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A Method for Determining Optimal Capacity of Virtual Energy Storage System Based on Grid-Connected Microgrid for Participation in Electricity Market

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Abstract: With the increasing prominence of renewable energy sources providing flexibility to the power grid, there is a growing recognition of the need to expand virtual Energy Storage Systems (ESS) to replace traditional ESS, which faces challenges in terms of supply and scalability. Grid-connected microgrids can supply power stably and are being built, so they can be used as virtual ESS to provide flexibility to the power system. This study proposes an approach to determine the optimal Power Conversion System (PCS) and battery capacity for a Virtual Energy Storage System(VEES) based on a grid-connected microgrid incorporating Photovoltaic (PV) and ESS. In this paper, it is assumed that microgrids can provide flexibility to the grid by participating in the energy trading market, there are corresponding profits and penalties for order. Numerical examples are performed to demonstrate the effectiveness of the proposed method.

Keywords: virtual energy storage system; grid-connected microgrid; grid flexibility; PV; energy storage system; electricity market

1. Introduction

Recently, due to the expansion of renewable energy such as solar and wind power generation, problems of variability and uncertainty in power balance, and the need to secure system flexibility is increasing to respond to this. Therefore, the role of flexible resources that can provide flexibility to the power system is becoming important, and among them, Energy Storage Systems (ESS) is receiving the most attention among flexible resources because it can contribute to system stabilization with its advantage of their rapid response capabilities [1-2]. However, ESS is difficult to expand its distribution due to its high costs and safety concerns such as fire risks [3].

Accordingly, Virtual Energy Storage Systems(VESS) that can replace ESS is attracting attention. In general, VESS is used like a physical ESS by quantifying the flexibility of temperature control load, and much research is being conducted to model HVAC (Heating, Ventilating, and Air Conditioning) as a VESS. [4-10] developed an HVAC thermodynamic model to model HVAC equipment as a virtual ESS. In [4], the thermodynamic relationship between the indoor temperature and outdoor temperature of a building was modeled mathematically using a first-order thermal equivalent model like an RC circuit. [5] developed a first-order thermal equivalent discrete-time model to supplement the continuous-time model in [4]. [8-10] proposed a thermodynamic modeling approach using LSTM (Long Short-Term Memory) models based on time-series data learning. [11-16] derived parameters for the HVAC thermodynamic model for use as virtual ESS. [11-14] suggested a method for parameter estima-tion based on mathematical models, while [15-16] proposed data-based parameter estimation using machine learning methods like transfer learning and auto-encoders. However, HVAC resources may have limitations in operation depending on external factors such as environmental variables such as temperature and humidity, and occupant comfort. Therefore, there are limits to securing system flexibility by utilizing HVAC resources as a VESS.

Meanwhile, microgrid is expanding, because it can stably supply power, has high utilization of distributed resources such as renewable energy sources and ESS, can be linked to large-scale power systems, and operates independently even in the event of a power outage [17]. A microgrid is consist around various distributed resources, and the role of ESS is especially important. This is because ESS can contribute to the power quality and supply stability of the microgrid by storing power when there is an oversupply of power and supplying the stored power to consumers when demand increases. In particular, microgrids linked to the power system can not only operate the microgrid stably using ESS, but can also provide flexibility by participating in the electricity market. However, existing research on microgrids focuses on the technology required for optimal operation rather than exploring their potential as flexibility resources using VESS modeling [18-22]. Therefore, in this paper, we propose an optimal capacity calculation method to provide grid flexibility by using a grid-connected microgrid consisting of an ESS as a VESS.

The remaining paper is organized as follows. Section II describes the concept of VESS based on the grid-connected microgrid considered in the paper. Section III describes the optimal capacity determination algorithm of VESS for participation in energy market. Section IV presents the numerical example results to demonstrate the effectiveness of the proposed method. The conclusions are presented in Section V.

2. Microgrid and Virtual Energy Storage System for Participation in Energy Market

2.1. Grid-connected Microgrid

A grid-connected microgrid is a power supply system that is integrated with the general power system. As shown in Figure 1, the power system is linked to a microgrid consisting of renewable energy such as PV and WT, energy storage system, and power loads. The power load can receive power from the power system, renewable energy, and ESS. When the power load receives power from the power system, the operating cost of the microgrid is calculated according to the electricity rate, such as time-of-use (ToU), for the amount of power supplied. If power is supplied from renewable energy and ESS, there are no microgrid operating costs.

