Application of Frequency Regulation Control on the 4MW/8MWh Battery Energy Storage System (BESS) in Jeju Island, Republic of Korea

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Abstract: Energy Storage Systems (ESS) have an impressive track record for providing stability and efficient power management in power system. With recent technological advancements and the decline in costs, the use of battery for ESS is gradually becoming popular in the power industry. In particular, Lithium-ion Battery (LiB) is being used in various power grids around the world. In Jocheon, Jeju Island, Republic of Korea, operation and control of grid-connected Battery Energy Storage System (BESS) of 4MW/8MWh capacity has been in demonstration phase since 2013. Several simulation tests were already performed for peak shaving, renewable energy output smoothing, and most recently, frequency regulation control. On-site tests are continuously performed for frequency regulation. In previous tests, control algorithm was coded, modified and tested to load into controller and communication system, and human-machine interface was developed. The BESS Energy storage was connected to grid for frequency regulation using both simulated and actual frequency variations. The most recent results are presented in this paper showing BESS frequency regulation with continuous operation duration for three days. It was also observed in the results that BESS frequency regulation has faster response, less costs and less capacity of energy storage systems which cover for frequency regulation of power plants. Time reduction and time-delay elements are also investigated.

Keywords: Battery, energy storage system, frequency regulation, grid-connected control system.

1. Introduction

The developments on Energy Storage System (ESS) recently focus on the compensation of maximum power system load, frequency regulation, and renewable energy output smoothing.

To assess the performance and benefits of ESS, Korea Electric Power Corporation (KEPCO) has an on-going demonstration project using Li-ion Battery-ESS (BESS) with capacity of 4MW/8MWh. Peak shaving and renewable energy output smoothing had already been assessed in this project and results are continuously evaluated. This is KEPCO’s first step towards the commercialization of ESS with the use of Li-ion battery.

In this paper, we concentrate on using BESS for frequency regulation on real system, in this case in Jocheon substation in Jeju Island. Frequency fluctuations are caused by small load perturbations which continuously disturb the normal operation of power systems. Therefore, the generation rate must be changed until the frequency and tie-line power are maintained close to their acceptable limits [1]. To some extent BESS will be able to execute this function instead of the generators. Several researches [1-3] have proposed several control schemes for frequency regulation function of BESS. This time we implement a control algorithm for the demonstration of frequency regulation on actual power system with BESS.

The frequency control algorithm developed for power system simulation programs in Jeju power grid
uses PSS/E with C# programming language. The frequency control used in the substation with BESS in conjunction with the installation requirements for commercial use. Control algorithms were modified to communicate with other already installed control equipment.

Since previous results of the demonstration project confirmed the use of BESS to control frequency fluctuations for actual power system, we continue in investigating the effectiveness of BESS frequency regulation response in longer duration.

2. Frequency Regulation Control Theory and Methodology

2.1 Domestic Power System Frequency Operating Status

The frequency operation reported by Korea Power Exchange (KPX) is shown in Table 1. Sampling is done for every 2 seconds in one month during December 2013. The provisions in Electricity Act require maintaining the power system frequency range of 60 ± 0.2 Hz [4].

2.2 Frequency Control in a Thermal Power Plant

Power plant turbine speed is 3600 [rpm] and varies depending on the turbine type, normally ranging from 0.06 to 0.4. Deviation of 0.036 Hz (± 0.018 Hz) corresponds to 0.06 % of the reference frequency. Fig. 1 shows the KPX’s Automatic Generation Control (AGC) signals when frequency changes continuously considering 482 MW generator output.

Points A, B, and C (uppercase letters) is set to the upper limit when the power system frequency is greater than 0.018 Hz-frequency dead band. Points a, b, and c (lowercase letters) are the points after the upper limit frequency points A, B, and C. The power output is increased to reduce the frequency. If the power system’s frequency variation is kept constant AGC setting maintains the frequency within the tracking operation limits. It can be seen that it has a time delay, and then the generator output fluctuation is outside the dead band frequency.

<table>
<thead>
<tr>
<th>Freq</th>
<th>No. of freq. variations</th>
<th>Share rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>59.8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>59.81</td>
<td>26</td>
<td>0</td>
</tr>
<tr>
<td>59.91</td>
<td>3730</td>
<td>0.28</td>
</tr>
<tr>
<td>59.96</td>
<td>635699</td>
<td>51.2</td>
</tr>
<tr>
<td>60.1</td>
<td>644055</td>
<td>48.09</td>
</tr>
<tr>
<td>60.06</td>
<td>5690</td>
<td>0.42</td>
</tr>
<tr>
<td>60.11</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60.2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig. 1 AGC provided by KPX.

