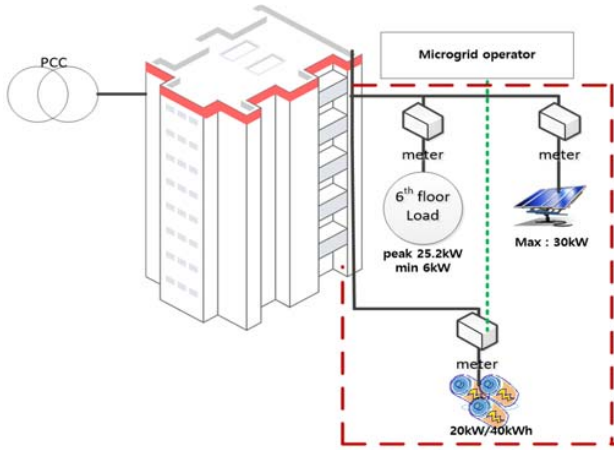


Fig. 1 System architecture

II. SYSTEM MODEL AND FORMULATION

This section presents design of system model and formulation. Fig. 1 shows the architecture of the microgrid we presented which is designed for heat and lamp load of 6th floor of ETRI 12th building. And we consider two types of DG (Distributed Generator) units; PV and BESS.

The microgrid is expected to operate in grid-connected mode to exchange of electricity with grid or in isolated mode in order to conduct isolation mode order. Grid-connected mode means normal operation mode and isolated mode means emergency operation mode. The focus of presented system is to minimize operation cost in each case of microgrid operation mode. In this paper, operation cost is limited to the cost of energy purchase from the main grid

We proposed three hierarchical strategies to operate the microgrid and the presented system operating strategies is illustrated with Fig. 2.

- 1) The first is scheduling the day ahead output of BESS which minimize system operation cost.
- 2) The second strategy is adjusting output of BESS in real time to compensate SOC error between day ahead and real time operation in case of error value within the certain value.
- 3) Last strategy is SOC compensation term same as second strategy. but it conducts when SOC error exceed certain value.

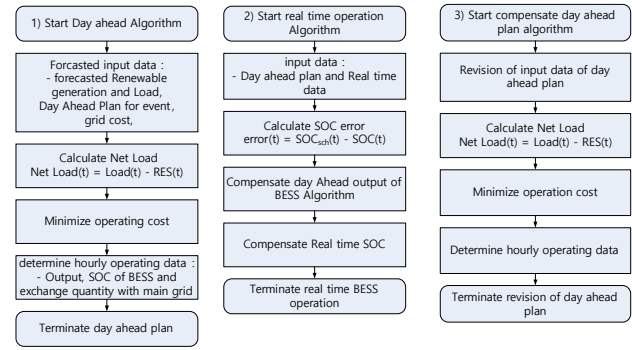
Through these three hierarchical strategies, the presented system can operate properly.

A. System Model Input Data

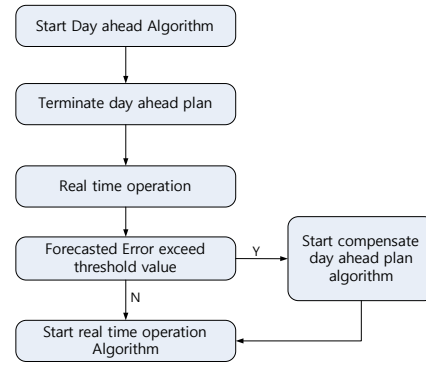
For scheduling day ahead output of BESS, forecasted load data are suitable. But, there is not forecasted system in current system, so we use historical load data instead of forecasted data. Fig. 3 shows historical load data of the presented microgrid.

Load has different patterns according to the weekday or weekend and season. On weekdays, it normally increases rapidly at 8 A.M. and decreases rapidly at 6 P.M. depending on working hour. On weekend, because there is only critical load being operated, load pattern has plat characteristics as

compared with weekdays'.



(a) Flowchart of operation strategies for each stage



(b) Flowchart of system operation strategies

Fig. 2 System operation strategies

We use hourly forecasted PV generation as shown in Fig. 4. It increases gradually starting at 7 A.M. when sun rises, it reaches peak between 12 P.M. and 2 P.M. and decreases gradually after peak.

For grid cost, we use two types of cost, SMP (System Marginal Price) which has small variation and PJM (Pennsylvania Jersey Maryland) LMP (Local Marginal Price) which has large variation between peak time and off peak time.

B. Objective Function and Constraint Condition

BESS is only controllable resource of DG (distributed generator) in this system and we set it as only variable that makes operation cost minimize for day ahead plan.

Objective function which makes operation cost minimize is shown as:

$$\min F = \sum_{t=1}^{24} [\text{price}_{\text{grid}}(t) \times P_{\text{grid}}(t)] \quad (1)$$

It minimizes operation cost caused by exchanged power with main grid for 24 hours. And we set (2)-(9) for a constraint condition:

$$P_{\text{grid}}(t) = P_L(t) - P_{\text{PV}}(t) - P_{\text{BESS}}(t) \quad (2)$$

$$P_{load}(t) = P_{DR}(t), (T_{DR1} \leq t \leq T_{DR2}) \quad (3)$$

$$P_{grid}(t) = 0, (T_{out1} \leq t \leq T_{out2}) \quad (4)$$

$$-P_{BESS}^{rate} \leq -P_{BESS}^{max} \leq P_{BESS}(t) \leq P_{BESS}^{max} \leq P_{BESS}^{rate} \quad (5)$$

