Effect Analysis for Frequency Recovery of 524 MW Energy Storage System for Frequency Regulation by Simulator

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Abstract

To test the effectiveness of using an energy storage system for frequency regulation, the Energy New Business Laboratory at KEPCO Research Institute installed a 4 MW energy storage system (ESS) demonstration facility at the Jocheon Substation on Jeju Island. And after the successful completion of demonstration operations, a total of 52 MW ESS for frequency regulation was installed in Seo-Anseong (28 MW, governor-free control) and in Shin-Yongin (24 MW, automatic generation control). The control system used in these two sites was based on the control system developed for the 4 MW ESS demonstration facility. KEPCO recently finished the construction of 184 MW ESS for frequency regulation in 8 locations, (e.g. Shin-Gimjae substation, Shin-Gaeryong substation, etc.) and they are currently being tested for automatic operation. KEPCO plans to construct additional ESS facilities (up to a total of about 500 MW for frequency regulation by 2017), thus, various operational tests would first have to be conducted. The high-speed characteristic of ESS can negatively impact the power system in case the 500 MW ESS is not properly operated. At this stage we need to verify how effectively the 500 MW ESS can regulate frequency. In this paper, the effect of using ESS for frequency regulation on the power system of Korea was studied. Simulations were conducted to determine the effect of using a 524 MW ESS for frequency regulation. Models of the power grid and the ESS were developed to verify the performance of the operation system and its control system. When a high capacity power plant is tripped, a 24 MW ESS supplies power automatically and 4 units of 125MW ESS supply power manually. This study only focuses on transient state analysis. It was verified that 500 MW ESS can regulate system frequency faster and more effectively than conventional power plants. Also, it was verified that time-delayed high speed operations of multiple ESS facilities do not negatively impact power system operations. It is recommended that further testing be conducted for a fleet of multiple ESSs with different capacities distributed over multiple substations (e.g. 16, 24, 28, and 48 MW ESS distributed across 20 substations) because each ESS measures frequency individually. The operation of one ESS facility will differ from the other ESSs within the fleet, and may negatively impact the performance of the others. The following are also recommended: (a) studies wherein all ESSs should be operated in automatic mode; (b) studies on the improvement of individual ESS control; and (c) studies on the reapportionment of all ESS energies within the fleet.

Keywords: Battery energy storage system, frequency regulation, governor-free control

I. INTRODUCTION

Battery energy storage systems (BESS) can be used for a variety of purposes such as peak reduction, renewable energy output stabilization, frequency regulation. In Korea, KEPCO currently uses BESS for frequency regulation only. The control system for frequency regulation developed for the 4 MW ESS demonstration facility in the Jocheon Substation was used in the development of the control system of the ESS facilities in Shin-Yongin Substation (24 MW ESS) and Seo-Anseong Substation (28 MW ESS). After the completion and commissioning of these facilities, the technology was used as a basis for frequency regulation purposes in the 54 MW ESS facility at the Power Testing Center at Gochang, Northern Jeolla Province. To verify the effect of increasing ESS capacity for frequency regulation on the efficient and economical operations of the power system, KEPRI developed a simplified power system simulation model. In this paper, the effectiveness of the frequency regulation control system to recover the system frequency in the event a power plant is disconnected from the grid was investigated.

II. MODEL FORMULATION AND SIMULATION RESULTS

A. Simplified Power Grid Model Design

Real-time monitoring of the power system frequency is highly important in maintaining the security and reliability of power supply, and it is therefore necessary to be able to simulate the system frequency. In this study, a simple model of the power system of Korea was created to simulate the effects of the ESS on the power system during an emergency situation. The model includes power generation of power plants, frequency tracking operations by the generator governor, and Automatic Generation Control (AGC) operations through an Energy Management System (EMS). The small-scale power system model was linked to the ESS model that adjusted its output (charge or discharge) depending on the system frequency, voltage, current, and state-of-charge (SOC) based on real-time conditions.

1) Power Grid Model

A simplified model of the power grid of Korea was created for the simulations. As seen in Fig. 1, each power plant was
modeled as a node directly connected to other substations. Also, substations at 154 kV or less were excluded; only those more than 345 kV, and their associated power plants, were included in the model. The power grid model consists of a total of 127 substations, comprised of substations that have a capacity of either 345 kV or 765 kV. Excluded also from the model were the transmission losses and reactive power compensation equipment of each substation. Frequency variations resulting from active power generation, resistive load and reactive power generation, and inductive and capacitive loads variations were calculated.