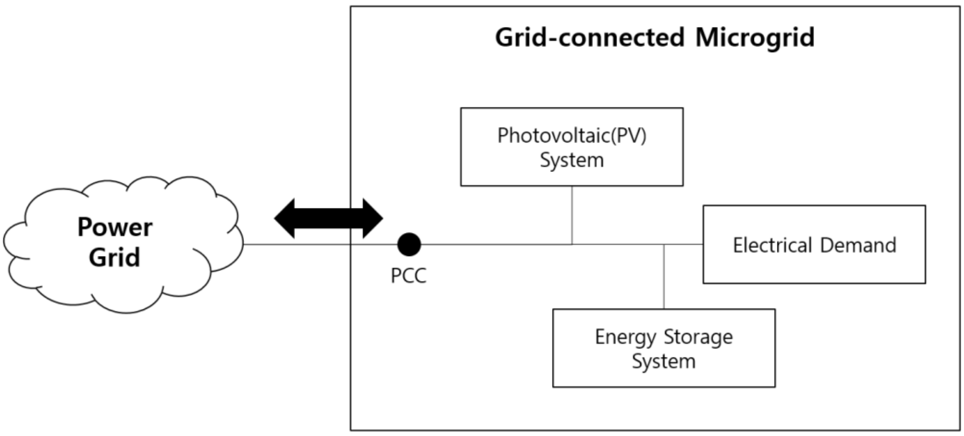

Figure 1. Overview of Grid-connected Microgrid.

In a grid-connected microgrid, the received power is calculated based on the CBL (Customer Base Line) measured at the PCC (Point of Common Coupling), which is a point connected to the power system. The microgrid receives power from the connected power system based on this measurement, and a portion of this power may be stored in the ESS within the microgrid.

2.2. Virtual Energy Storage System

A virtual energy storage system (VESS) is a form that operates in a similar manner to a physical ESS by integrating various controllable elements such as batteries, EVs, thermal demand, smart home,

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and residential load. VESS can store surplus power or supply insufficient power depending on system requirements. As shown in Figure 2, in the case of a grid-connected microgrid, it is possible to provide the same effect as ESS by depending on the relationship between the received power($Pgrid$) and CBL or by adjusting the received power depending based on the remaining capacity of the ESS within the microgrid. For example, assuming that the grid-connected microgrid itself is a VESS, if the received power is increased compared to CBL by charging of the ESS, more power will be supplied to the microgrid, so the VESS will takes the form of charging, and if the received power is reduced compared to CBL by discharging of the ESS, less power will be supplied to the microgrid, so the VESS will takes the form of discharge.

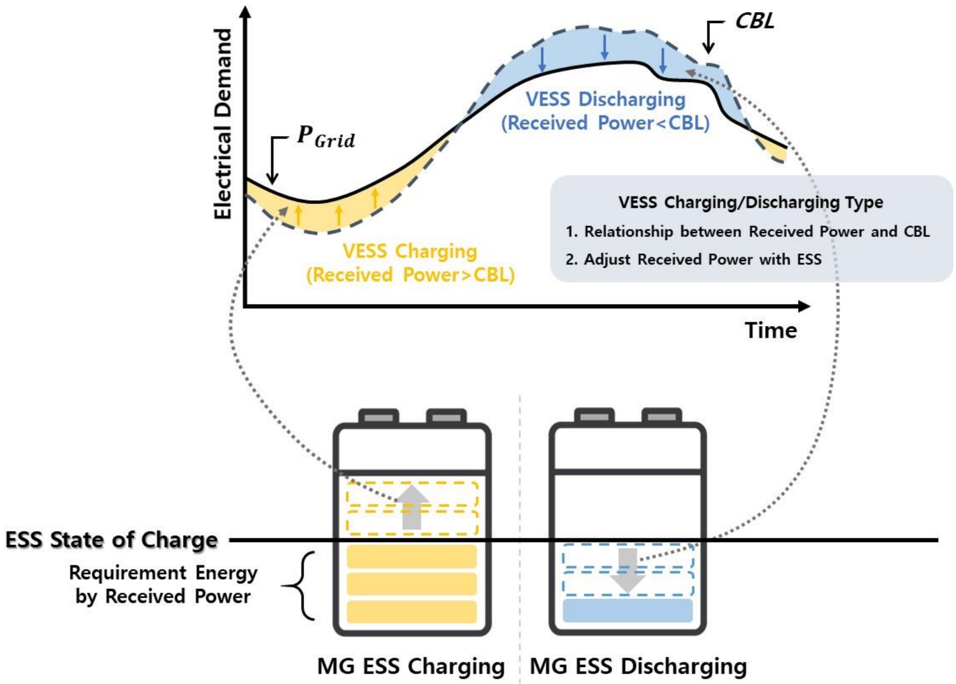

Figure 2. Concept of VESS Charging/Discharging.

