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# Control Strategy of BESS for Providing Both Virtual Inertia and Primary Frequency Response in the Korean Power System

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**Abstract:** As the battery energy storage system (BESS) has been considered to be a solution to the diminished performance of frequency response in the Korean power system, in which renewable energy resources (RESs) are expected to increase rapidly, this paper proposes a control strategy for providing both the virtual inertia and primary frequency response considering the MW-scale BESS installed by the Korea Electricity Power Corporation (KEPCO). The benefit of such a fast and flexible BESS can be maximized by the proposed control strategy for making it provide both the inertia and primary frequency response, which would be deficit with the increased RES. In the proposed control strategy, the state of charge (SOC) is maintained in the specific range in which the life cycle is maximized, the interference of SOC recovery by frequency control is minimized, the responding capacity for providing the virtual inertia response is maximized during the transient period, and the performance requirements for frequency response are satisfied. The effectiveness of the proposed strategy is verified by both Korean power system model-based simulation and on-site operations.

**Keywords:** energy storage system; virtual inertia response; primary frequency response; control strategy

## 1. Introduction

The demand for reducing greenhouse gas emissions while increasing the supply of electricity in the electric power industry has led to a rapid increase of the penetration level of renewable energy resources (RESs) in many power systems [1]. Since RESs have lower or no inherent inertia characteristic and limited frequency response capability, many power system operators with high penetration of RESs have faced challenges in maintaining the required frequency control performance [2].

In recent years, as its economics have been improved, the battery energy storage system (BESS) has arisen as an alternative measure to secure frequency stability. Since BESS has especially fast response capability, distinct from the conventional generator, applying BESS to provide frequency response is one of the most widely proposed applications. Moreover, the Korean power system, which has no interconnections with neighboring countries, would attain many benefits from BESS when the penetration level of RESs becomes high. For this reason, the Korean Electric Power Company (KEPCO) has carried forward a plan of MW-scale BESS to provide frequency response [3].

In the power system, the frequency control is usually composed of an inertia response and primary and secondary frequency response [4]. Although only the primary and secondary frequency responses have been managed systematically as system reserves in most electricity markets, the importance of the inertia response increases as the penetration level of RES increases to a very high level. If the

system inertia in the power system decreases more than a certain level, it becomes impossible or very inefficient to maintain frequency response performance using the primary frequency response during a transient period because the frequency could drop below the threshold before the primary response could be delivered [5,6]. As a solution for compensating the performance of the frequency responses with high penetration level of RES, BESS is proposed for providing both the inertia and primary frequency response [7–21]. Since the inertia response and primary frequency control are required to provide response just after a disturbance, BESS is perfectly suitable for providing a rapid response even with a limited energy capacity [10–13]. However, since the BESS provides those responses by discharging the charged energy with the limited energy capacity, it should be able to manage the state of charge (SOC) to be ready to respond to a disturbance in a long-term operation [16–18]. There are also operating conditions of BESS to be considered for maximizing its benefits.

For accomplishing this, this paper proposes a control strategy of the BESS for providing both the inertia and primary frequency maximizing its fast and flexible capability. The proposed control strategy also considers various aspects of BESS such as maintaining the SOC in the specific range in which the life cycle is the longest, minimizing the interference of SOC recovery with frequency control, maximizing the responding capacity for providing a virtual inertia response during a transient period, and meeting the performance requirements for frequency response. Its effectiveness is especially verified not only by the short-term and long-term simulation but also by on-site operation results in this paper. Accordingly, the MW-scale BESS installed by KEPCO has been contributing effectively to the frequency control by using the proposed control strategy since it began commercial operation in the Korean power system.

## 2. Application of BESS for Frequency Response Service in the Korean Power System

### 2.1. Frequency Control in the Korean Power System

As the frequency is a major parameter indicating the balance between generation and demand of a power system, it is controlled in the Korean power system by providing frequency control services. The frequency control services consist of primary and secondary frequency control, which are provided by the resources' local responses and the automatic generation control (AGC) central response, respectively, as shown in Table 1.

**Table 1.** Frequency control services in the Korean power system.

	Category	Capacity
Frequency Control	Primary Frequency Control (Governor and ESS)	1500 MW
	Secondary Frequency Control (AGC and ESS)	

The primary frequency control is the frequency response provided mainly by the generator's governor, and ESS was permitted to participate in the primary frequency control service in 2015. Table 2 summarizes the requirements for providing the frequency response service defined in the Korean electricity market rule [22].

**Table 2.** Requirements for primary frequency control in the Korean power system.

Requirement	Value
Responding Time	Activation time: within 10 s
	Duration time: at least 30 s
Speed Droop	Hydro turbine: 3.0–4.0%
	Combustion turbine: 3.0–4.0%
	Gas turbine: 4.0–5.0%
	Steam turbine: 5.0–6.0%
	Electric Energy Storage: less than 2.0%

In addition, in the Korean power system, the frequency response is evaluated by using two indices, the speed droop and the response quantity. The speed droop is evaluated by calculating the ratio of the responding amount of a generator power to the frequency change in percentage. The responding quantity, which is defined as the governor free response quantity (GFRQ), is evaluated by the difference between outputs before and after the disturbance using the Equation (1):

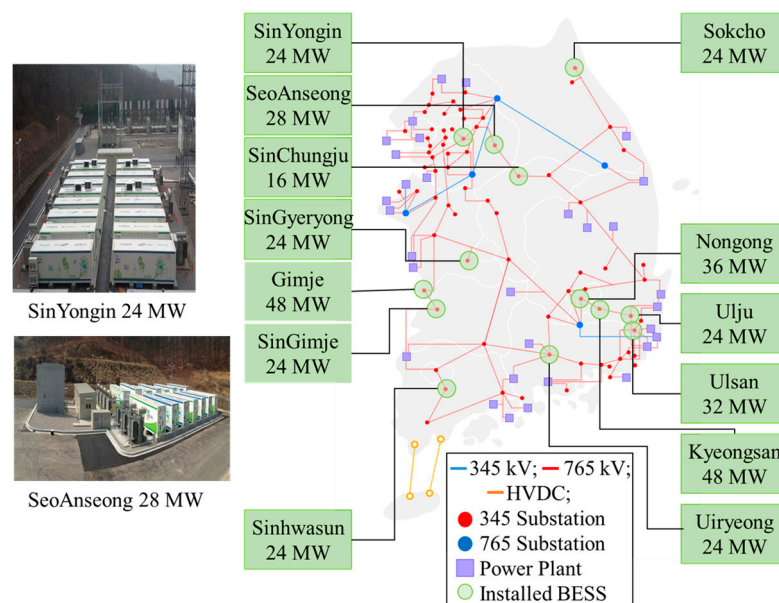
$$GFRQ = \frac{1}{50} \sum_{t=10}^{60} P_{t_{at\ 59.8Hz+t}} - \frac{1}{20} \sum_{t=0}^{20} P_{t_0-t}, \quad (1)$$

where  $t_0$  is the time of a disturbance,  $t_{at\ 59.8Hz}$  is the time of reaching 59.8 Hz after the disturbance, and  $P_t$  is the power at time  $t$ .