For the modeling of power plants, only the four following types were included: thermal, combined cycle, nuclear, and pumped hydro. Only these four types of power plants directly connected to substations with capacities of 345 kV or more were included in the model. The actual capacities of these power plants may slightly differ from those used in the model; however, the capacities used in the model accurately depict actual values [1].

2) Daily Load Model
It is important to create a power grid model that accurately depicts the actual power system response during emergency situations to be able to obtain simulation results that are closely similar to those obtained under real-world conditions. In the simulations conducted in this study, the modeled power plants and substations changed their outputs depending on load changes to maintain a system frequency of 60 Hz. A 24-hour load fluctuation model was created based on actual load values [1].

Shown in Fig. 2 is the daily load demand, measured (solid red line) and the measured load (solid blue line) for the year 2014. It can be seen that the load fluctuates throughout the day, with a maximum of 60.1 GW, a minimum of 45.3 GW, and an average of 55.9 GW for the actual load measurements. A 24-hour load fluctuation model was created based on actual load values [1].

Fig. 1. Configuration of the power grid model.

Fig. 2. 24-hour load demand, measured (actual values) and model-based.

3) Frequency Control Model
In an actual power system, there is an imbalance between power supply and demand. In order to respond to these variations, power plants would have to be operational for 24 hours to continuously provide adjustable power. Each power plant is capable of governor-free (GF) frequency tracking, and to be controlled through automatic generation control (AGC) signals sent by an energy management system (EMS).

In this study, the control system was modeled for both frequency tracking operations (governor-free) and for AGC operations. The governor-free, frequency tracking operation of a frequency regulation power plant should be able to respond within 10 seconds after a disturbance occurs, and the frequency regulation power output should be sustained for at least 30 seconds. AGC operations of a frequency regulation power plant should take place within 30 seconds after frequency fluctuations occur, and should be able to maintain an output for 30 minutes [1].

4) Governor Free Model
The equation for generator output change with respect to the frequency tracking operation of the system is formulated as follows:

\[ dP = \frac{P_{gN}}{S_G \times F_N} \times df = -R_p \times df \]  

\[ dP \]: Change in generator output (MW)  
\[ P_{gN} \]: Nominal output of generator (MW)  
\[ S_G \]: Generator droop (%)  
\[ F_N \]: Nominal Frequency (Hz)  
\[ df \]: Change in power system Frequency (Hz)  
\[ R_p \]: Regulating Power (MW/Hz)

In Eq. 1, the generator output, \( dP \), changes depending on the generator droop characteristics and the change in system frequency. In this study, a generator droop ratio, \( S_G \), of 4% to 5% was used for the frequency tracking mode.

The frequency tracking mode operates proportionally with the system frequency change, in that when a power generation loss occurs, a corresponding amount of power should compensate for the loss in order for the power grid to return to a stable state [1].

5) Automatic Generation Control Model
The equation for generator output change with respect to the AGC operation of the system is formulated as follows:
Within 5 to 10 minutes of a grid disturbance, frequency tracking (governor-free) operations must take place and provide power until the target power output for GF operations has been met. AGC operations take place for 30 minutes after a grid disturbance and must provide power until the system frequency stabilizes (denoted as the "dead zone" in Fig. 3).

6) Power System Simulation

Shown in Fig. 4 is a display to simulate the power system. The output capacity of each power plant is displayed, along with the power output requirement. With this simulation, the power output per minute of each generator can be controlled and governor free mode and automatic generation control mode were implemented similarly to the control system of the actual power plants. The daily load was applied to the model to simulate actual plant operations. To perform a simulation case where a power plant is suddenly tripped in the grid, the RUN/TRIP mode can be enabled [2][3].

7) ESS Simulation

Shown in Fig. 5 is the 24 MW ESS frequency adjustment controller used for the simulations. With this model, the ESS capacity can be manually adjusted to 4~500 MW. This ESS model mimics the real-world response of a battery ESS, providing near-instantaneous power output at maximum level [5].