Similar to physical ESS, VESS has the potential to provide flexibility to the system and generate revenue through participating in the power market. Therefore, microgrid operators can contribute flexibility to various power markets by utilizing the grid connected microgrid as a VESS.

3. Optimal Capacity Determination Algorithm of Virtual Energy Storage System for Participation in Energy Market

In order for microgrid operators to participate in the power market by utilizing grid-connected microgrids as VESS resources, the supplyable capacity of VESS (that is PCS and battery capacity), must be submitted to market operator, just like ESS was used in the market. At this time, the supplyable capacity of the VESS must be able to satisfy the operating conditions of the grid-connected microgrid and the market operator's command value and command implementation time, and must be a reliable capacity that can minimize the operating cost of the microgrid. Therefore, in this chapter, we present a VESS optimal capacity calculation method based on the 2-Stage Stochastic Decomposition method that can take all of the above conditions into account, as shown in Figure 3, and each stage are described in detail below.

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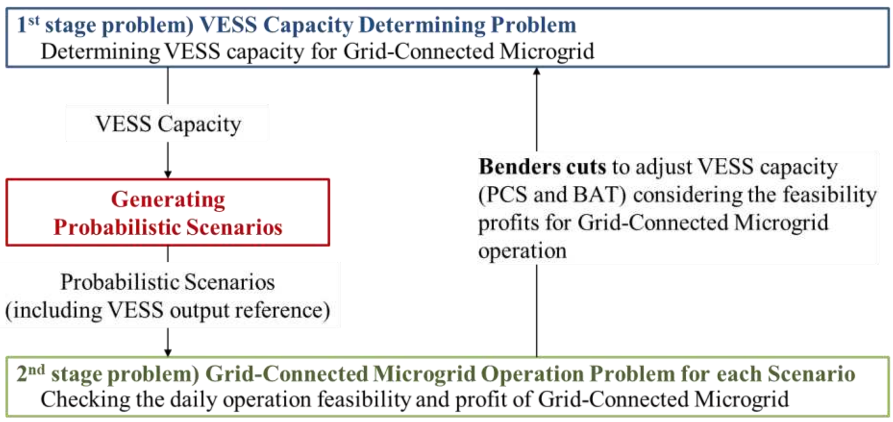

Figure 3. Optimal Capacity Determination Algorithm of VESS based on 2-Stage Stochastic Decomposition.

3.1. 1st Stage Problem

In the first stage, the optimal capacity of the PCS and battery of the VESS to be presented to the market operator is determined. At this time, the capacity is determined considering the order execution time in the microgrid, and the objective function is set to minimize the operating cost (θ) of the grid-connected microgrid.

$$minimize\ \theta, \tag{1}$$

- The VESS Initial SOC Constraint is expressed as follows:

$$iniBATv \leq BATv_{Cap}, \tag{2}$$

$BATv_{Cap}$ is the battery capacity of the VESS and is a decision variable that must be determined in the first stage problem, $iniBATv$ is the initial SOC of the VESS and is a constant.

- The VESS PCS Capacity Constraint is formulated as follows:

$$0 \leq Pvess_{Cap} \leq P_{ess}^{max}, \tag{3}$$

$Pvess_{Cap}$ is the PCS capacity of the VESS and is a decision variable that must be determined in the first stage problem along with $BATv_{Cap}$, and P_{ess}^{max} can output up to the PCS capacity (P_{ess}^{max}) of the ESS in the microgrid.

- The VESS BAT (Battery) Capacity Constraint is expressed as follows:

$$0 \leq BATv_{Cap} \leq BAT_v^{max}, \tag{4}$$

VESS can be used from 0 to the maximum battery capacity of the VESS (BAT_v^{max}) and BAT_v^{max} is a constant that takes into account the battery capacity of the ESS in the microgrid and the SOC upper/lower limit values.