The secondary frequency control is provided by participating resources' responses to the AGC frequency control signal, which are determined by the energy management system (EMS). All generators, except for the nuclear generators, participate in the secondary frequency control service. ESS was permitted to participate in the secondary frequency control service in 2016, but it is not yet participating.

## 2.2. BESS for Providing Frequency Response in the Korean Power System

KEPCO announced a plan to install MW-scale BESS to provide a frequency response in 2015. According to the plan, a BESS of 376 MW is being operated commercially to provide the frequency response by KEPCO in 13 substations. Figure 1 shows each location and the capacity of installed BESS in Korea.



**Figure 1.** Expansion plan of battery energy storage system (BESS) for a frequency response in the Korean power system.

The main purpose of MW-scale BESS is substituting the existing primary frequency response reserves from a thermal generator, which has low generation cost. By doing that, the thermal generator can increase the generation level, and the system marginal price (SMP) will be reduced by excluding high-cost generators in the electricity market. Furthermore, the BESS can provide or absorb the power within 200 ms, considering the communication delay. Therefore, the BESS can provide the needed frequency response by injecting the power into the power system just after the disturbance.

Presently, the proposed control strategy has been implemented in a 376-MW BESS installed at 13 substations to provide both virtual inertia response and primary frequency response. The proposed

control strategy is loaded in the individual control unit, where four power conversion systems (PCS) are dispatched, as shown in Figure 2. Additionally, there is another control algorithm upstream of the individual control unit. However, this paper focused on the more indicative control strategy-related frequency response.

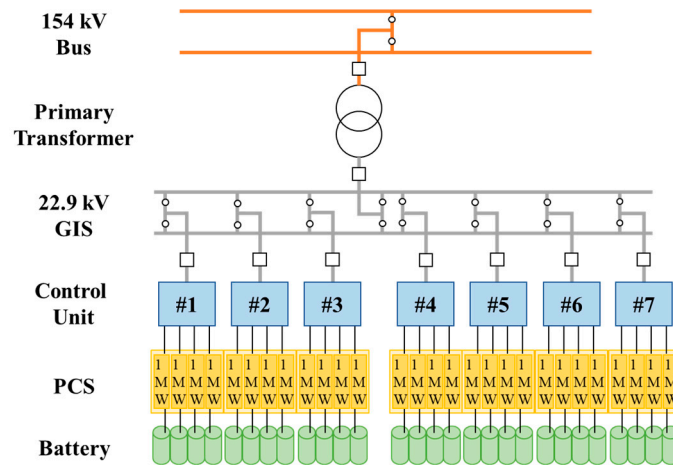


Figure 2. The typical configuration of BESS based on a single substation.

### 3. Considerations for Providing a Virtual Inertia Response and Frequency Response of BESS

As BESS has a completely different operating mechanism than the conventional generator, it should be controlled to maximize rapid responsiveness and supplement the limited life cycle and energy capacity, while also meeting the required performance of power system operation. This section describes these considerations for controlling BESS providing the virtual inertia and frequency response.

#### 3.1. The Life Cycle of BESS

The battery life of BESS is determined by the number of complete charge/discharge cycles that the battery is able to support before its capacity falls below 80% of its original capacity. As the BESS would be required to charge and discharge repeatedly, depending on the frequency changes, the control algorithm needs to operate BESS under the operating conditions in which the life cycle of the battery would be longest. It is known that the life cycle of the battery depends on the depth of discharge (DoD) and the operation range of SOC. The following Figure 3 and Table 3 show specific examples of these characteristics [23,24].

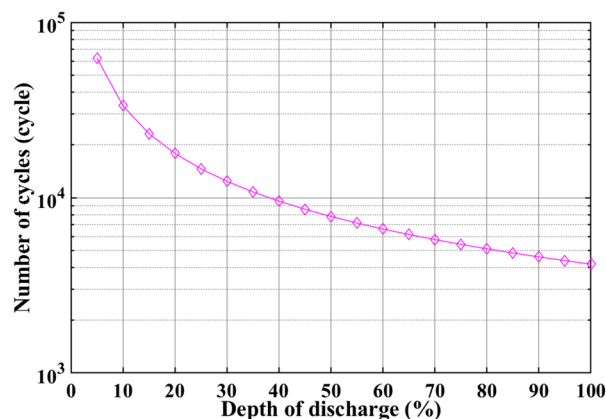


Figure 3. Example of the life cycle of a battery depending on the depth of discharge (DOD).

**Table 3.** Life cycle characteristic of a battery depending on DOD and the operation range of the state of charge (SOC).

DoD (%)	Operation Range of Battery SOC (%)	Life Cycle (Cycles)
100	0–100	4000
75	25–100 0–75	5651 8508
50	50–100 25–75	7746 11,556
30	50–80	20,317

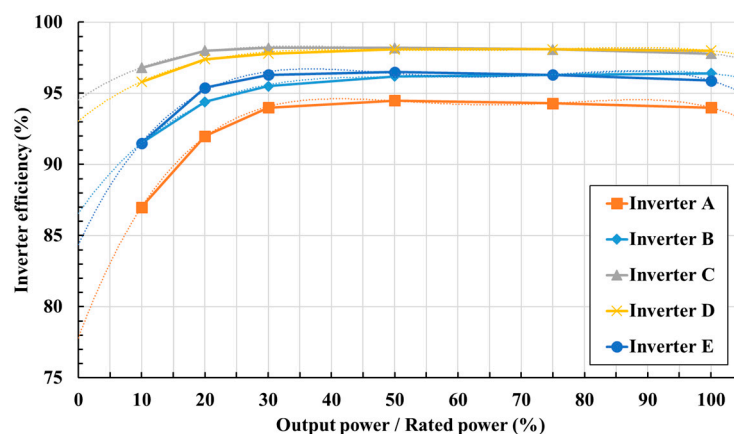
These characteristics of the battery are different in different BESS, but the preferred operating range of SOC can be determined to maximize the life cycle considering the battery specifications provided by manufacturer. In the case of this paper, the range of 50–80% of SOC can be chosen for the preferred operating range based on the characteristics of the battery shown in Figure 3 and Table 3.