B. Power Plant Outage Test

In this study, four cases of power plant outages were conducted. In each case, power plant capacities of 500 MW, 1,000 MW, 1,500 MW, and 2,000 MW, respectively, were turned off. In each case, the response of the power system to restore the system frequency to 60 Hz was observed. Simulations were conducted in two phases: first, without ESS connected to the power system and, second, with the 524 MW ESS connected to the power system to provide frequency regulation. 24 MW ESS was operated by automatic control system and 500 MW ESS was connected manually just after power plant was tripped.

1) Frequency Drop After Power Generation Loss

Shown in Fig. 6 is the change in the system frequency after a 500 MW power plant was disconnected from the grid. From 60 Hz, the system frequency dropped to a minimum of 59.943 Hz in approximately 29 seconds. It took approximately 2 minutes and 40 seconds for the system frequency to return to 60 Hz from the minimum.

Shown in Fig. 7 is the change in the system frequency after a 1,000 MW power plant was disconnected from the grid. From 60 Hz, the system frequency dropped to a minimum of 59.868 Hz in approximately 23 seconds. It took approximately 3 minutes and 56 seconds for the system frequency to return to 60 Hz from the minimum. Compared to the previous case where 500 MW was disconnected from the grid, the minimum frequency was 0.08 Hz lower and was reached in approximately 5 seconds faster. Also, the time it took for the grid to recover and return to 60 Hz was approximately 1 minute and 15 seconds longer.

Shown in Fig. 8 is the change in the system frequency after a 1,500 MW power plant was disconnected from the grid. From 60 Hz, the system frequency dropped to a minimum of 59.868 Hz in approximately 23 seconds. It took approximately 3 minutes and 56 seconds for the system frequency to return to 60 Hz from the minimum. Compared to the previous case where 1,000 MW
was disconnected from the grid, the minimum frequency was 0.06 Hz lower and was reached at approximately the same time. The time it took for the grid to recover and return to 60 Hz took approximately the same amount of time as the previous case.

Shown in Fig. 9 is the change in the system frequency after 2,000 MW of power generation was disconnected from the grid. (This was achieved by turning off two 1,000 MW power plants.) From 60 Hz, the system frequency dropped to a minimum of 59.728 Hz in approximately 26 seconds. The time it took for the system frequency to recover and return to 60 Hz was longer than the previous case at approximately 4 minutes and 14 seconds.

Fig. 6-9 show that the power system model reflects real-world operations after generation loss occurs, resulting to a drop in the system frequency. A power system should be capable of restoring the system frequency of 60 Hz after power generation loss by utilizing reserve resources through governor-free and AGC operations [3].

2) Effect of ESS Frequency Response During Power Plant Outage

Discussed in this section are the simulation results conducted with 524 MW frequency regulation ESS connected to the power system. If needed, the frequency regulation control model can be increased to 500 MW.

As with the first phase of the simulations, power plant generation of 500 MW, 1,000 MW, 1,500 MW, and 2,000 MW will also be disconnected from the power plant in the second phase of the simulations. The output of the frequency regulation ESS will be shown in this section together with system frequency measurements.

Shown in Fig. 10 is the change in the system frequency after a 500 MW power plant was disconnected from the grid. From 60 Hz, the system frequency dropped to a minimum of 59.966 Hz in approximately 22 seconds. It took approximately 2 minutes and 17 seconds for the system frequency to return to 60 Hz from the minimum. Compared with the results shown in Fig. 6, the minimum frequency in Fig. 10 is higher by 0.0227 Hz.

Shown in Fig. 11 is the change in the system frequency after a 1,000 MW power plant was disconnected from the grid. From 60 Hz, the system frequency dropped to a minimum of 59.930 Hz in approximately 16 seconds. It took approximately 2 minutes and 38 seconds for the system frequency to return to 60 Hz from the minimum. Compared with the results shown in Fig. 7, the minimum frequency in Fig. 11 is higher by 0.0617 Hz.

Shown in Fig. 12 is the change in the system frequency after a 1,500 MW power plant was disconnected from the grid. From 60 Hz, the system frequency dropped to a minimum of 59.872 Hz in approximately 19 seconds. It took approximately 3 minutes and 6 seconds for the system frequency to return to 60 Hz from the minimum. Compared with the results shown in Fig. 8, the minimum frequency in Fig. 11 is higher by 0.0618 Hz.