3.2. Generating Probabilistic Scenarios

The market operator, who has the VESS's PCS and battery capacity information, instructs the microgrid operator to supply the power required for electricity market operation. In this step, considering the optimal value of the VESS determined in the first stage, a dedicated charge and discharge order scenarios of VESS to be delivered to microgrid operator is generated. Scenarios are stochastically generated through Monte Carlo simulation based on uniform distribution, as shown in Figure 4. After randomly determining the operation mode (discharge, stop, charge) of the VESS, the order (discharge and charge values) for each time period are determined considering the operation mode of the VESS, the battery capacity of the VESS (that is the VESS SOC), and the PCS capacity.

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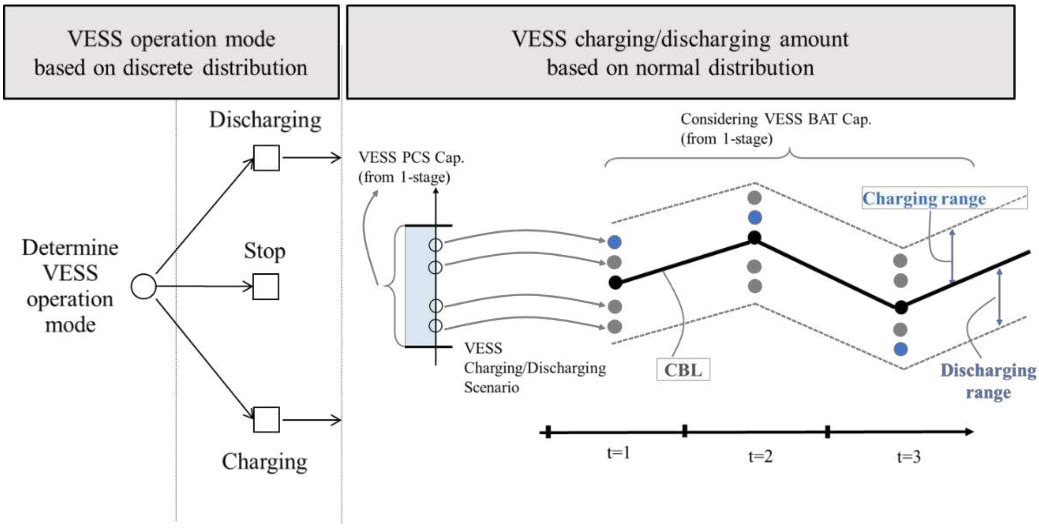

Figure 4. Concept of Generating Probabilistic Scenarios.

3.3. 2nd Stage Problem

In the second stage, it is examined whether it is possible to operate a microgrid while satisfying market orders with the optimal capacity of the PCS and battery determined in first stage. At this time, it is assumed that the grid-connected microgrid can participate in the electric energy trading market as a VESS, and that a penalty exists depending on whether or not the order is implemented. The objective function was set to minimize the cost of purchasing power within the microgrid and maximize the revenue generated from sold power. The charging/discharging power of the VESS ($Pvessc, Pvessd$), received power from the connected power system ($Pgrid$), the ESS charging/discharging power ($PESSc, PESSd$) and microgrid penalty cost ($Pencost$ t) within the grid are decided.

$$minimize\ Z_s = \sum_t TOU(t) * Pgrid(t) - \sum_t (MPd(t) * Pvessd(t) - MPc(t) * Pvessc(t) - Pencost(t)), \quad (5)$$

$\sum_t TOU(t) * Pgrid(t)$ represents the cost of purchasing electricity supplied from the connected power system, and TOU is the electricity rate plan by time. $\sum_t (MPd(t) * Pvessd(t) - MPc(t) * Pvessc(t) - Pencost(t))$ means VESS market profit, where MPd is the unit discharge profit price of VESS, and MPc is the unit charging cost of VESS, $Pencost$ is a penalty cost. Detailed constraints are as follows:

- Power Balance Constraint within the Microgrid

$$Pgrid(t) + PPV(t) + PESSd(t) = PLoad(t) + PESSc(t), \quad (6)$$

$PESSd$ and $PESSc$ are decision variables of the two-step problem. $PESSd$ represents the discharging power of the ESS within the microgrid, $PESSc$ represents the charging power. PPV and $PLoad$are constants, PPV is the power from PV, and $PLoad$ is the demand within the microgrid.

- Upper and Lower Constraints on Received Power

$$Pgrid\_min \le Pgrid(t) \le Pgrid\_max, \quad (7)$$

The received power ($Pgrid$) can supply or receive power up to the transformer capacity at the Point of Common Coupling (PCC).