### 3.2. SOC Recovery Control

As BESS has to be charged to discharge the electricity and loss occurs in both of these processes, its SOC should be recovered to maintain the preferred operating range. Since BESS control for recovering its SOC results in charging or discharging of the battery, it should occur when the power output of BESS would not interfere with the frequency control of the power systems.

In addition, as the output of BESS for recovering its SOC should not change the frequency, it needs to be minimized. However, as the efficiency of PCS between BESS and the power system depends on its power output, the recovering power for BESS should be determined to avoid any conflict of the frequency control and maintain high efficiency.

In the case of Figure 4, showing typical efficiency characteristics of PCS depending on the power output [25], as the efficiency of PCS decreases sharply when the power output is lower than 10% of the rated power, the power output for recovering SOC of BESS can be chosen to be higher than 10% of the rated power while minimizing its impact on the frequency.

**Figure 4.** Example of inverter efficiency depending on the power level.

### 3.3. Maximizing the Responding Capacity for Virtual Inertia Response

As BESS can respond almost instantly to the frequency change, it can contribute to the inertia response of the power system by providing its capacity just after the disturbance occurs. Since in the steady state, the frequency change is small and slow, the BESS can respond just as required by the frequency change in a steady state in which coordinated control with the generator's governor is preferred.

For accomplishing this, the BESS can be controlled to save its capacity by responding to the frequency change as much as the generator's governor in a steady state and maximize its response to a disturbance by applying a separate strategy for providing a virtual inertia response once a transient state is detected. The transient state can be detected by measuring the RoCoF (rate of change of frequency), and the responding capacity of BESS for the virtual inertia response can be maximized by responding with its full availability. In addition, in a steady state, the SOC of BESS needs to be managed to secure the availability of the responding capacity of BESS for the virtual inertia response.

### 3.4. The Performance Requirements for Frequency Response

As one of the resources for providing frequency response service, the BESS has a function for meeting the performance requirements in the power system. In practice, as the BESS has a completely different operating mechanism from the conventional generator, the power system authorities in various countries have been revising the new rules into performance requirements by considering the characteristics of the BESS. In particular, the power system authorities in Germany, Korea, etc., announce the performance requirements of BESS for providing frequency response [26].

In the case of the Korean power system, the energy capacity of the BESS should have a duration time of more than 15 min with rated power. As BESS has more availability for frequency response [27], despite its low capacity, than a conventional generator, it is required to apply a speed droop of less than 2% to respond to the frequency change. Furthermore, according to the agenda, it is recommended that the BESS set a speed droop similar to that of a typical generator. As BESS also should maintain its response for at least 6 min during the transient state, depending on the frequency changes, the average SOC should be maintained within  $\pm 5\%$  from the SOC target for every 5 min when the frequency deviation is within 0.1 Hz.

Based on this wisdom, the performance requirements for the BESS have been revised to manage the frequency more effectively in the many power systems. For accomplishing this, it will be required to use an appropriate control strategy of BESS for meeting performance requirements.

## 4. Proposed Control Strategy of BESS

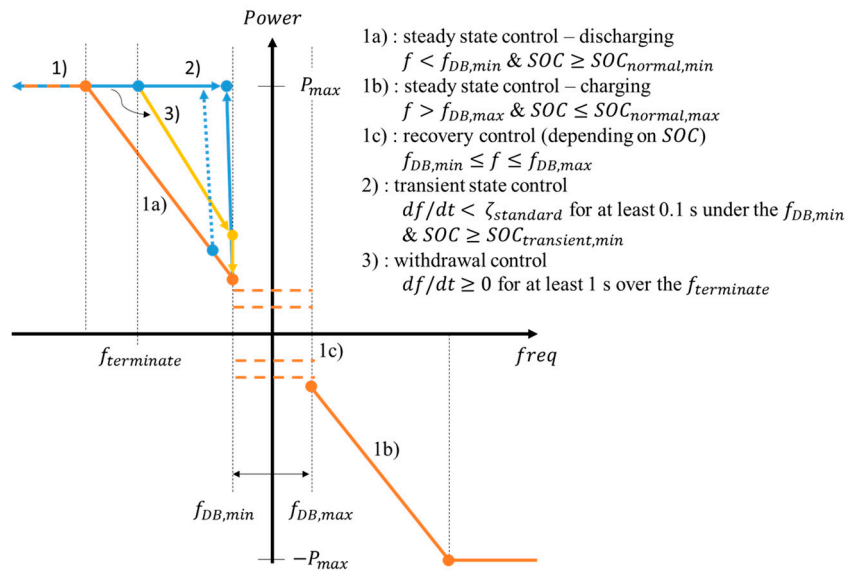
### 4.1. Control Strategy for Providing Both Virtual Inertia Response and Frequency Response

The proposed control strategy consists of three different control modes for effectively compensating the frequency performance of the Korean power system. Figure 5 summarizes the proposed control strategy for BESS.

The first control mode is the steady state control mode for providing frequency response with the droop characteristics to the frequency deviations ( $\Delta f$ ) and managing the SOC of the battery when the frequency is within the dead band range ( $f_{DB,min} - f_{DB,max}$ ). The droop characteristic of BESS is set to make its performance similar to that of a typical generator in the Korean power system, as shown in 1a) and 1b) of Figure 5. The speed droop of BESS in the steady state control mode ( $SD_{BESS, steady state}$ ) is determined by Equation (2):

$$SD_{BESS, steady state} = \frac{Capacity_{BESS} \times SD_{gen.}}{Capacity_{gen.}}, \quad (2)$$

where  $S.D._{gen.}$  is the speed droop of the typical generator and  $Capacity_{BESS}$  and  $Capacity_{gen.}$  are the capacity of the BESS and the typical generator, respectively. Control actions for managing the SOC of the battery are limited to the period when the frequency is within its dead band, as shown in 1c), and detailed control strategies are described in the following section.