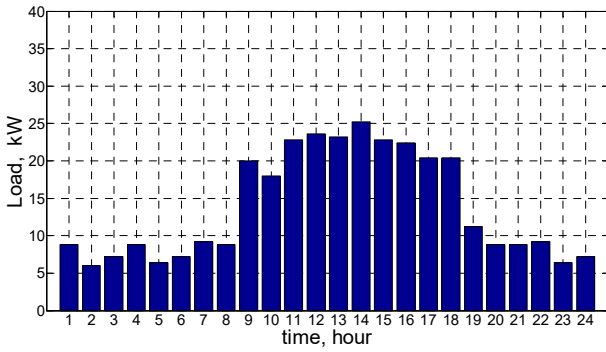
$$S_{BESS}(t) - S_{BESS}(t-1) = -\frac{1}{\eta_{dch}} \frac{P_{BESS}(t)}{E_{BESS}^{rate}}, (P_{BESS}(t) > 0) \quad (6)$$

$$S_{BESS}(t) - S_{BESS}(t-1) = -\eta_{ch} \frac{P_{BESS}(t)}{E_{BESS}^{rate}}, (P_{BESS}(t) < 0) \quad (7)$$

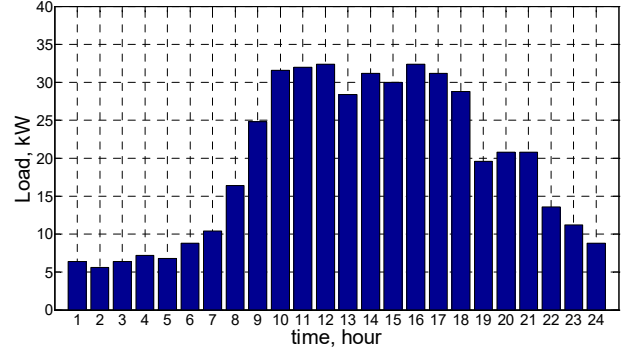
$$S_{BESS}^0 = S_{BESS}(t=1) = S_{BESS}(t=T+1) \quad (8)$$

$$0 \leq S_{BESS}^{min} \leq S_{BESS}(t) \leq S_{BESS}^{max} \leq 100[\%] \quad (9)$$

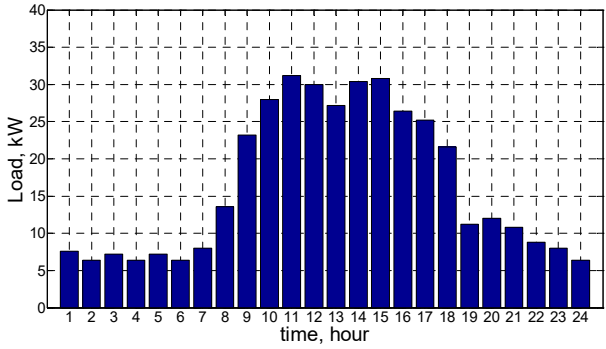
Equation (2) considers exchanged power with main grid to balance demand and generation difference. Equations (3), (4) restrict power flow of load and main grid for a demand response and net zero period. Equations (6), (7) consider State of Charge (SOC) level caused by charging or discharging of BESS. Equation (8) limits the same SOC level at first and last time of scheduling. Equations (5)-(9) consider upper and lower boundary of available capacity.