- Upper and Lower Constraints on ESS Charging/Discharging Amount

$$-1 * PESS\_max \le PESSc(t) \le 0, \quad (8)$$

$$0 \le PESSd(t) \le PESS\_max, \quad (9)$$

ESS can output as much as PCS capacity($PESS\_max$).

- Definition of VESS Charging/Discharging Amount

$$Pvessd(t) + Pvessc(t) = CBL - Pgrid(t), \tag{10}$$

VESS can output an amount equal to the difference between the Customer Base Line (CBL) and the received power.

- Upper and Lower Constraints on VESS Charging/Discharging Amount

$$0 \le Pvessc(t) \le Pvess_{Cap}, \tag{11}$$

$$0 \le Pvessd(t) \le Pvess_{Cap}, \tag{12}$$

The maximum output of VESS is the PCS capacity decided in the first stage.

- Definition of Penalty Cost

$$Pencost(t) = Pen(t) * max|Pvessd(t) + Pvessc(t) - (1 + \alpha) * Ord(t)|, \tag{13}$$

Pen refers to the penalty unit price, Ord is the market command value, and α is the tolerance for the command.

- ESS SOC Constraint

$$ESS\_SOC\_min \le ESS\_SOC(t-1) - ESS\_eff * \frac{PESSc(t)}{ESS\_BAT} - \frac{PESSd(t)}{ESS_{eff} * ESS\_BAT} \le ESS\_SOC\_max, \tag{14}$$

ESS_eff is the efficiency of ESS.

- VESS SOC Constraint

$$0 \le iniBATv + \sum_{k=1}^{t} VESS\_eff * Pvessc(t) - \sum_{k=1}^{t} \frac{Pvessd(t)}{VESS\_eff} \le BATv_{Cap}, \tag{15}$$

$$VESS\_SOC\_min \le VESS\_SOC(t) \le VESS\_SOC\_max, \tag{16}$$

$VESS\_eff$ is the efficiency of the VESS, and in this study, it is assumed to be a constant.

3.4. Bender's Cut

In the second stage problem, the operation schedule of the microgrid and ESS is determined according to the capacity and operation command of the VESS determined in the first stage. Through this, the microgrid operating cost can be estimated, and the operating cost estimation information is added as a constraint to find the optimal capacity in the first stage problem to minimize the microgrid operating cost as follows.

- Constraint on Estimated Operational Revenue Information Based on VESS Capacity

$$\theta \ge \sum_s w_s Z_{dual,s}, \tag{17}$$

$$Z_{dual,s} = A * Pvess_{Cap} + B * BATv_{Cap} + C, \tag{18}$$

$$0 \ge Z_{dual,s}, \tag{19}$$

w_s represents the probability, and $Z_{dual,s}$ means the profit. s is the number of simulations, A, B and C are coefficients that can reflect information on the result of the two-stage.

4. Numerical Example

In this chapter, to verify the proposed method, we numerically tested it under the assumption that grid-connected microgrids participating in the market are only available during specific time periods (3 AM to 1 PM). It was assumed that the microgrid had one PV unit and one ESS unit and had constant values as shown in Table 1 and Figures 5 to 7. Figure 5 shows the ToU and market price

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of the microgrid, Figure 6 shows the predicted and actual power generation of PV, and Figure 7 shows the predicted and actual load and CBL of the microgrid.

Table 1. Parameters for case study.

DER	Parameter	
PV	Capacity	50kW
ESS	Capacity	500kWh
	Charging Limit($PESS\_max$)	100kW
	Discharging Limit($PESS\_max$)	-100kW
	Efficiency(ESS_eff)	0.95%
	Min/Max SOC	20~90%
	Initial SOC	20%
Power System	Grid Max($Pgrid\_max$)	170
	Grid Min($Pgrid\_min$)	-170
VESS	Initial SOC($iniBATv$)	0
	Efficiency($VESS\_eff$)	95%
	Min/Max SOC	0~100%
	Maximum PCS Capacity(P_{ess}^{max})	100
	Maximum Battery Capacity(BAT_v^{max})	350
Pen		SMP
Number of Scenarios(s)		100
Order Time		3H~13H