**Figure 5.** Control strategy of the BESS for providing virtual inertia and primary frequency response.

The second control mode is the transient state control mode for providing both the virtual inertia and frequency response with the maximized responding amount just after the disturbance. For this purpose, this mode is activated by detecting RoCoF exceeding its threshold ( $\zeta_{threshold}$ ) for more than 0.1 s. The power output of the BESS ( $P_{BESS}$ ) for providing a required frequency response is determined by Equation (3) [28]:

$$P_{BESS} = \min(10 \times B \times \Delta f, Capacity_{BESS}), \tag{3}$$

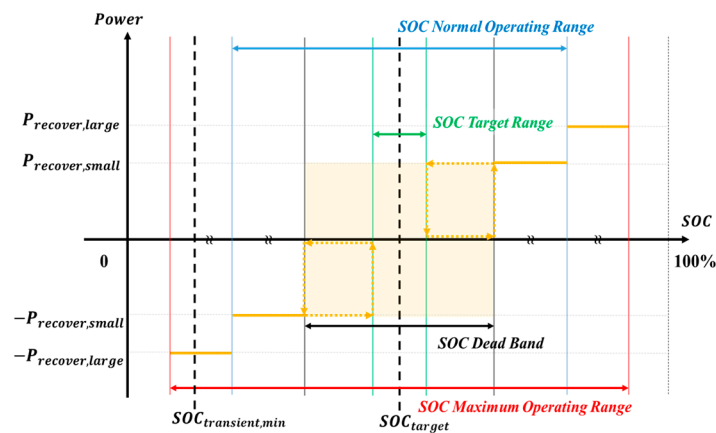
where ( $B$ ) is a frequency bias of the Korean power system.

The last control mode is the withdrawal control mode for terminating the transient state control mode and returning to the steady state control mode. This mode is activated by detecting a frequency exceeding its threshold ( $f_{terminate}$ ) with a positive RoCoF for more than 1 s. During this mode, the frequency response is provided with a droop characteristic and its speed droop ( $SD_{BESS,withdrawal}$ ) is determined by Equation (4), which allows the output of the BESS to be controlled continuously even when the transient control mode is changed to the withdrawal control mode.

$$SD_{BESS,withdrawal} = \frac{Capacity_{BESS} \times \Delta f_{terminate}}{f_0}. \tag{4}$$

#### 4.2. Control Strategy for Managing the SOC

To ensure the availability of the frequency response from BESS, its SOC should be maintained above a certain level. In the proposed control strategy, the SOC of the BESS is maintained within a specific range in which its life cycle is longest, and the SOC recovery control occurs while minimizing the interference with the frequency response. Figure 6 summarizes the output of BESS for recovering its SOC in each range.



**Figure 6.** Recovery control of BESS on state of charge (SOC) ranges.

As shown in Figure 6, once the maximum operating range of SOC is defined by its specification, the SOC target and its normal operating range are set considering the required duration of the frequency response and the life cycle in each SOC range. If the SOC moves off its dead band, BESS is charged or discharged to recover its SOC until it reaches the target range. By setting the target range narrower than the dead band of the SOC, unnecessary transition of the SOC recovery control can be avoided. In addition, by activating the SOC recovery control mode only when the frequency is within its dead band range, as shown in 1c) of Figure 5, the interference between the frequency response and the SOC recovery of BESS can be minimized. The  $SOC_{transient,min}$  is set to be a minimum level of SOC for allowing the transient control mode of BESS, where a certain amount of SOC is required to provide the frequency response.

## 5. Case Study

### 5.1. Specification of BESS Referred to Operating Condition in the Korean Power System

The control requirement of BESS was determined, depending on the SOC and frequency, by the control strategy. For the simulation, the operation parameters of BESS were referred based on the actual operation values used on-site. Table 4 summarizes those several specifications of operation.

**Table 4.** Specifications for operating BESS.

Index	Parameter	Value
Facility Specifications	Total capacity of BESS	236 MW/65 MWh
	C-rate of BESS	4 C-rate or 2 C-rate
Control Parameter	Frequency dead band	$60 \pm 0.03$ Hz
	$f_{terminate}$	59.9 Hz
	SOC maximum operating range	10–90%
	SOC normal operating range	50–80%
	SOC target range	$65\% \pm 0.5\%$
	SOC dead band	$65\% \pm 2\%$
	Ratio for recovery control	10%/15%
	$SOC_{transient,min}$	15%
$\zeta_{standard}$	$-0.0279$ Hz/sec	

The BESS installed in the Korean power system was typically composed of multiple control units that operate four PCS, as shown in Figure 2. Each PCS controlled a 1-MW battery, for which the discharge rate is 4 C-rate in most of the substations, except for the SinYongin substation where two PCS controlled a 2-MW with a discharge rate of 2 C-rate.

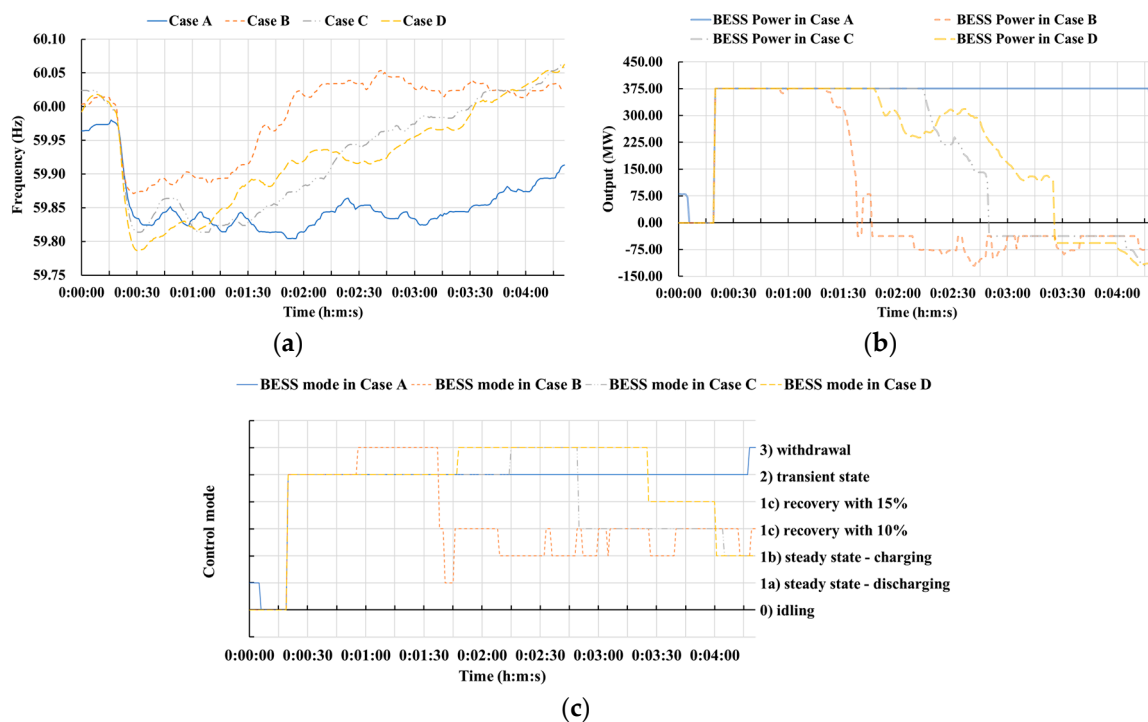


The control parameters for operating BESS reflected both the characteristics of the BESS and the Korean power system. Each SOC range was selected by considering the reported life cycle characteristic from the battery manufacturer and the objective of each control mode. To operate for a long period, the specific range having the maximum number of cycles in the performance specification was applied as 50–80%, as a normal operating range. The target SOC in the control strategy was set to 65% considering both the electricity market rule in the Korean power system and the center of the normal operating range. However, the range was expanded to 10–90% to maximize the availability in the transient state. Additionally, the ratio for recovery control was determined based on the efficiency characteristic of the PCS depending on the loading level.

