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BESS를 활용한 전력계통 주파수 안정도 향상

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Frequency Stability Enhancement of Power System using BESS

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요 약

한국은 단위기 발전기 용량 1.4 GW, 20 GW를 초과하는 몇 개 지역의 대단위 발전단지, 대단위 발전단지에서 발전력을 인출하는 2~3개의 초고압 송전선로, 비수권에서 수도권으로 발전력을 수송하는 6개의 초고압 송전선로 구성 등 대용량 발전, 대규모 송전시스템 등 전통적인 전력계통 시스템의 특징을 가지고 있다. 이런 전력계통 특성으로 신재생에너지 진입 단계는 낮으나 주파수 안정도 문제 등으로 일부 발전기 출력 감발을 시행하고 있으며 향후 신재생에너지 확대 정책으로 전력계통 안정도 유지 문제가 가장 중요한 현안으로 떠오를 전망이다. 태양광, 풍력발전 같은 비관성 인버터 기반 신재생에너지 급증시 독립계통에서 전력계통 안정도를 향상시키는 수단은 Natural 관성 자원인 동기조상기와 가상 관성 자원인 BESS를 계통에 설치하는 것이다. 본 연구에서는 신재생에너지가 계통안정도에 미치는 영향을 분석하고 최저주파수를 유지하기 위한 BESS 효과를 계통모의를 통하여 분석하였다. 발전제약 용량에 따른 BESS 효과는 최대 122.81%에 도달하는 것을 확인하였다.

ABSTRACT

Korea has the characteristics of traditional power system such as large-scale power generation and large-scale power transmission systems, including 20 GW large-scale power generation complexes in several regions with unit generator capacity exceeding 1.4 GW, 2−3 ultra-high-voltage transmission lines that transport power from large-scale power generation complexes, and 6 ultra-high-voltage transmission lines that transport power from non-metropolitan areas to the metropolitan area. Due to the characteristics of the power system, the penetration level for renewable energy is low, but due to frequency stability issue, some generators are reducing the output of generators. In the future, the issue of maintaining the stability of the power system is expected to emerge as the most important issue in accordance with the policy of expanding renewable energy. When non-inertial inverter-based renewable energy, such as solar and wind power, surges rapidly, the means to improve the power system stability in an independent system is to install a natural inertial resource synchronous condenser (SC) and a virtual inertial resource BESS in the system. In this study, we analyzed the effect of renewable energy on power system stability and the BESS effect to maintain the minimum frequency through a power system simulation. It was confirmed that the BESS effect according to the power generation constraint capacity reached a maximum of 122.81 %.

키워드

Power System Stability, Low-Inertia, Battery Energy Storage System, System Non-Synchronous Penetration
전력시스템 안정도, 저관성, 배터리 에너지 저장 시스템, 시스템 비동기 침투량

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Ⅰ. Introduction

When inverter-based renewable energy, such as PV (: Photovoltaic) and WT (: Wind Turbine), replaces the conventional generator, the natural inertia supplied by the rotor and turbine of the conventional generator decreases, making the power system frequency vulnerable, and acting as an unstable factor in terms of frequency stability [1-3].

First, if the power system inertia is reduced, a frequency change problem occurs in the case of system failure. This is usually expressed as ROCOF (: Inertia and Rate of Change of Frequency), as the electromagnetic energy supplied from the rotor of a conventional generator is replaced with renewable energy, and immediately after the occurrence of system failure, the system frequency drops very quickly beyond the allowable range[4-5].

Normally, when the system frequency changes rapidly, if the frequency change exceeds the set value within a set time, the ROCOF relay of the traditional generator or renewable generator shuts off the generator. Relay operation setting is displayed in Hz/s, and as a result of the spread of PV and WT, as the system inertia decreases, the ROCOF becomes very large. The frequency change rate means that the higher the system inertia, the smaller the change rate. The most important task in an independent system is to prevent a wide-area blackout by preventing the generator from being cut off by maintaining the frequency change rate at an appropriate level. Second, in the event of a system failure, the lowest frequency (or nadir frequency) drops below the operating point of the Under Frequency Load Shedding (UFLS), causing a major blackout [6-8].