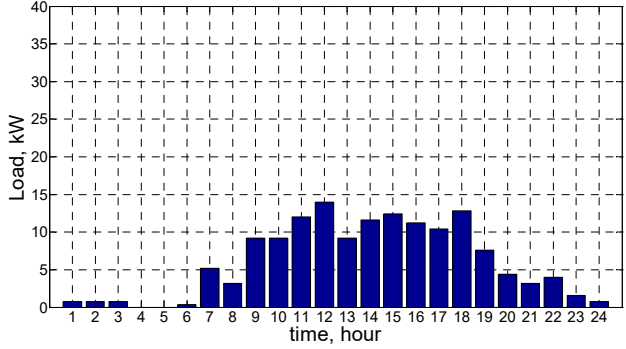
(a) Weekday, winter



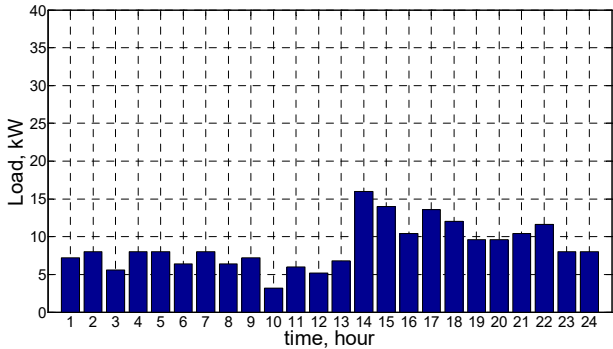
(b) Weekday, spring



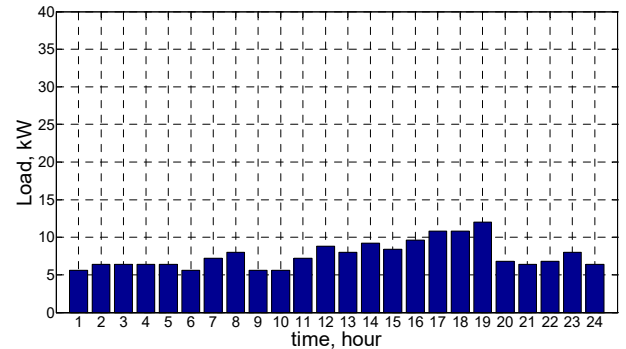
(c) Weekday, summer



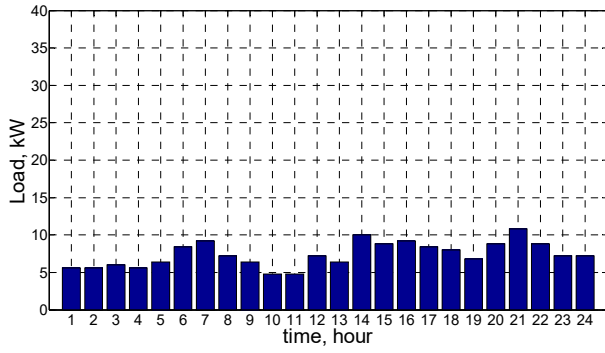
(d) Weekday, fall



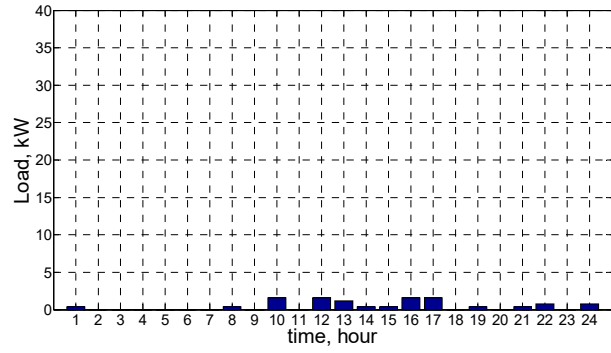
(e) Weekend, winter



(f) Weekend, spring



(g) Weekend, summer



(h) Weekend, fall

Fig. 3 Load data

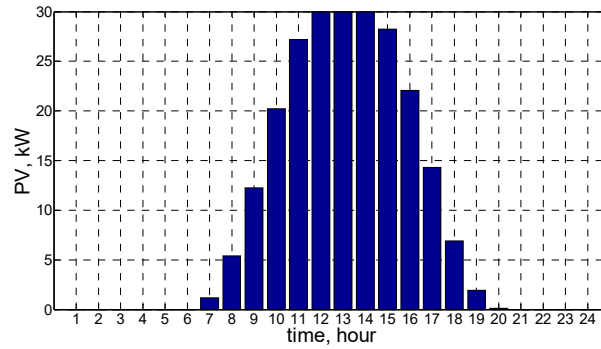
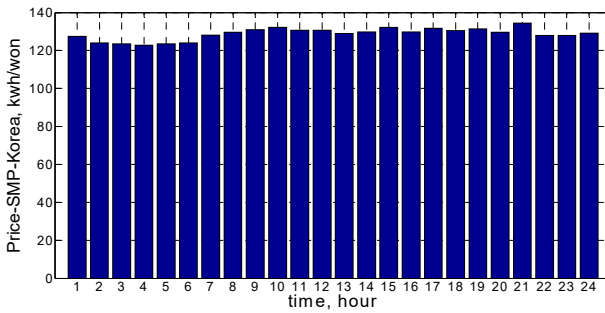
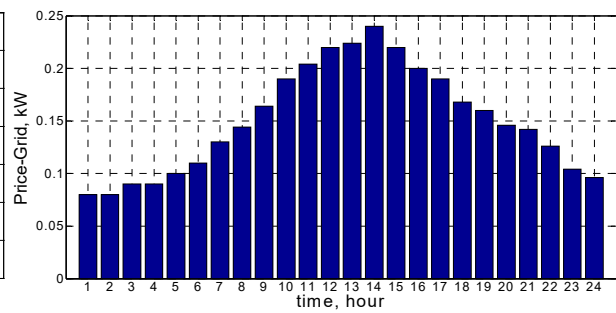


Fig. 4 PV generation data



(a) Korea SMP data



(b) PJM LMP data

Fig. 5 Price data

TABLE I
BESS OUTPUT/CAPACITY CHARACTERISTIC

Characteristic	Value
P_{BESS}^{rate}	20kW
E_{BESS}^{rate}	40kWh
S_{BESS}^{max}	90%
S_{BESS}^{min}	10%
$\eta_{dch} \cdot \eta_{ch}$	60%
S_{BESS}^0	60%

C. Real Time Operation Algorithm

When the BESS is operated scheduled power, it can have an error between day ahead scheduled SOC and real operated SOC. Because efficiency can vary over SOC level and output of inverter can differ from scheduled power in real operation. And it can have a problem when SOC error exceeds certain range, so it needed to compensate the SOC error by compensating output of BESS Fig. 6 shows the idea of compensating algorithm and formulated in PSCAD/EMTDC tool to verify compensating algorithm. Table II shows compensating output power of BESS according to SOC error range.

TABLE II
COMPENSATING OUTPUT POWER OF BESS

SOC range	Output power of BESS
$-0.05 < SOC_{sch} - SOC(t) < 0.05$	$P_{compen} = 0 p.u.$
$0.05 < SOC_{sch} - SOC(t) < 0.1$	$P_{compen} = -0.1 p.u.$
$SOC_{sch} - SOC(t) > 0.1$	$P_{compen} = -0.2 p.u.$
$-0.1 < SOC_{sch} - SOC(t) < -0.05$	$P_{compen} = 0.1 p.u.$
$SOC_{sch} - SOC(t) < -0.1$	$P_{compen} = 0.2 p.u.$

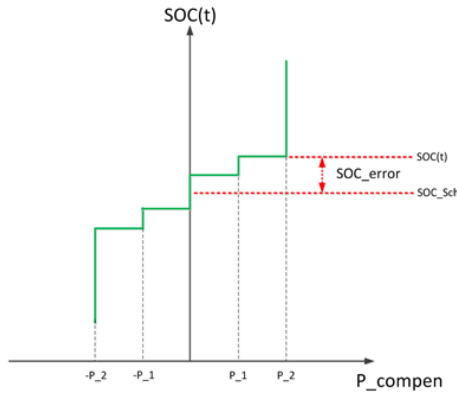
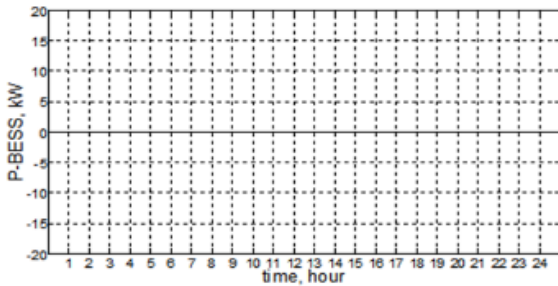


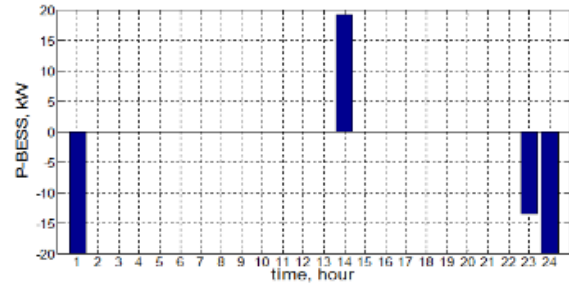
Fig. 6 Idea of compensating SOC error

III. CASE STUDY AND SIMULATION

Considering operation scenario like Table III, we consider different type of grid cost for each scenario, SMP for KOREA and LMP for PJM.