### 5.2. Verification of the Proposed Control Strategy

The verification of frequency response can be based on how properly the requirement was followed depending on the frequency change. To accomplish this task, the C++ based simulation platform was used for verification of the proposed control strategy by applying the several measured frequency data when a generator was tripped in the Korean power system. As the assumptions for simulation, the installed capacity of the BESS was 376 MW and the initial SOC was 65%. Figure 7 shows the frequency data and results from the control output of BESS.

Before a disturbance, the power output of BESS idled in the stable frequency for the initial 15 s. However, after detecting RoCoF exceeding  $-0.0279$  Hz/s for more than 0.1 s, the transient state control mode was activated rapidly to prevent and arrest the frequency drop with a rated power (376 MW). When the frequency increased more than 59.9 Hz and the RoCoF exceeded 0 Hz/s for more than 1 s, the withdrawal control mode was activated until the frequency recovered into its dead band. In the frequency dead band, the BESS started to manage the SOC with the recovery control mode. From those results, the accuracy of the proposed control strategy could be verified, as shown in Figure 7b,c. Additionally, Table 5 describes the evaluation of the proposed control strategy.



**Figure 7.** Simulation verification of the proposed control strategy: (a) measured frequency data; (b) control output of BESS and (c) control mode of BESS.

Table 5. Evaluation result of the control strategy.

Index	Mode Changing to 2)		Mode Changing 2) → 3)		Mode Changing 3) → 1)	
	Time Generator Tripped (s)	Mode Change Time (s)	Time at $f \geq f_{terminate}$ (s)	Mode Change Time (s)	Time at $ \Delta f  < f_{DB}$ (s)	Mode Change Time (s)
Case A	20.0	20.8	259.0	260.0	N/A	N/A
Case B		20.6	56.0	57.0	98.0	98.0
Case C		20.6	134.0	135.0	171.0	171.0
Case D		20.5	108.0	109.0	206.0	206.0

The changing of the control mode by the control strategy considered not only the frequency change but also the duration time of the RoCoF. Therefore, there were some brief delays for changing the control mode. On the other hand, the change to the SOC recovery control mode was changed without delay as it was based only on the frequency change. These simulation results show that the proposed control strategy of BESS could properly assess the control mode depending on the system frequency after a disturbance.

5.3. Evaluation of the Virtual Inertia Response and Frequency Response from BESS

Verifying the contribution of the frequency response using the proposed control strategy is also important. In this section, a simulation was conducted to evaluate the frequency response from BESS by using the power system simulator for engineering (PSS/E) from Siemens PTI (Schenectady, NY, USA), which is the most widely used simulation tool for power system analysis. For modeling the BESS, the Electric Power Research Institute’s (EPRI) CBEST model was adopted, as shown in Figure 8. The proposed control strategy was applied to the auxiliary signal  $P_{AUX}$ , which determines the output of the BESS. For this simulation, the CBEST model was applied to the system model of Korean power.

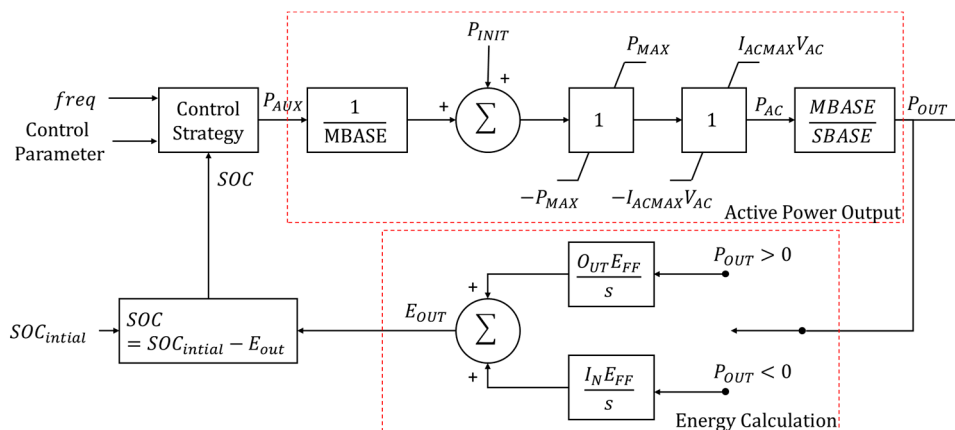


Figure 8. Modeling the BESS using the CBEST model in PSS/E.

As an analysis, the following simulation result shows a comparison of the frequency response from a 26-MW BESS and thermal generator with the same amount of reserve from rated power and a speed droop of 5%. Figure 9 and Table 6 contain those results when a generator of 1.46 GW was tripped.

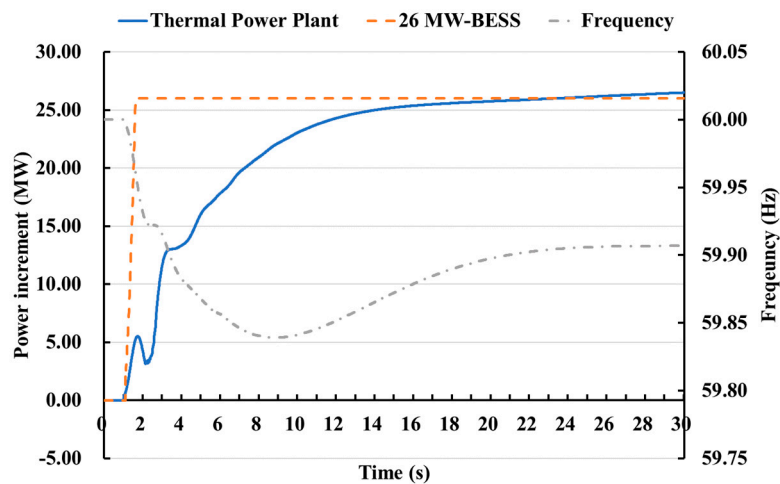


Figure 9. Comparison between the thermal generator and BESS.