The key to determining the grid acceptability of renewable energy in the power system when expanding IBR (: Inverter Based Resource), such as PV and WT, is to maintain the ROCOF and nadir frequency problems at an appropriate level through a precise analysis of low inertia. The ROCOF and nadir frequency problems are ultimately expressed as power system stability, and the power system acceptability is evaluated by transient stability, small signal stability, and frequency stability [9-10].

In the case of an independent system without interconnection lines between countries, such as in Korea, when IBR is rapidly increased, the means to improve the stability of the power system are as follows:

a. IBR's fast frequency response performance requirement (Grid Code)
b. Installation of synchronous Phase Measurement Unit (improving system analysis conditions through precise measurement of system physical quantity)
c. Application of automatic control device of IBR (automatic adjustment of renewable energy output when the power grid is overloaded)
d. Improvement of reserve (securing very fast response reserve capacity against low inertia due to the increase in IBR)
e. IBR modeling characteristic test (securing an appropriate facility model for system analysis)
f. Application of the power load model (load model for sophisticated analysis of the IBR)
g. Expansion of installation of natural inertial resource, Synchronous Condenser (SC)
h. BESS installation of primary reserve and synthetic inertia resource role

Among them, items a - f are recognized as indirect means in terms of operation to improve the stability of the power system compared to items g and h, so the fundamental means are the installation of a SC and BESS. In more detail, a natural inertial resource, SC, and a virtual inertial resource, BESS, are installed in the system, but no clear distinction is made between the two resources [11-13].

However, the SC is more suitable for the relaxation of ROCOF, while the BESS is more suitable for the relaxation of nadir frequency. In an independent system without external assistance of inter-connectors, it is more urgent to mitigate sudden frequency changes in a very short time (transient). Thus, in this inertial response time aspect, the roles between the two resources can be clearly distinguished. Therefore, in the actual system, the purpose of improving the stability of the power system can be achieved more clearly by combining SC and BESS. As IBR expands rapidly, the role of BESS with delayed response time is limited, so the faster the response time of BESS, the more important it is to secure system stability [14-16].

In the current power system infrastructure, transient stability, small signal stability, and frequency stability are reviewed to examine the grid acceptance limits of IBR. In this study, the ROCOF and nadir frequency are analyzed by expanding the proportion of on-line IBR step-by-step from the 50% or more level, and the contribution effect of BESS and of shortening its response time are systematically simulated. And also, the results of simulation will be reviewed and analyzed for enhancement of power system stability.

Ⅱ. Renewable Energy Penetration Limit Due to Power System Stability

2.1 IBR backgrounds

When the power demand changes in real time in the power system, the output of the conventional generators that are in balance with the power demand also changes, and when the amount of PV and WT increases, the output variability of the conventional generators expands. Fig. 1 shows that therefore, the volatility in the system inertia supplied by the existing traditional generators becomes very high [10].

System inertia and frequency change rate are defined as follows :

$$H = \frac{E_{kinetic}}{S_{rated}} = \frac{1}{2}\frac{Jw^2}{S_{rated}} \tag{1}$$

$$H_{sys} = \frac{\sum H_i S_i}{S_{sys}} \tag{2}$$

$$\frac{df}{dt} = \frac{\triangle P}{S_{sys}}\frac{f_0}{2H_{sys}} \tag{3}$$

where, $\triangle P$ = Power Variation (MW), f = System Frequency (Hz), H_i = i_{th} Generator Inertia (S), and S_i = i_{th} Generator Capacity (MVA).

The expansion of IBR results in a change in the generator phase angle (frequency stability). Due to the nature of Korea's electricity system, large-scale renewable energy is inevitably installed in the southern non-metropolitan area, and it is difficult to install renewable energy in the northern metropolitan area, where more than 40% of electricity demand is concentrated. As a result, a large amount of active power is transmitted from the south to the metropolitan area, resulting in a large phase angle deviation, which is a factor that negatively affects the stability of the power system as shown in Fig. 1. In a country that is usually a grid island, how many IBRs are included in the grid, which is defined as System Non-Synchronous Penetration (SNSP), is managed, and the limit is set and operated in the real-time system [11].

$$SNSP = (online)\frac{[P_{WT+PV} + P_{HVDC}(import)]}{[P_{road} + P_{HVDC}(\mathrm{export})]} \times 100(\%) \quad (4)$$