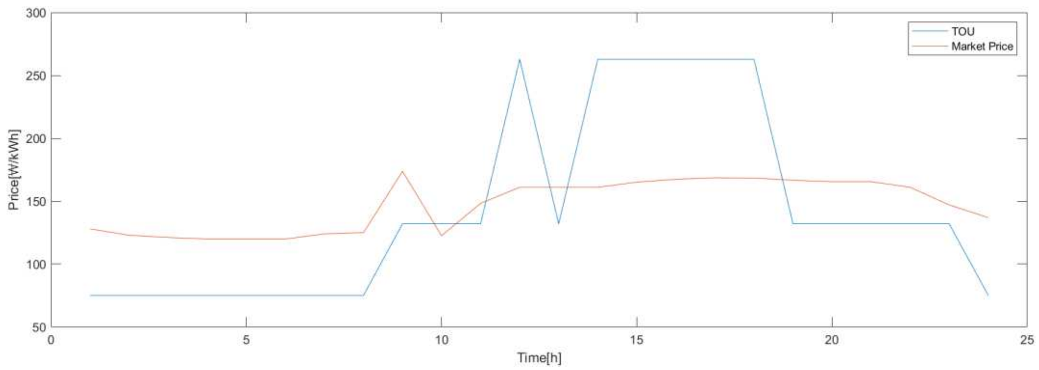

Figure 5. Hourly prices in TOU and Market Price.

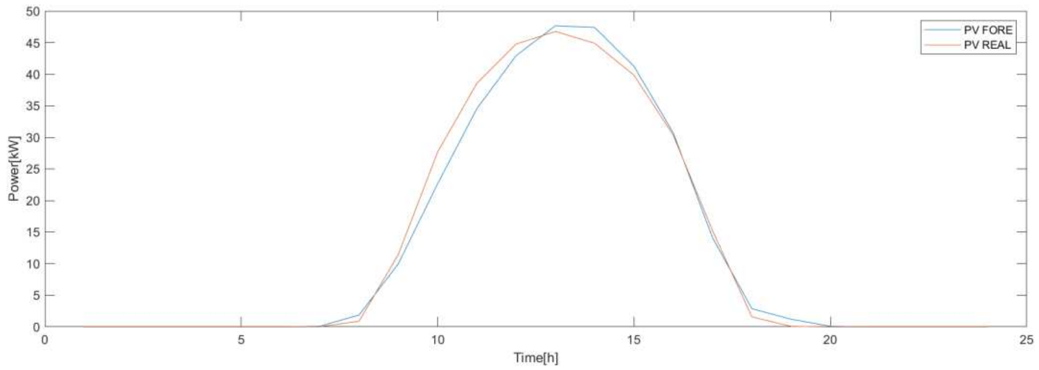

Figure 6. Hourly PV generation profile.

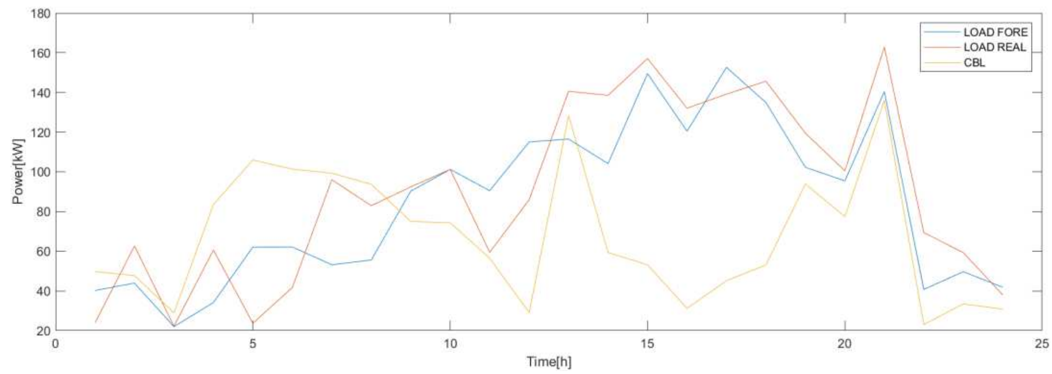

Figure 7. Hourly Load generation profile.

The day before participating in the market, have to present the PCS and battery capacity of the VESS to the market operator. Therefore, an optimization solution was performed using the predicted values of PV and load. In that scenario, the optimal PCS capacity was 35.81kW and the battery capacity was 45.21kWh. The operating status of the microgrid according to this is shown in Figure 8, and the compliance of VESS with market orders is shown in Figure 9. To analyze the flexibility provision capability of the VESS, this study examined whether the VESS complied with order during the available time. During the VESS's available time (from 3 AM to 1 PM, 11 hours), it was confirmed that the VESS satisfied order during all time periods except for one hour, demonstrating compliance for a total of 10 hours.