Table 6. Comparison of the frequency response results.

Index	Time at Reaching Full Availability (s)	Power Availability at Nadir (%)	Service Evaluation Indicator	
			Speed Droop (%)	GFRQ Based on Nadir (MW)
Thermal Generator	T + 21.358	84.734	6.471	25.376
BESS	T + 0.625	100.000	0.276	26.000

The thermal generator reached full availability 20 s after the disturbance. On the other hand, the BESS shows full availability within hundreds of milliseconds as a virtual inertia response. By using the evaluation indices in the Korean power system, the speed droop of BESS was calculated as 0.276%, which was 23.45 times more sensitivity than the case of a thermal generator. The GFRQ of both resources was almost the same as the available power, which means that they could fully contribute to the frequency response. Here, the GFRQ was calculated based on the outputs at 10 s after the nadir frequency using method carried out in [29].

In this context, the BESS for providing frequency response would have more powerful frequency stability. The following Figure 10 and Table 7 show the difference of frequency stability depending on substituting the same amount of frequency reserve with the 376-MW BESS when a generator of 1.46 GW was tripped.

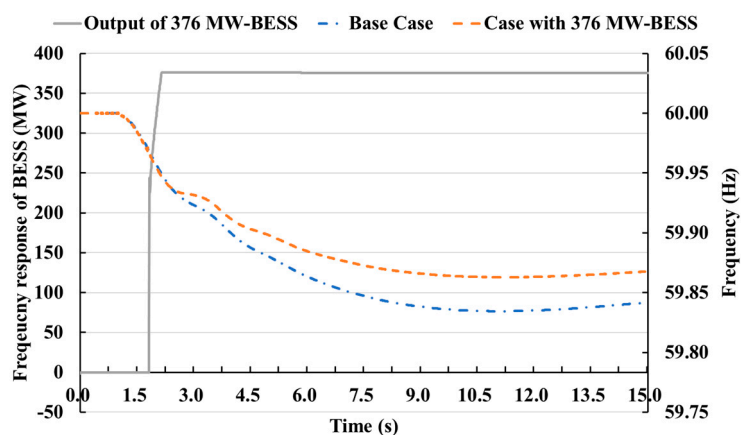


Figure 10. Comparison of result without and with BESS.

Table 7. Evaluation result from Figure 10.

Index	RoCoF (Hz/s)	Nadir Frequency (Hz)	Time at Reaching to Full Availability (s)
Without BESS	-0.043	59.834	N/A
With BESS	-0.036	59.862	T + 1.150

The results show that the RoCoF and nadir frequency increased by 0.007 Hz/s and 0.028 Hz compared to the base case, respectively. From this result, the BESS could effectively contribute to both the inertia response and frequency response by providing the frequency response right after the disturbance.

5.4. SOC Management of the Proposed Control Strategy for Long-Term Simulation

Another main issue of control the BESS is maintaining its SOC to maximize the life cycle and the availability of the transient state. For accomplishing this, in this section, verification of the SOC management was performed based on measured frequency for eight days, including the transient state for a few minutes, in the Korean power system. The C++ based simulation platform was also used for this verification. Figure 11a,b show the overall frequency data and the frequency distribution, respectively. Figure 11c,d show the result of the SOC and its distribution, respectively.