(a) Korea SMP



(b) PJM LMP

Fig. 7 Simulation results of Basic results

2. Case 2 – Net Zero Mode

Fig. 8 shows the simulation result with LMP considering net zero mode at 7 p.m. using input data like Case 1. In addition to BESS output pattern in basic case, it is charged at 5 p.m. and 6 p.m. and discharged at 7 p.m. for net zero mode as in Fig. 8. First of all, BESS is discharged at 7 p.m. for net zero mode and it is discharged at 2 p.m. and charged at 1 a.m., 11 p.m. and 12 p.m. which is the cheapest time for the arbitrage and charged for the net zero at 5 p.m. and 6 p.m. which is the cheapest time before the net zero time.

TABLE III
OPERATION SCENARIO

Day ahead Operation scenario	Cost of power exchanged with Main grid
Basic case	PJM LMP
	Korea SMP
Net zero process	PJM LMP
	Korea SMP
Demand response process	PJM LMP
	Korea SMP

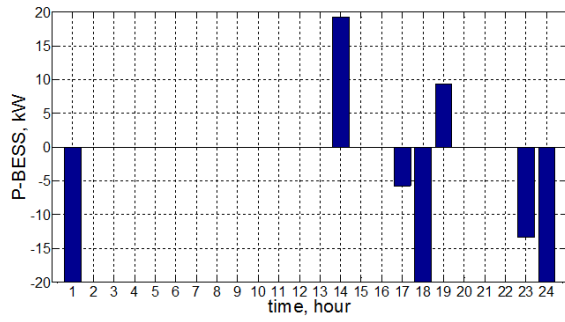
A. Day Ahead Operation

Objective function is minimized using PSO method using historical PV in Fig. 4 and load data in Fig. 3 (a) and considering demand response and net zero mode, BESS constraint condition.

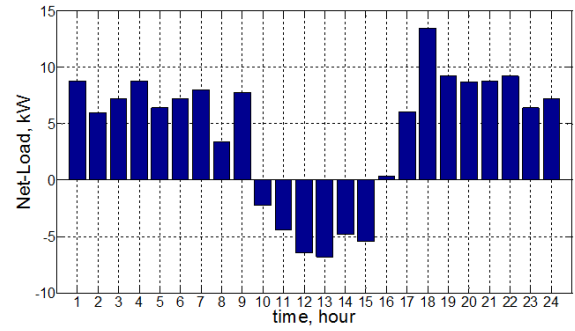
1. Case 1 – Basic Case

BESS output is hourly scheduled to minimize the cost of power exchanged with main grid in Fig. 7. BESS output is not deployed on Korea SMP and it can be analyzed that cost of discharging and charging efficiency loss is bigger than the profit of the arbitrage, but it is shown that output of BESS is deployed with PJM LMP data that has large variability. It is charged at 1 a.m. when the LMP is the cheapest and discharged at 2 p.m. when the LMP is the most expensive and after that it is charged at 11 p.m. and 12 p.m. to satisfy SOC constraint condition. Because efficiency of BESS is 60%, BESS output pattern is determined minimizing occurrence of charging and discharging and considering grid cost variability and SOC constraint condition.

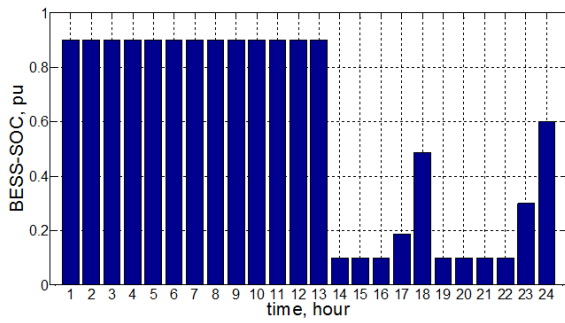
Fig. 9 provides the results using KOREA SMP instead of PJM LMP. In addition to KOREA SMP basic case, it is charged at 4 a.m., 10 p.m. and 11 p.m. and discharged at 7 p.m. to process net zero. Because there is no variability and hourly characteristics in Korea SMP, BESS is not deployed for arbitrage. It is fully charged at the cheapest time, 4 a.m. and charged separately the rest capacity in 10 p.m. and 11 p.m. which is the cheapest time after net zero time for SOC constraint.



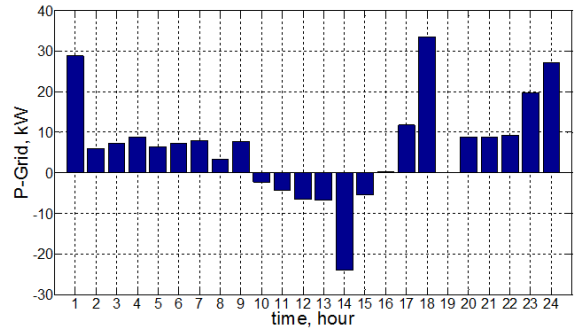
(a) Output of BESS



(b) Net_Load(Load-PV)