Fig. 2 shows the frequency variation with the generator power output when the power exchange falls to 455 MW from 485 MW with AGC signal. This fluctuation continues until a 5 MW deviation occurs as seen on the AGC signal output after point D. Frequency is rising after point D despite the fall after point d, where you can see frequency adjustment by AGC.

2.3 Configuration of BESS Frequency Regulation Controller

Fig. 3 shows the BESS frequency regulation controller configuration, the power charge and discharge system (Power Conditioning System (PCS)), and connection to the battery.
The frequency regulation controller device consists of control algorithm computing devices, communication apparatus, and a frequency measuring unit. The frequency controller receives the frequency signals as input and is sent to the PCS in order to determine the dispatch operation. The PCS system consists of a control panel, the drive panel, and the input panel. The charging and discharging dispatch for the battery will be according to the request signal received from the frequency controller.

The actual frequency regulation control system for BESS configuration is shown in Fig. 4. The whole control system consists of a control algorithm computing devices, communication apparatus, the frequency measuring device and a set of console for driving the frequency regulation controller device. The PCS system is composed of four sets of 1 MW power charge and discharge system. The PCS is in conjunction with one set 1 MW frequency regulation controller with a set of controls and communication configuration. The smallest unit of a battery (cell) constitutes a 1MWh multiple cell battery connected to the battery monitoring system. The BESS has eight (8) 1-MWh batteries, and two of them are linked to one (1) MW PCS, one set of frequency regulation controller, and corresponding set of communication controllers.

2.4 Frequency Regulation Control Method for the BESS

The frequency regulation control method is divided into three separate control method categories or states for adjusting the frequency of the BESS. These states are transient control state, steady state, the exit state.

Fig. 5 shows an overview of the frequency regulation control for BESS. The algorithm is coded using C# programming language. The algorithm first receives input data, such as frequency and battery charge status. Then, it calculates a frequency error to determine the state of operation.

During transient state, signal is sent to the PCS, and then battery output target value is now set to transient state control mode. While in a non-transient state, the
battery output target value is set to steady-state control mode. After experiencing a transient state, the process returns to the normal state control mode which passes through the exit state control mode. Steady-state control mode is applied when there is no fault and in consideration of the battery State of Charge (SOC). It does not require a control system to ensure a fast control response of the available capacity of the battery energy storage system (to minimize the steady-state). Eq. (1) represents the control strategy of the steady-state control mode [5].

\[
P_{\text{ess}} = \begin{cases} 
0\% \leq SOC \leq 40\%: & \begin{cases} 
0, f \leq -30 \text{ mHz} \\
-10, f -30 \text{ mHz} \leq f \leq 30 \text{ mHz} \\
P_{\text{req}}^{30} 30 \text{ mHz} < f 
\end{cases} \\
40\% \leq SOC < 80\%: & \begin{cases} 
-5, f -30 \text{ mHz} \leq f \leq 30 \text{ mHz} \\
P_{\text{req}}^{30} 30 \text{ mHz} < f 
\end{cases} \\
80\% \leq SOC \leq 100\%: & \begin{cases} 
10, f -30 \text{ mHz} \leq f \leq 30 \text{ mHz} \\
P_{\text{req}}^{30} 30 \text{ mHz} < f 
\end{cases} 
\end{cases}
\] (1)

We set the discharge limit and this is decreasing all throughout the BESS operation lifetime. The dead zone was set to control the frequency shift in order to prevent a reduction in battery life due to frequent charging and discharging operations. Very small amounts of charging and discharging for the BESS as response to the fast-changing frequency fluctuations may result to decreased efficiency and may negatively affect the overall facility life [6]. These small amounts of charging and discharging are not recognized by the system.

In the state of charge between 40 % to 80 %, and the charge and discharge control in other areas other than the dead band, constant K is applied with output change rate of 4 % of the existing power generation source in accordance with the grid frequency variations. Control is enabled for discharging during 80 % - 100 % state of charge while charging is enabled during 0 % to 40 % state of charge.