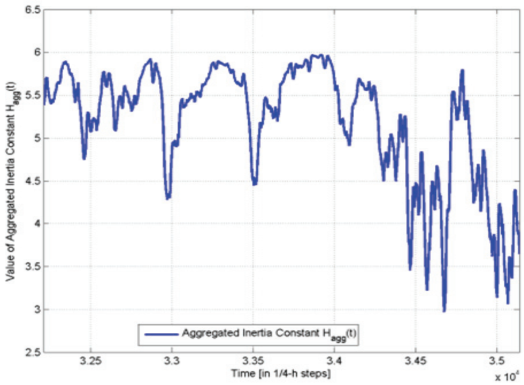

Fig. 1 Time-variant aggregated rotational inertia H_{agg} in German power system (Dec. 2012).

2.2 Transient Stability

When evaluating the renewable energy penetration limit from the viewpoint of transient stability, the limiting capacity is determined by evaluating the stability as shown in Fig. 2 with the maximum tolerance for fault (CCT, Critical Clearing Time), so that in the event of system failure, the generator can recover from the transient state to a stable state. CCT standards in Korea are 5 cycles at 170 and 362kV, and 4 cycles at 800kV. Here, CCT can be defined as the maximum allowable time for which a fault must be eliminated when a system failure occurs. If, as a result of the system analysis, the time required to remove the fault is shorter than the CCT, further IBR is not acceptable, and other countermeasures are required. If the system inertia decreases due to the increase in IBR, the time required to clear the fault will be very short.

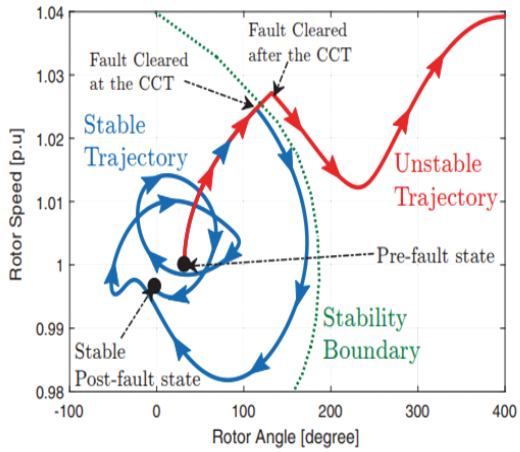

Fig. 2 Conceptual visualization of the use of CCT to establish a stability boundary.

Korea's CCT standard is a concept of minimum time in terms of system protection, and due to the spread of renewable energy, the definition of CCT has not yet been clearly established in terms of transient stability. However, as a result of examining foreign cases and the existing CCT, 6 cycle (0.1s) was set as the limit value, and the system was simulated at the minimum or maximum load level according to the proportion of renewable energy capacity. As a result, in the case of the minimum load, the CCT decreases to less than 0.1s at the SNSP level of about 35%, and in the case of the maximum load, it decreases from the level of about 40% to less than 0.1 s. When evaluating the actual penetration limit, even if some of the many cases become unstable, it cannot be immediately taken as the limit. Each country needs a very diverse approach depending on the power system situation at the level of 30% or higher, areas exceeding 0.1s appear, and it is expected that the appropriate SNSP limit can be determined at the level in the range 40~55%.

Note that the limit is the operable capacity of the renewable energy in the real-time power system. In Korea, in 2019~2020, in preparation for a situation in which a large-capacity unit generator was tripped in the case of minimum load, there were several system situations in which the generator output was lowered due to concerns about frequency instability and high ROCOF, i.e., power generation was restricted. Prediction of time exceeding the limit reflecting the real-time system situation based on the limit set value and countermeasures against it is expected to be an important task in the future.

2.2 Small Signal Stability

Small Signal Stability refers to the ability of the power system to maintain a synchronized state, in the event of a small disturbance in the load or generator. Since it considers a sufficiently small disturbance, the nonlinear power system equation is linearized and analyzed. The instability of Small Signal Stability means that after a small disturbance, an oscillation with a large amplitude occurs due to insufficient damping torque. In particular, the electric/mechanical mode generates low-frequency oscillation, and may act as a serious threat to the power system, due to insufficient damping. Small Signal Stability analysis is mainly performed through eigen value analysis of the power system, and the eigen value of the power system can be calculated through the linearization process of the power system model. To secure stability from the viewpoint of Small Signal Stability, the eigen values appearing in the actual power system must have a sufficient damping ratio. The power system characteristic equation can be expressed by Eq. (5), and the solution can be expressed by Eq. (6) & (7).