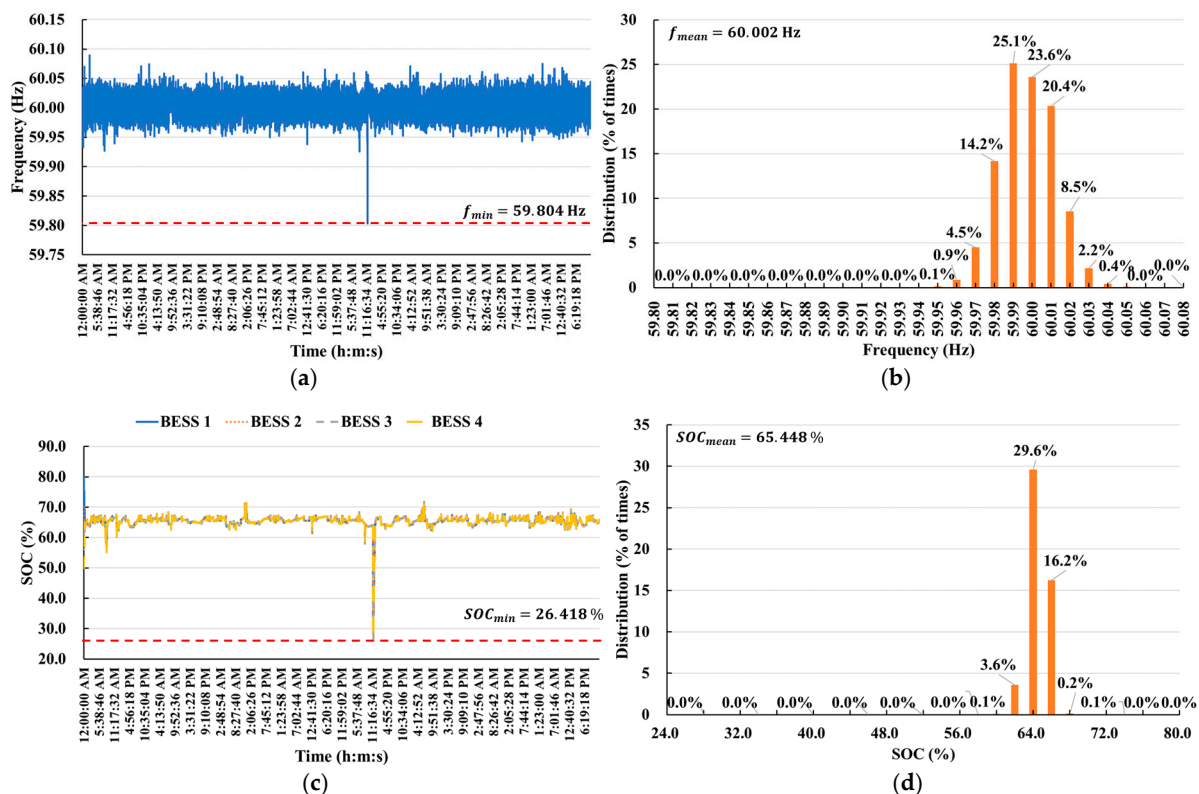


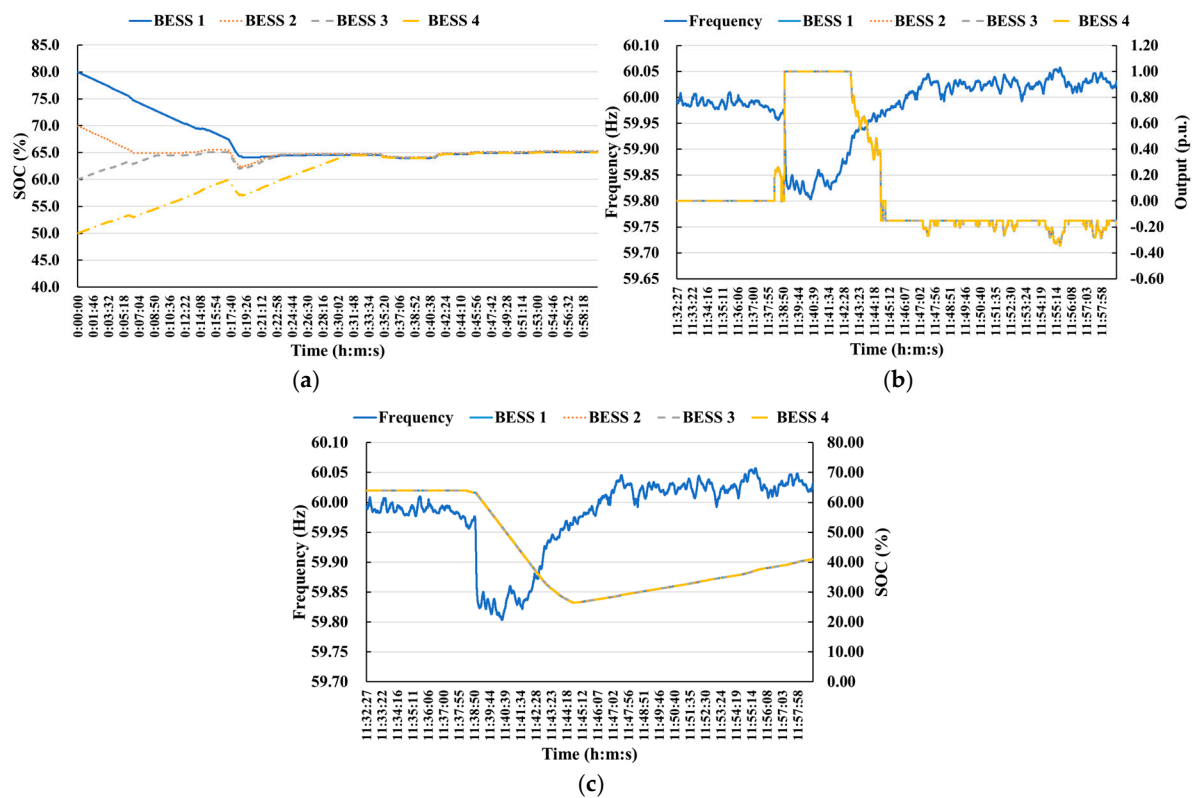
Figure 11. Frequency data for the simulation and SOC result: (a) measured frequency data for eight days; (b) distribution of frequency data; (c) SOC results from four BESS; and (d) distribution of SOC.

Except for the transient period, which measured the 59.804 Hz nadir frequency, the frequency for eight days remained within its dead band, which occupied a proportion of 98.41%, as shown in Figure 11b. For the verification of SOC management, this simulation was performed to four BESSs with different initial SOC, 50%, 60%, 70%, and 80%, respectively. Although the initial SOC was different, the SOC became similar, as shown in Figure 11c. Through this control, 98.67% of the results were

properly managed in the normal operating range, as shown in Figure 11d. Figure 12 shows the results of the details from Figure 11.

Since most of the frequency was within its dead band in a steady state, the SOCs could be managed by the recovery control mode so that the SOCs became similar within 30 min despite providing frequency response. After the disturbance, the BESS rapidly increased the output as much as the rated power by the transient state control mode, as shown in Figure 12b. As soon as the frequency was recovered, the BESS decreased the control sensitivity by the withdrawal of the control mode. Through those responses in a transient state, the SOCs decreased to 26.42%, as shown in Figure 12c. After the transient state was terminated, the SOCs were managed by the recovery control mode in the frequency dead band. Those results show that the proposed control strategy could effectively manage the SOC while also providing a frequency response.

Table 8 summarizes the results in the steady state and the transient state. From the steady state result, the average SOC for every 5 min was almost maintained within  $\pm 5\%$  from its target, which is a performance requirement in the Korean power system. The speed droop from the response was calculated as 0.28%, which was the same as the performance of the substituted generators. The transient state results also show that the BESS could provide full availability within 0.42 s. In the withdrawal control mode, the speed droop was calculated as 0.17%, which could continuously provide the response when the transient control mode was finished.



**Figure 12.** Details of the simulation result: (a) synchronized SOC result from each BESS; (b) output of BESS in a transient state; and (c) variation of SOC in a transient state.

**Table 8.** Verification result from the long-term simulation.

Index	Steady State Except for Synchronizing Period				Transient State			
	5 min Average SOC (%)			Speed Droop (Steady State; %)	Time at Reaching to Full Availability (s)	Power Availability at Nadir (%)	Speed Droop (Withdrawal; %)	
	Min.	Max.	Avg.					Probability of Acceptance
Value	59.58	70.53	65.54	99.73	0.28	T + 0.42	100.00	0.17

### 5.5. On-Site Operation Results in the Korean Power System

As the proposed control strategy was implemented in the 376-MW BESS installed by KEPCO, following the on-site operation results shows that the BESS provided both a virtual inertia and primary frequency response. Figure 13 shows one of those operation results when a thermal generator of 1000 MW was tripped in the Korean power system.

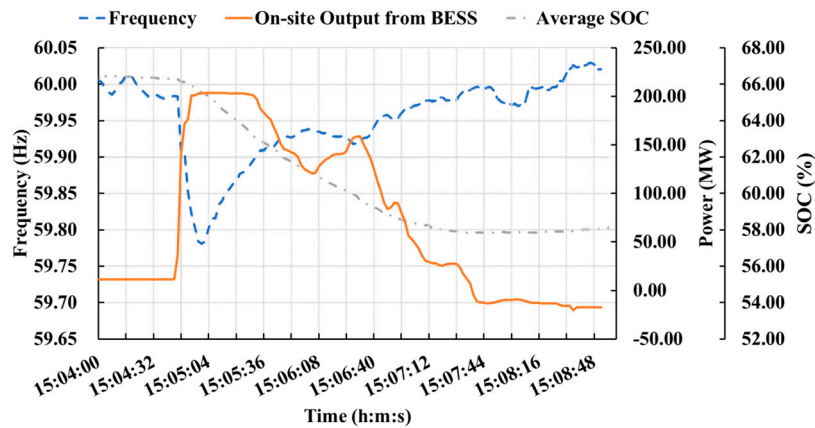


Figure 13. Operation result response to a large generator trip (Case 1).