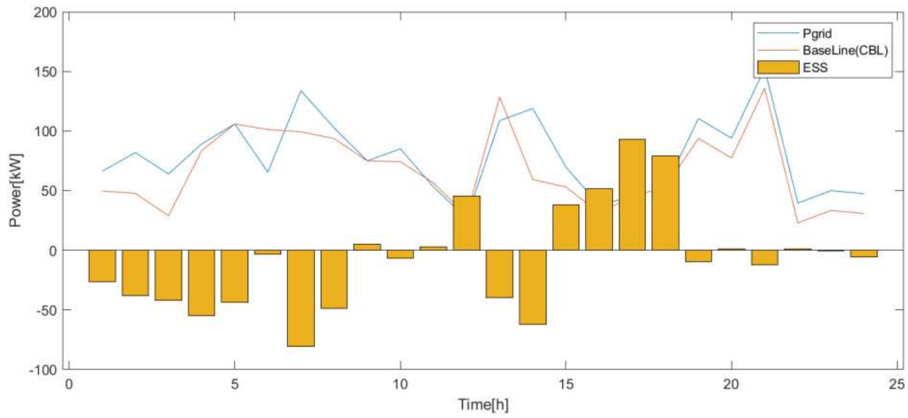

Figure 8. Microgrid operation schedule.

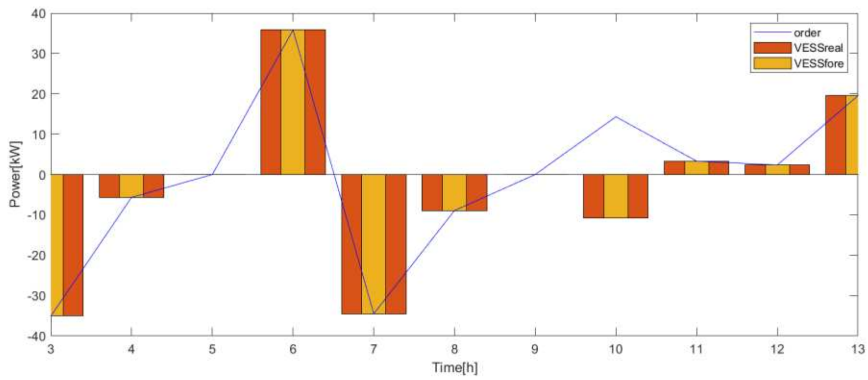

Figure 9. Order Conduction status of VESS.

Figure 9 shows the operation of the VESS the day before and the operation of the VESS on the same day for the same order. Since the PCS and battery capacity were determined based on the assumed scenario environment, we studied whether the flexibility provision capability remained consistent when the actual operational situation deviated from the predicted values, such as PV output or load. Since PCS and battery capacity are capacities calculated in a virtual scenario environment, we studied whether the ability to provide flexibility remains unchanged with the proposed capacity when the PV output or load has an output different from the predicted value in an actual operating situation. As a result, even when applying the real PV value and load value presented in Figures 6 and 7, it was possible to fulfill the order with the capacity presented as the result the day before. And then, these results show that grid-connected microgrid can be used as VESS and provide flexibility.

5. Conclusions

Microgrids can be linked to large-scale power systems and can operate stably due to high utilization of distributed resources. In addition, by exchanging power with the connected power system, it is possible to solve the variability problem caused by renewable energy and ensure flexibility. Therefore, this paper proposes an optimal capacity estimation method based on 2-Stage Stochastic Decomposition that models a grid-connected microgrid as a VESS that can provide flexibility to the power system. The proposed method calculates the PCS and battery capacity in the first stage, and estimates the optimal capacity by examining whether the randomly generated order can be implemented and the microgrid can be operated with the calculated capacity in the second stage. The numerical results showed that using a grid-connected microgrid, not only stable microgrid operation but also providing flexibility to the power system was possible.

In the future, research is needed to advance the VESS modeling of grid-connected microgrids by considering the uncertainty associated with distributed re-sources (PV) and operational directives. This includes methods to account for the uncertainty of distributed resources (such as PV, Load) and market order. Additionally, there is a need for studies on optimal determining the efficiency of VESS based on grid-connected microgrids.

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