$$S^2 + 2\zeta\omega_n S + \omega_n^2 = 0 \tag{5}$$

where, ζ = Damping Ratio, ω_n= Natural Frequency.

$$\text{Eigen Values } \lambda_{1,2} = -\zeta\omega_n \pm j\omega_n\sqrt{\zeta^2 - 1} = \sigma \pm j\omega \tag{6}$$

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \times 100 \tag{7}$$

Damping ratio standards for overseas power companies are operated at 3~5%, and in Korea, which is in the early stage of the spread of renewable energy, there is no explicit standard, but in consideration of the unique characteristics of independent power systems, it is set to 3% or more. In the case of minimum load and maximum load, the number of damping modes with damping ratio less than 3% is simulated while increasing the proportion of renewable energy operating capacity by 5%. The number of cases where the damping ratio is less than 3 % according to the share of the renewable energy operating capacity, increases rapidly when the proportion of the renewable energy operating capacity is 50% or more in the minimum load case, and 55% or more in the maximum load case. In the Small Signal Stability review, as with transient stability, even if some cases fall below the standard, it cannot be immediately determined as the penetration limit. It is reasonable to select and evaluate an appropriate ratio value that does not have to satisfy the standard ratio. Considering the rapidly increasing proportion, the penetration limit is likely to be set at the level 50-55 %. That means that the SNSP is 50~55%. The limit tends to slightly increase over the transient stability result, and the transient stability responds more sensitively. However, the

Small Signal Stability problem needs to be carefully dealt with, as once it occurs, it can become a nationwide system instability problem, such as oscillation between nearby generators, intra-area oscillation, and inter-area oscillation, and the mitigation method cannot immediately be implemented.

2.3 Frequency Stability

Maintaining the frequency determined by a reliability standard is the problem of maintaining an appropriate frequency in a normal system and under frequency load shedding (UFLS) caused by a generator trip in the case of a system failure. Fig. 3 shows that it is directly related to the nadir frequency and the ROCOF according to the decrease in system inertia[17].

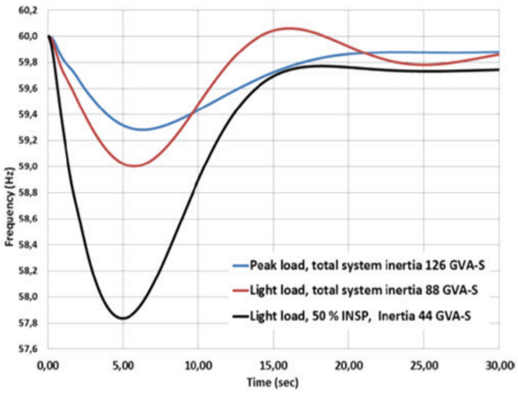

Fig. 3 Comparison of frequency response for loss of 1000 MW in peak load and light load conditions.

In Korea, the frequency maintenance standard is set as: ① Maintaining grid frequency of 59.7Hz or higher when one generator trips, and ② Maintaining grid frequency of 59.2Hz or higher when two generators trip. Despite these operating standards, the UFLS standards shown in Table 1 are more important in the actual system low inertia situation.

When IBR operation is expanded, the ROCOF is steeper, and the nadir frequency is much larger, even with the same system failure. In Korea, the maximum generator unit capacity is 1.4GW, and reaching the lowest frequency when the generator is tripped requires analysis only in the case of minimum load, while in the case of maximum load, a very severe scenario is required, but the effect on the frequency stability is less.

Table 1. UFLS action time and shedding load

Stage	f [Hz]	Action Time	Shedding Load
1	59.0	Each 0.1 s	Each 6 %
2	58.8		
3	58.6		
4	58.4		
5	58.2		
6	58.0		
Backup	59.0	12 s	4 %
Total			40 %

In the case of minimum load, when the largest unit generator at the 45% level of the renewable energy operating capacity is tripped, it approaches the first stage (nadir frequency 59.0Hz) by the UFLS relay. This means that it is difficult to recover the frequency with the current frequency reserve of 1.7W, within 10s response time, and it is likely that in the future, the frequency reserve will need to be upgraded. However, this problem is costly and, above all, it is directly related to the problem due to the expansion of renewable energy of the shortage of generators to secure the frequency reserve that is operated in real time in the system. This is an intrinsic problem. Table 2 summarizes the three review results for determining the power system stability:

Table 2. IBR penetration limit according to power system stability

Power System Stability	SNSP allowable
Transient Stability	40–55%
Small Signal Stability	50–55%
Frequency Stability	45%

Ⅲ. Frequency Stability Enhancement Using BESS

3.1 Power System Configuration in Korea

The stage of this study deals with the frequency instability problem related to excessive power generation constraint in the East Coast in the Korea power system, and examines the change in ROCOF before and after BESS operation in the 50, 60, and 65% stage of IBR-oriented renewable energy. In addition, the same analysis is performed even when the response time of the BESS is improved. The reliability criteria related to frequency are ① Maintaining grid frequency of 59.7Hz or higher when one generator trips, and ② Maintaining grid frequency of 59.2Hz or higher when two generators trip. The meaning of the above standard is that the frequency should be maintained at a level at which the UFLS relay does not operate, even when the two largest unit generators (2.8GW) in Korea are tripped from the system. The UFLS step 1 is set at 59.0Hz, but 0.2Hz is operated as a margin.

Fig. 4 shows Korea's PV and WT generation performance in 2020 by time period. The figure shows that Korea still has only 12.2% of the maximum SNSP (: System Non-Synchronous Penetration). Nevertheless, during the light load period in 2020, the 1.4GW nuclear power plant was operated by lowering by about 300MW several times. This is a problem of frequency instability and lack of spinning reserve when a lot of IBRs operate during light load time. As such, it shows that even in relatively low SNSP in independent systems like Korea, the impact of IBR is significant.

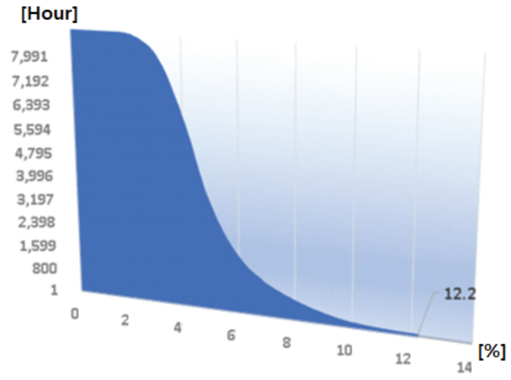

Fig. 4 Hourly SNSP of mainland in korea(2020).

In the event of a 765kV transmission line fault in a large-scale power generation complex in the East Coast of Korea shown in Fig. 5, a system that trips the generator with SPS is operated due to generator transient instability influenced by low inertia. Therefore, to lower the generator trip amount, the power generation constraint operation is implemented by lowering the power generation output in advance.

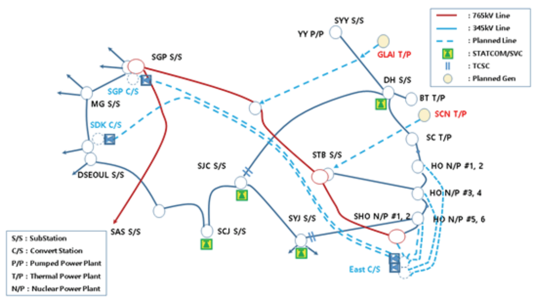

Fig. 5 Power system configuration in the east area of korea.

The problem is that the power generation constraint is currently at 2GW, but is expected to increase significantly from 2024 to a maximum of 6GW. In this case, it is very uneconomical in terms of power generation cost, but the problem of a shortage of reserve is expected due to power supply and demand problems according to the increase in constrained power generation. In Korea, lowering the power generation constraint on the east coast is a very urgent issue, because it is both economical and related to power system stability and power supply and demand issues. If in the future, large-scale renewable energy is built on the east coast, the frequency stability problem will become more severe. Therefore, we examine the method of mitigating ROCOF and nadir frequency using BESS, which has the fastest response among existing facilities.