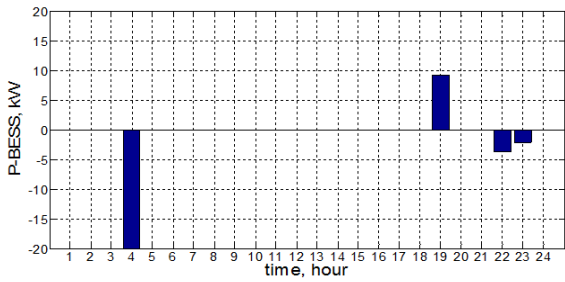


(c) SOC of BESS

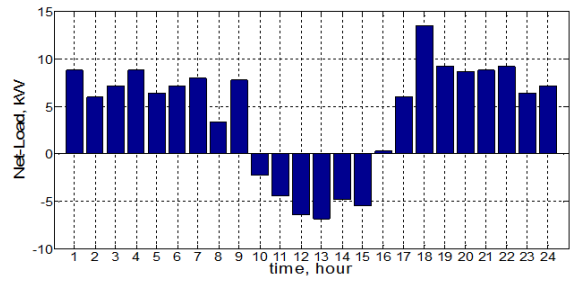


(d) Exchange power with main grid

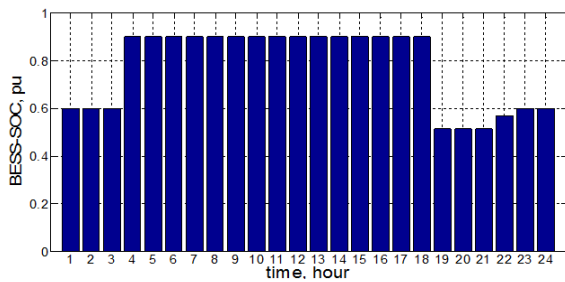
Fig. 8 Simulation results of Net zero mode with PJM data



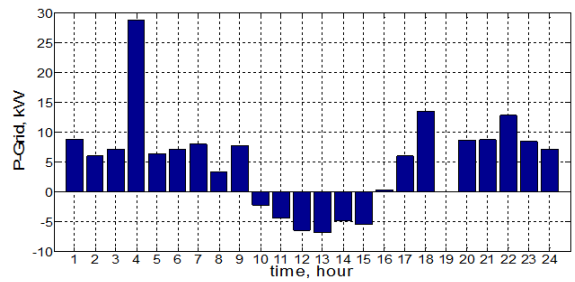
(a) Output of BESS



(b) Net_Load(Load-PV)