As shown in Figure 13, the BESS instantly provided the frequency response in the transient control mode just after the generator trip by indicating the frequency drop, and this can be considered to be an inertia response from the BESS. It can be seen that the responding amount of the BESS was 204 MW, which was as much as the available capacity of the BESS excepting some substations stopped for maintenance. The BESS provided the frequency response in the transient control mode for 40 s by its full availability. From this response, it is regarded as a contribution to arresting the frequency drop after the disturbance. Once the frequency recovered also to 59.9 Hz, the transient control mode was terminated and BESS started providing the frequency response in the withdrawal control mode. During this transient period, because the frequency recovered to nominal frequency within 4 min, the BESS consumed the energy with approximately 8.5% of the total SOC. In addition, when the frequency deviations became smaller than the frequency dead band, BESS was started to charge to recover the SOC of the battery.

Figure 14 shows another operation result when a thermal generator of 500 MW was tripped.

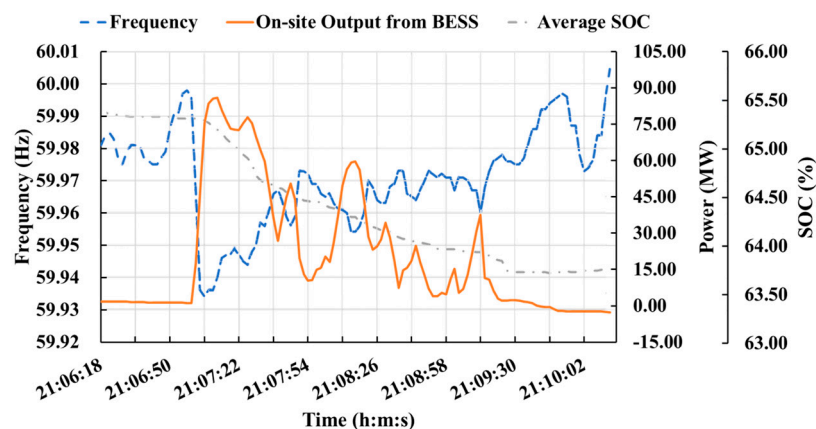


Figure 14. Operation result response to a large generator trip (Case 2).

As the amount of the tripped generator was small, the RoCoF was not steep enough to change the control mode to the transient control mode. Therefore, the BESS provides a frequency response with a

steady state control mode with 0.324% of speed droop as governor response from the conventional generator. It can be seen that the responding amount of the BESS was 248 MW, which is as much as the available capacity of the BESS except for some substations stopped for maintenance. Therefore, the BESS provided the frequency response of up to 85.9 MW depending on frequency variation. Although this case may not seem to have a major impact on the Korean power system, this result shows that the BESS could provide the frequency response as the substituted governor response, when the small disturbance occurs. During this period, because the frequency was maintained at a higher frequency contrary to the previous case, the BESS consumed the energy with only 1.6% of the total SOC. When the frequency was also within its dead band, the BESS started to charge to recover the SOC. Based on these on-site operation results, the frequency responses from BESS were evaluated, as shown in Table 9.

**Table 9.** Evaluation results of on-site responses from Figures 13 and 14.

Index	Available Capacity (MW)	Time at Reaching to Full Availability (s)	Power Availability at Nadir (%)	Speed Droop (Withdrawal; %)	Service Evaluation Indicator	
					Speed Droop (%)	GFRQ Based on Nadir (MW)
Case 1	204	6	99.76	0.17	0.28	171.31
Case 2	248	N/A	34.64	N/A	0.32	55.22

Case 1 shows that the BESS could provide the full availability in 6 s, depending on the frequency change. The speed droop in withdrawal control was calculated as 0.17%, the same as the intentional value. From the evaluation indices, the speed droop and GFRQ were evaluated as 0.289% and 171.306 MW, respectively, which was less than the available capacity because the frequency was recovered quickly. On the other hand, Case 2 shows that the BESS provided 34.64% of power availability. Therefore, the speed droop and GFRQ were 0.32% and 55.22 MW, respectively. However, this response was still more sensitive than the typical generator in the Korean power system.

From these results, the BESS could provide the frequency response, depending on the variation of the frequency. When the frequency was dramatically dropped after a disturbance, the responding capacity was maximized within a few hundreds of milliseconds to arrest the frequency as a virtual inertia response. Although the frequency was not steep enough to change the control mode, the BESS could effectively provide the power with a speed droop of the conventional generator. If the response availability needs to increase based on the small amount of the generator tripped, the proper parameter setting of  $\zeta_{standard}$  might be required.

## 6. Conclusions

This paper proposed a control strategy of BESS, which has been operating to provide the frequency response in the Korean power system. The proposed control strategy reflects not only the inherent characteristics of BESS, such as the life cycle, fast response characteristic, and SOC, but also the electricity market rules in the Korean power system. Through these considerations, the proposed control strategy comprises the three control modes. Firstly, the steady state control charges/discharges BESS in response to deviations of frequency and manages the SOC to get it ready for a transient period. Secondly, the transient state control mode provides the maximum response from BESS with its rating in a transient state. Lastly, the withdrawal control mode charges/discharges BESS with less sensitivity to the frequency deviations as the frequency recovers to a steady state.

Furthermore, this paper verified the effectiveness of the proposed control strategy. Based on the short-term simulation results, it showed that the decision of the control modes is properly determined depending on the system frequency and SOC of the BESS. It was also shown that the BESS can effectively contribute to both the inertia response and primary frequency response during a transient period. From the long-term simulation, the SOC of BESS can be managed well even though the initial SOC varies. Especially, the on-site operation results of the MW-scaled BESS using the proposed control

strategy verified the effectiveness of the proposed control strategy for providing the frequency response. In the future, the virtual inertia and frequency response from BESS using the proposed control strategy are expected to greatly contribute to securing the frequency stability of the Korean power system as the penetration level of RES gets much higher. The proposed control strategy can be also applied to other power systems with BESS by tuning its control parameters if similar BESS is operated in the same framework for providing the frequency responses. Moreover, if BESS performance increases and its compensation becomes fair in the electricity market, the benefit from its frequency response can be also increased by modifying the proposed control strategy accordingly.

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