3.2 Power system frequency response of BESS

As shown in Fig. 6, frequency control reserve (FCR) refers to the reserve in response to the deviation of the local frequency $f(t)$ from the grid frequency normal value f_N Low frequency occurs when the grid demand is higher than the total power generation, and high frequency occurs when the total power generation is greater than the grid demand. Therefore, the BESS is discharged in response to a positive (+) frequency deviation, and when a negative (−) frequency deviation is measured, a charging strategy must be applied. In general, the power response of the BESS used as a frequency response resource should be provided in proportion to the frequency deviation calculated by the following equation:

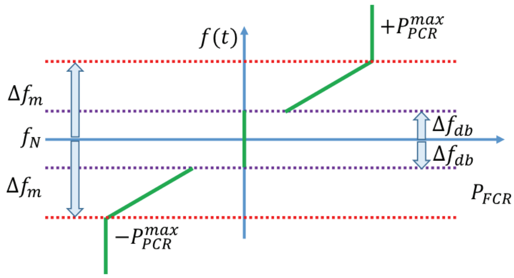

Fig. 6 Frequency response reserve parameter.

$$\triangle f(t) = f_N - f(t) \tag{8}$$

$$P_{FCR} = \begin{cases} P_{FCR}^{\max}\left(\frac{\triangle f(t)}{|\triangle f(t)|}\right), & |\triangle f(t)| \le |\triangle f_m| \\ P_{FCR}^{\max}\left(\frac{\triangle f(t)}{|\triangle f_m|}\right), & |f_{db}| < |\triangle f(t)| < |\triangle f_m| \\ 0, & |\triangle f(t)| \le |\triangle f_{db}| \end{cases} \tag{9}$$

where, $\triangle f(t)$: Frequency deviation,
P_{FCR} : FCR Power,
$P_{FCR}^{\max}$: FCR Maximum Power,
$\triangle f_m$: Full activation frequency deviation,
f_{db} : Frequency deadband.

According to Eq. (9), if the current absolute value of frequency deviation is greater than or equal to the maximum output frequency deviation, the resource provides $+P_{FCR}^{\max}$ or $-P_{FCR}^{\max}$ output according to the positive (+)/negative (−) of the frequency deviation. If the absolute value of the current frequency deviation is greater than the frequency deadband and lower than the maximum output frequency deviation, the P output of the frequency control reserve is provided according to the ratio of the current frequency deviation to the maximum output frequency deviation; while if the absolute value of the current frequency deviation is equal to or lower than the frequency deadband, the P output is not provided. Not all frequency control reserve resources implement a deadband, or provide active power with a proportional rule, such as Eq. (9). The parameter that needs to be defined when providing the frequency control reserve is the time to reach the maximum output, which is defined as the full activation time. It can be said that the shorter the maximum output response time, the more accurate the response to the frequency change. This full activation time can be said to be the essential difference between natural inertia, which has virtually no activation time, and synthetic inertia. By lowering this difference, the role of BESS to mitigate nadir frequency, as well as ROCOF, is an essential function of BESS in an independent system where IBR is extremely expanded. By lowering the activation time of the BESS through the controller, the ROCOF improvement effect will be shown. Another parameter is the minimum activation duration, which means the minimum period that frequency-controlled reserve power suppliers must maintain at maximum output. In other words, a frequency-controlled reserve power supplier with a BESS supply capacity limit must be able to provide maximum power in a single direction for a minimum activation period. Fig. 7 shows a schematic to explain the definitions of these two parameters:

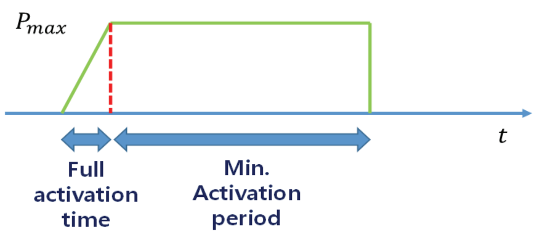

Fig. 7 Full activation time, and minimum activation period.

The full activation time of BESS is divided into T1-T4 shown in Fig. 8. ① T1 : Frequency data acquisition and average frequency time 60~100ms. ② T2 : Region calculation time applied ROCOF Control ~100ms. ③ T3 : PMS and PCS Communication time ~150ms. ④ T4 : PCS response time~50ms.