(c) SOC of BESS



(d) Exchange power with main grid

Fig. 9 Simulation results of Net zero mode with Korea SMP data

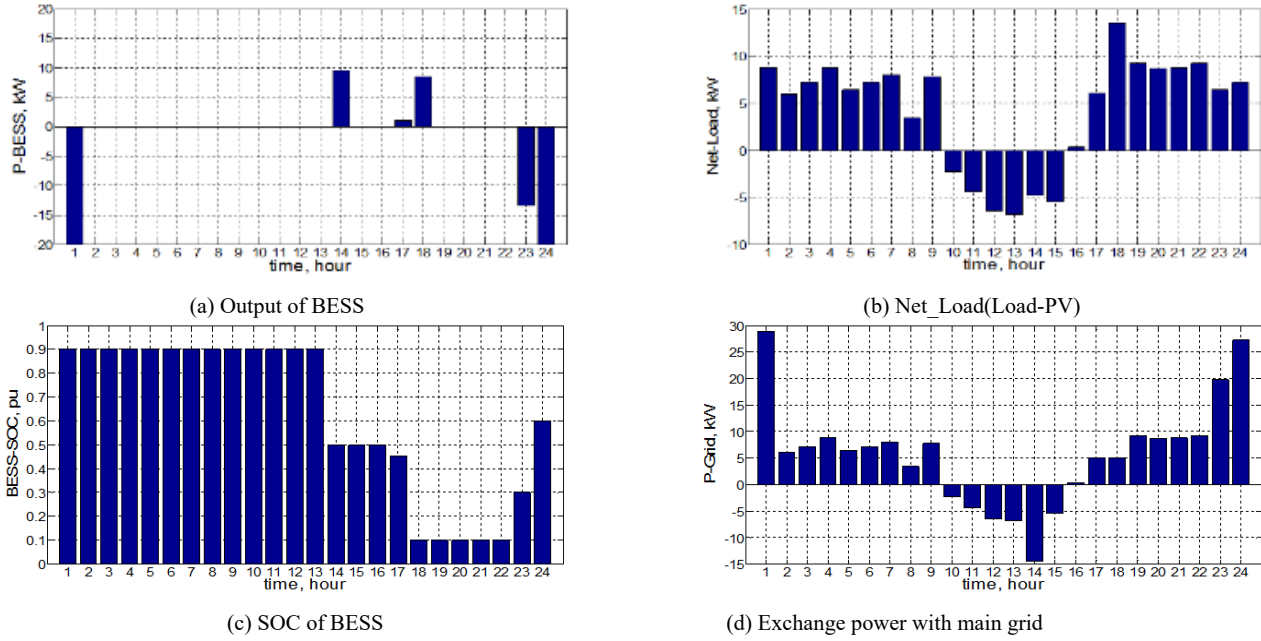


Fig. 10 Simulation results of demand response mode with PJM data

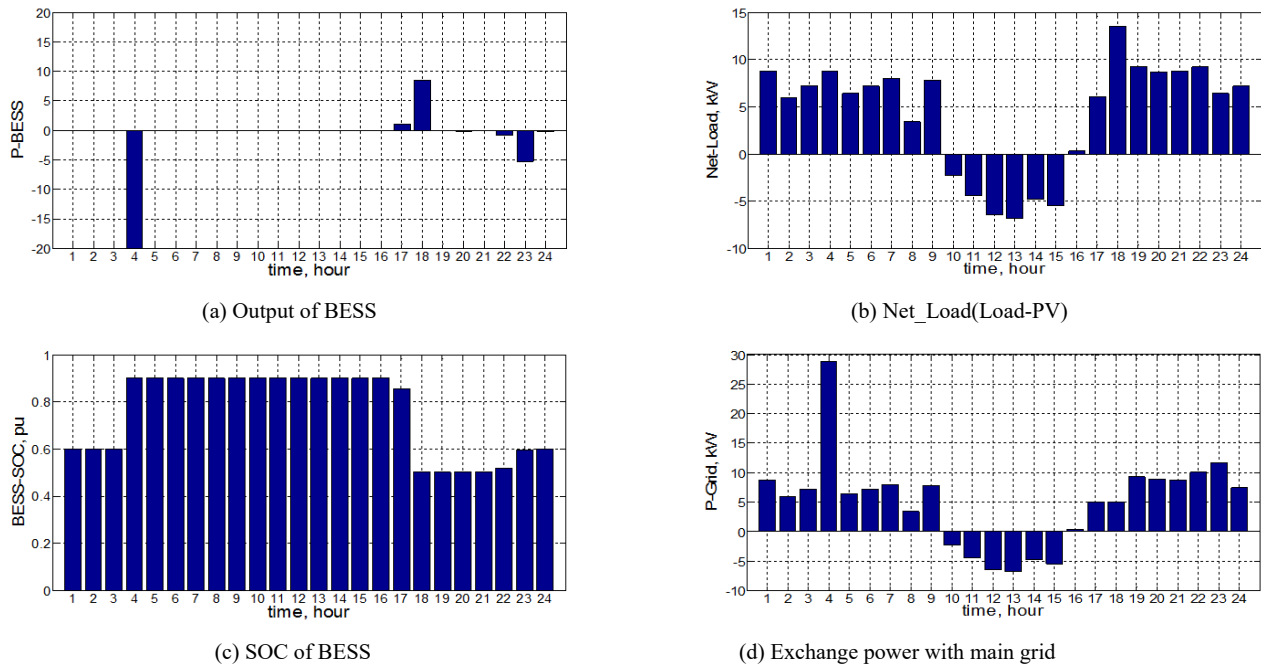


Fig. 11 Simulation results of demand response mode with Korea SMP data

3. Case 3 – Demand Response Mode

Fig. 10 provides simulation results considering demand response instead of net zero mode. In this paper, demand response means that power flow from main grid remains constant to 5 kW during specific hours, 5 p.m. and 6 p.m. It is needed to be discharged to process demand response at 5 p.m. and 6 p.m. and it is discharged at 2 p.m. and charged at 1 a.m., 11 p.m. and 12 p.m. for arbitrage.

Fig. 11 provides the results using KOREA SMP data. It is discharged at 5 p.m. and 6 p.m. to process demand response and charged at 4 a.m. 10 p.m. 11 p.m. to comply SOC constraint. Same as other KOREAM SMP case, it is not deployed for the arbitrage. Because it has no variability of cost for the arbitrage and has low efficiency of the BESS deployment. Demand response case is almost the same case as net zero case. Because there is only one difference between them that is the amount of the power flow from main grid.

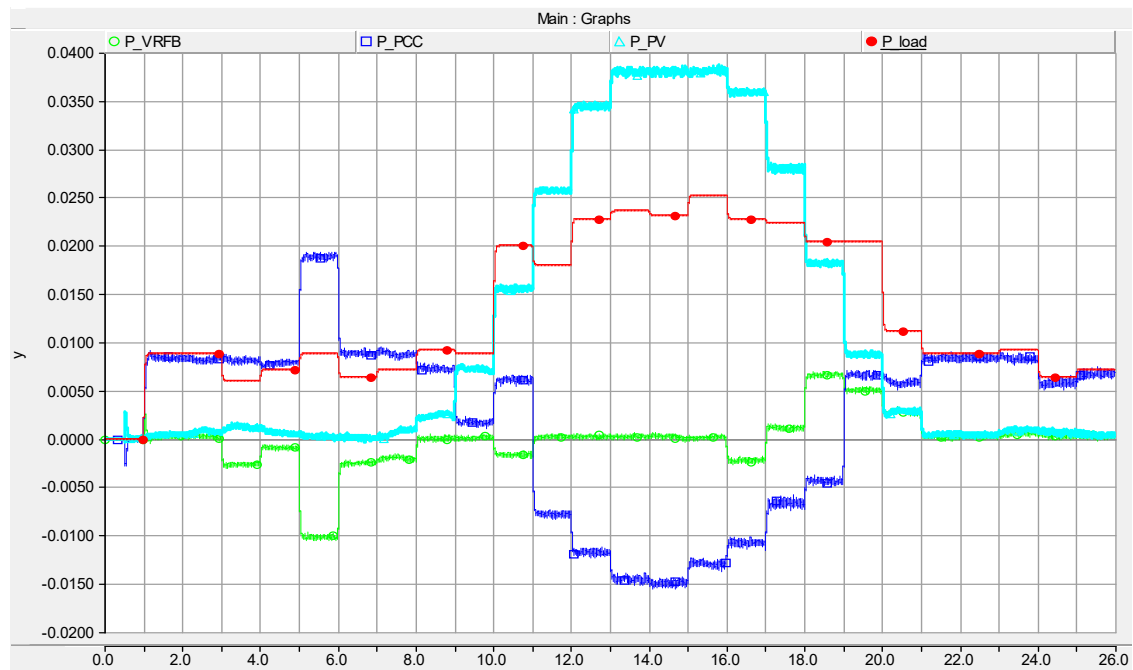
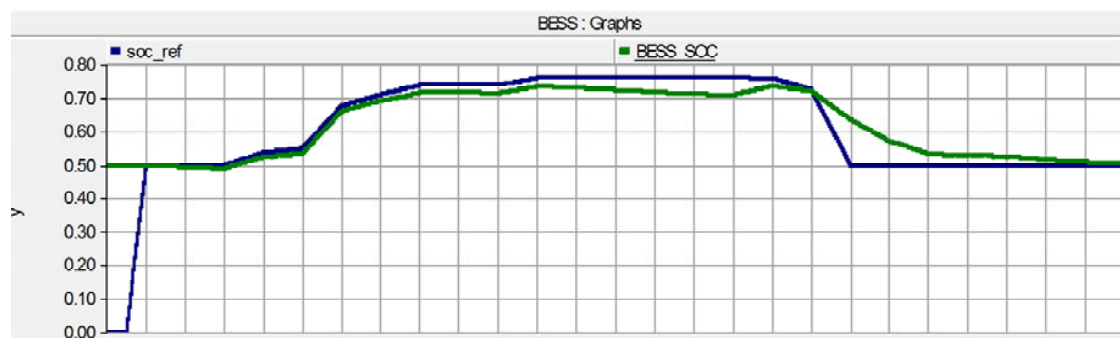
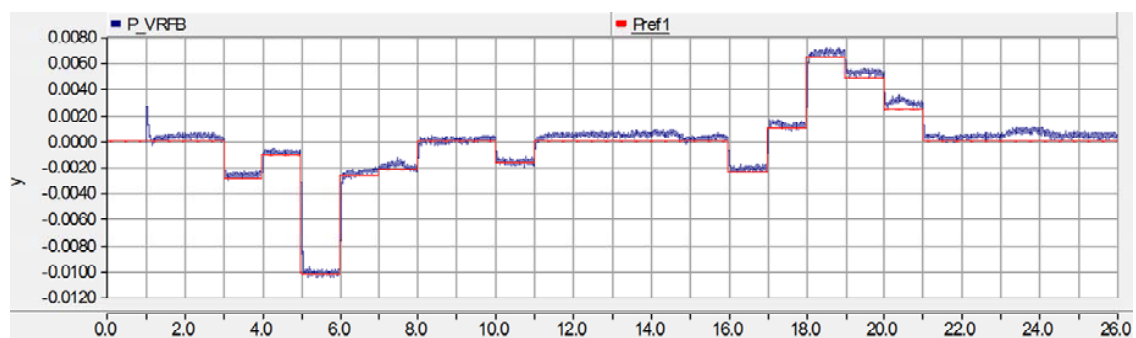