Shown in Fig. 13 is the change in the system frequency after 2,000 MW of power generation was disconnected from the grid. (This was achieved by turning off two 1,000 MW power plants.) From 60 Hz, the system frequency dropped to a minimum of 59.761 Hz in approximately 21 seconds. It took approximately 3 minutes and 32 seconds for the system frequency to return to 60 Hz from the minimum. Compared with the results shown in Fig. 9, the minimum frequency in Fig. 11 is higher by 0.0327 Hz.

Based on the results of each case obtained from the second
3. Analysis of the effect of Using ESS for Frequency Regulation During Power Plant Outages

Based on the simulation results presented above, it can be seen that the frequency regulation ESS control model was able to improve the recovery of the system frequency in the event that a power plant is suddenly disconnected from the power system. As shown in Table 1, the ESS is capable of responding in less than one second to deliver maximum power output. This is a significant difference over the response time of conventional frequency regulation assets that take several seconds before maximum power output is reached. It can also be seen that the frequency nadir (lowest point) is improved when ESS is used. Moreover, the speed by which the system frequency returns to 60 Hz is also faster. This is attributed to the fast response of the ESS, which can provide maximum power output while other conventional frequency regulation assets are still ramping up power.

These results show that using ESS for frequency regulation

Table 1. Frequency regulation simulation results

| Gen. Loss (MW) | Event | Time (MM:SS) | Freq. (Hz) | Time (MM:SS) | Freq. (Hz) |
|----------------|-------|--------------|------------|--------------|------------|
|                |       | Without ESS  | With ESS   |              |            |
| 500            | Gen. Loss | 00:06.660   | 60.0013    | 00:15.430    | 60.0018    |
|                | ESS Start | 00:16.780   | 59.9921    |              |            |
|                | Freq. Nadir | 00:35.630   | 59.9434    | 00:22.240    | 59.9661    |
|                | Full Recovery | 03:14.940   | 60.0018    | 00:44.930    | 60.0018    |
| 1,000          | Gen. Loss | 00:09.540   | 60.0003    | 00:03.840    | 60.0003    |
|                | ESS Start | 00:04.520   | 59.9921    |              |            |
|                | Freq. Nadir | 00:33.350   | 59.8687    | 00:20.340    | 59.9304    |
|                | Full Recovery | 04:29.530   | 60.0003    | 02:58.690    | 60.0023    |
| 1,500          | Gen. Loss | 00:12.240   | 60.0013    | 00:13.210    | 60.0018    |
|                | ESS Start | 00:13.710   | 59.9921    |              |            |
|                | Freq. Nadir | 00:37.280   | 59.8098    | 02:58.690    | 59.8716    |
|                | Full Recovery | 04:27.540   | 60.0008    | 03:39.470    | 60.0008    |
| 2,000          | Gen. Loss | 00:08.630   | 60.0008    | 00:02.320    | 60.0013    |
|                | ESS Start | 00:03.520   | 59.9825    |              |            |
|                | Freq. Nadir | 00:35.410   | 59.7284    | 00:24.580    | 59.7611    |
|                | Full Recovery | 04:50.040   | 60.0008    | 03:56.720    | 60.0008    |
during events of sudden power generation loss improves the reliability of the power system.

III. CONCLUSIONS

In this study, the effect on the power system of using ESS for frequency regulation was investigated. The ESS control algorithm developed for the ESS facilities in Seo-Anseong (28 MW ESS) and in Shin-Yongin (24 MW ESS) was used in this study. A simplified model of the power system of Korea was also used in the simulations. In the simulations, generators were turned off to simulate a power plant outage. Four cases were considered for the simulations: 500 MW, 1,000 MW, 1,500 MW, and 2,000 MW of power generation where disconnected from the power system. The first phase of the simulations did not include an ESS so as to establish base cases and observe how the power system will respond to frequency change due to the power plant outage. The second phase included a frequency regulation ESS model with a capacity of 524 MW.

It was observed that the 524 MW frequency regulation ESS model was capable of responding in less than one second after power plant disconnection. It was also observed that the addition of the ESS was able to reduce the amount by which the system frequency drops and also increase the speed by which the system frequency recovers and returns to 60 Hz. These benefits are attributed to the quick charging and discharging characteristics of the ESS.

The results of this study demonstrate the benefits of installing ESS for frequency regulation services. This study also provides a basis for conducting simulation tests for the 500 MW ESS that is planned to be installed by KEPCO in 2017.

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