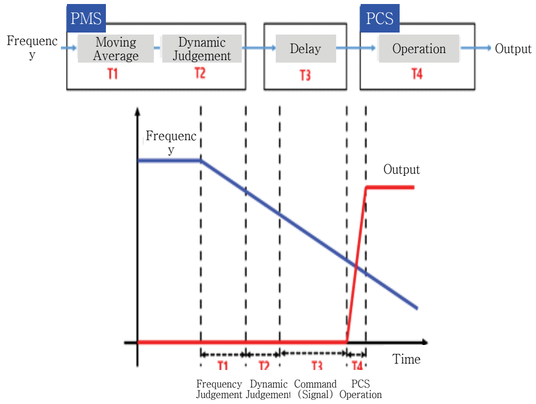

Fig. 8 BESS control full activation time period

BESS Control Full Activation Time Delay is generally set to 500ms. For the BESS to play a similar role, like natural inertia, which has no activation time, it is necessary to reduce the activation time. Table 3 shows the parameters of the BESS installed in Korea. After that, the same parameters are applied to the system simulation.

Table 3. BESS control parameter

Parameter		Setting
Steady state mode	Dead Band	±0.03Hz
	SOC Recovery Control	5%
		10%
	Droop	0.28%
	Sampling frequency	5
Transient state mode	ROCOF	0.0279Hz/s
	System Constant	787 MW/Hz
Recovery mode	Droop	0.16%
	Min frequency	59.9Hz
	Target frequency	60.0Hz
	Sampling frequency	5

3.3 Results of Frequency Stability Enhancement of BESS

The BESS effect verification system simulation (off peak in 2024) scenario for the mitigation of the nadir frequency is as follows:

(Step 0) East Coast Power Complex (SC T/P, SCN T/P, GL, BP T/P) constraint

(Step 1) Simulation of phase angle stability and frequency of the East Coast complex

- (0.5 s) 765kV SGP-STB LINE fault
- (1.583 s) Fault clear, LINE CB Open and HO N/P (5, 6 Unit), SHO N/P (1 Unit) trip
- (1.733s) TCSC Boost control (compensation 50 → 70%, 10s duration)
- Confirm phase angle stabilization and minimum frequency of 59.2Hz or higher in HO N/P

(Step 2) Decrease in generation constraint and increase in generation unit trip

- Increased HO N/P unit trip after reducing T/P generation constraints
- Stability and frequency simulation of Step 1
- Confirm phase angle stabilization and minimum frequency of 59.2Hz or higher in HO N/P

(Step 3) Analysis of increasing effect of nadir frequency of BESS

- Applied BESS increase in a certain unit to 154kV substations (5 places) in power demand areas
- Stability and frequency simulation of Step 1
- Confirm phase angle stabilization and minimum frequency of 59.2Hz or higher in HO N/P

The results of frequency stability enhancement of BESS are shown in Table 4.

Table 4. Frequency stability enhancement (mitigation of generator constraint by BESS increase)

BESS Output	Gen constraint / Gen Trip		
	3,864MW / 3,627MW	3,164MW / 4,093MW	2,264MW / 5,148MW
0MW	59.21 Hz	-	-
570MW	-	59.21Hz 122.81%	-
1,750MW	-	-	59.20Hz 91.43%

When the BESS is operated at 570MW, the decrease in Gen constraint through mitigation of nadir frequency is 3,864 → 3,164MW, which is 700MW; and when 1,750MW is operated, 3,864 → 2,264MW, the decrease is 1,600MW. This means that the frequency stability is improved as much as the installed capacity of the BESS, so that the generator can be operated additionally in the real-time system.

Ⅳ. Conclusion

Although Korea's special power system situation, such as having a huge independent system, large-capacity unit generators, clustering of power generation complexes in specific regions, and dependence on a small number of ultra-high voltage transmission lines, is at a low stage of entry into renewable energy, some generators experience output constraint, due to frequency stability issues, etc. It is expected that in the future, large-scale curtailment of renewable energy will be inevitable at the 45% level of SNSP. The means to improve the frequency stability is to install an SC and BESS in the system. The review in this paper found that when 1GW of BESS is installed, it is possible to achieve mitigation of generation constraints up to 90~120% of the installed capacity of BESS by improving the lowest frequency (nadir frequency). In the future, in a situation such as in Korea, in a system where interconnection lines between countries are virtually impossible, the role of the high-speed inertial response facility, SC, and BESS, is very important. In line with the expansion of renewable energy, it is necessary to promote the expansion of renewable energy based on the effect of installing BESS.

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