Fig. 12 Dynamic characteristics of scheduled operation



(i) Scheduled and real operated SOC of BESS



(ii) Scheduled and real operated output of BESS

(a)

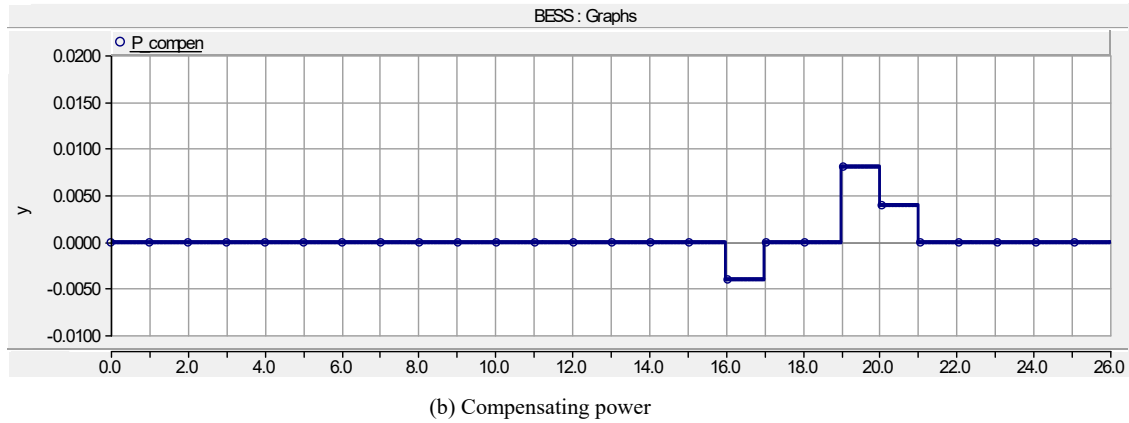


Fig. 13 Results of compensating SOC error

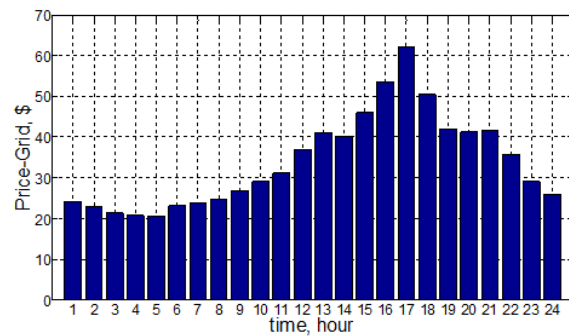
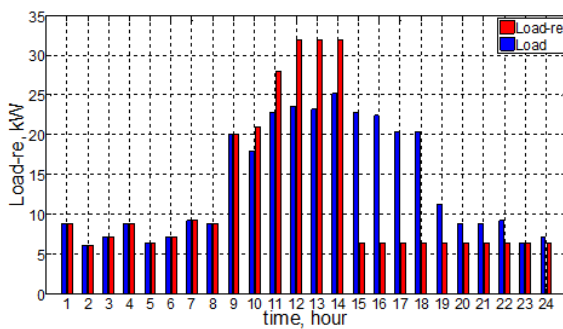


Fig. 14 Modified and forecasted load data and grid cost

B. Real Time Operation Algorithm

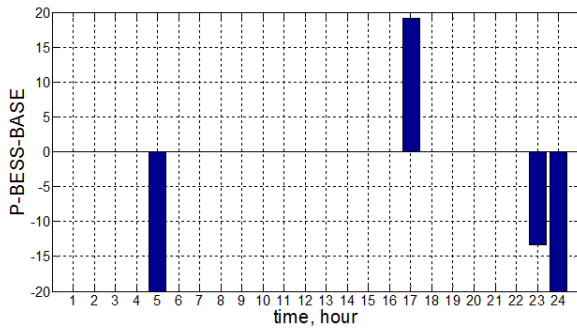
Day ahead scheduled output of BESS is used as input data and add compensating SOC error to BESS output in PSCAD/EMTDC simulation. Fig. 12 provides dynamic characteristics of system model operated using day ahead scheduled data. And Fig. 13 shows simulation results compensating SOC error. In Fig. 13 (a) (i), there is difference between scheduled and real operated output of BESS. Because of that and efficiency according to SOC level, real operated and scheduled SOC has an error shown as Fig. 13 (a) (i). And Fig. 13 (b) (ii) shows output of compensating output power of BESS according to SOC error algorithm in Table II. In Fig. 13 (a) (i), the end of the scheduled SOC has a little error with real operated SOC. Because of proposed real time algorithm, SOC error can be minimized to properly operate microgrid in scheduled plan.

C. Real Time Rescheduling Algorithm

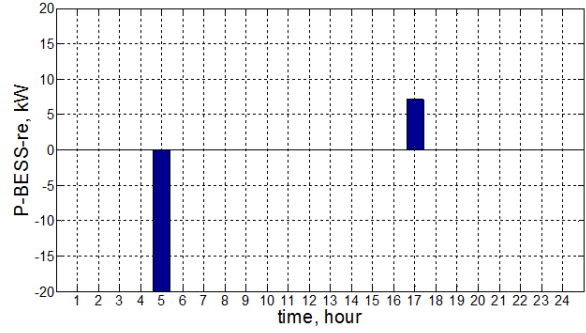
Input data which are forecasted load, grid cost and PV output using day ahead scheduling can be different from data in real time operation. If an error exceeds certain value, microgrid cannot be operated in minimized operation cost scheduled in day ahead plan. It is needed to have an additional algorithm to be operated in minimized cost. It is presented in Fig. 2 (a).

Rescheduling Algorithm corrects scheduled output of BESS according to modified input data and initial SOC of BESS. In this paper, it is assumed that only forecasted load data has an error and modified properly in rescheduling algorithm. Fig. 14 shows the modified and forecasted load data and grid cost which is used in rescheduling algorithm.

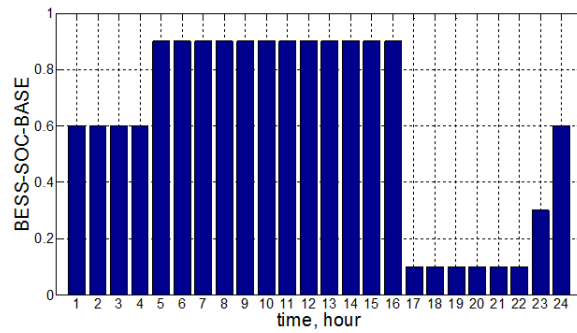
Fig. 15 shows that the system can reduce operation cost by 20% during 24 hours by rescheduling compared to existing scheduling. The scenario used in rescheduling is extreme and simple, but it is the simulation result that shows why rescheduling is necessary.



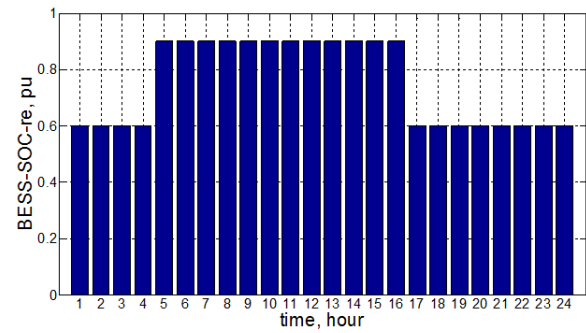
(a) Forecasted BESS output



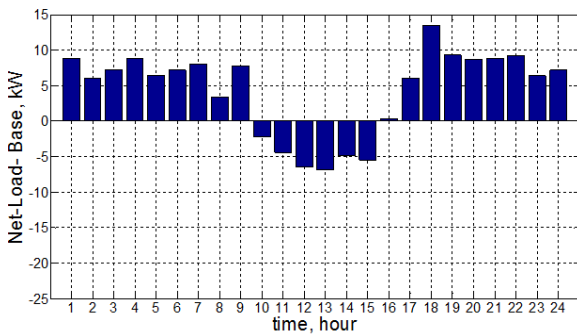
(b) Modified BESS output



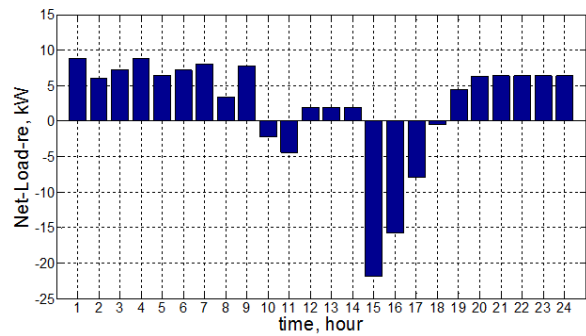
(c) Forecasted BESS SOC



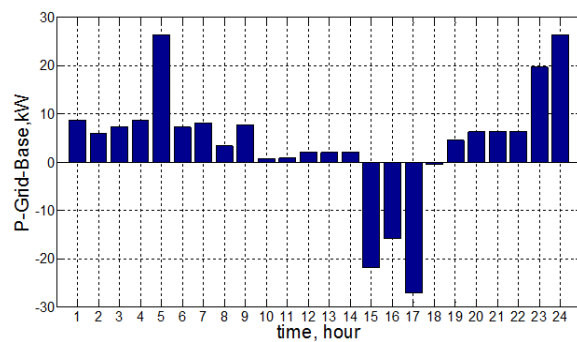
(d) Modified BESS SOC



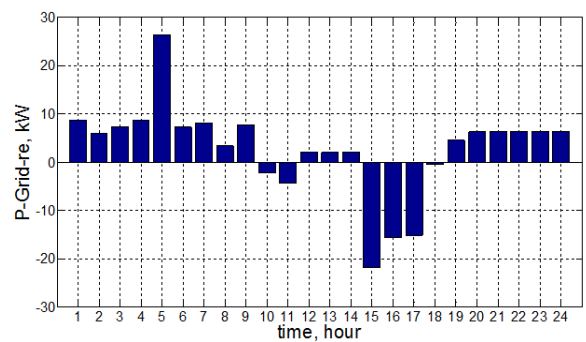
(e) Forecasted Net Load



(f) Modified Net Load



(g) Forecasted Grid power



(h) Modified Grid power

Fig. 15 Forecasted and modified data

IV. CONCLUSION

In this paper, we set up a microgrid operation and control plan in three steps. First, we set up the operation plan of microgrid using full day scheduling. Second, for normal operation of ESS used for scheduling, we added SOC compensating output in real time operation. Third, we planned the rescheduling when the error of predicted input data occurs. Since we used the scenario used for algorithm verification, we can see that the SOC error is large in Fig. 13. The scenario test to be used in actual operation will need to further reduce the error by setting a compensation output that further subdivides the SOC section.

ACKNOWLEDGMENT

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