In the above mentioned charge-discharge limits and controls, the output of the BESS is determined by applying K (domestic power system). Constant integer K is eliminated from the generator power system: The amount of the minimum frequency will be eliminated at the generators that correspond to the values for frequency error. Since it is possible to control the nature of fast energy storage device to store excess energy when the power system based on the frequency required by the system, constant K was estimated by calculating the requirements of the device in proportion to the drop in the operable region before reaching the point of maximum yield point and then to the minimum frequency grid disturbance. There is a need to avoid sudden changes in the output when it returns to the steady-state control mode, starting from the transient period until the system recovers. When the exit state mode changes to the normal state control mode, it yields a dynamic or transient control mode state of the energy storage device.

\[
P_{\text{ess}} = \begin{cases} 
0\% \leq SOC \leq 40\% & \begin{cases} 
\frac{df}{dt} < 0, K\Delta f \\
\frac{df}{dt} \geq 0, & P_{af} \geq (Kd, f) 
\end{cases} \\
40\% \leq SOC < 100\% & \begin{cases} 
\frac{df}{dt} > 0, & P_{af} < (Kd, f) 
\end{cases} 
\end{cases}
\] (2)

Eq. (2) represents the dynamic state control mode the control strategy of the energy storage device, the formula [4].

3. Simulation and Demonstration Results

Tests using simulated frequency variations were conducted in previous demonstrations of the project to verify the control algorithm before it is used in BESS for actual power system frequency regulation. In the case of large energy storage devices, a proportional constant is determined for the control of the output value of the BESS in order to correct the error on the power system frequency. In testing energy storage system devices in different power ranges, KPX’s system auxiliary services operating criteria shall apply. Control is applied only when the measured driving speed is out of the dead band or deviated by ± 0.03 Hz from the reference value of the power system frequency [7]. Separate conditions are simulated whether on steady-state or transient state.
Figs. 6-7 show the results of the said simulations for both steady state control mode and transient state control mode. The 102.21 MW/Hz Line Regulation are subjected to a constant strain of 4 % by the Jeju system simulation testing.

In Fig. 6, system power generation capacity is 702 MW, the system load is 699 MW, Jeju’s peak load for the year 2013. Battery charging status of batteries 1-4 are 5, 55, 75, and 95 % respectively.

In Fig. 7, power generation is 702 MW, and system load is 699 MW during the state of the frequency regulation operation of the High-Voltage Direct Current (HVDC) power transmission. Battery SOC for the four units are 5, 55, 75, and 95 %, by applying a peak load of Jeju Island in 2013 and were tested by dropping 35 MW.

It was confirmed that it is possible to control the output of the battery, as shown in the simulation results in Figs. 6-7. It can be discharged even when the battery is partially discharged. In contrast to the steady state, the transient state is determined based on the frequency variation exceeding a continuous span of time.

Each battery charging status, 40 % or more, has to be raised to the maximum power. After the transient control mode is complete, the control was found to decrease the battery output at a constant rate by switching the control mode to the exit state. After completing the simulation test, the frequency regulation control system is connected to the PCS system with all the necessary communication links as shown in Figs. 3-4.

Without connection to the BESS, we used a console controller and Rx3i of GE for frequency regulation control performance and install the corresponding control algorithm in the device. Proficy Machine Edition 7.0 was used to control the logic of Rx3i development program. A control algorithm is developed initially in C# programming language. This must be loaded into this controller device. However, because the inputs that are loadable in the Rx3i device must be in C programming language, the algorithm structure associated must be modified. The new structure could be expressed in the form of a combined ladder diagram and functional block diagram. It is therefore necessary to debug the manually modified automatic control logic [8].

Once the control algorithm is loaded into the controller similar results are obtained between the simulation shown in Figs. 6-7 and the simulation shown in Figs. 8-9. The process proceeds without the communication associated with PCS. This confirms that the controller is operating normally in accordance with the control algorithms. As the coded algorithm is verified and performed properly, we proceeded with the field test connecting the BESS.

The task was to develop a parallel operation of the console screen and the control strategy developed in the controller. Fig. 10 shows the configuration of the console controller for individual and collective control. This includes controller tuning function, frequency fluctuations simulated function, alarm and event functions, trend function, communication network surveillance, starting sequence, automatic control and
monitoring functions.

A phenomenon occurred when the scan time is relatively long, and indicated the linear portion from the measured results. The delay occurred for 79 ms during the steady state control. Similarly, there is also a communication delay between the controller and the PCS. During charging and discharging dispatch, delays are required to reach the battery output target value. Currently, the system has a very short time (ms) during dispatch including the processing time of the controller system itself, and the communication between controller and PCS. The system latent period was measured as the amount of time it takes for BESS dispatch to respond after signal is sent. The delay in the entire loop was found out to be 79 ms. The measured time delay was verified considering the output target value of (180 ~ 100 kW.)

If the frequency variation rate is -0.306 [Hz/sec] or less, the system is considered to be in transient state. It is shown in Fig. 11 that it took around 7 ms for the algorithm process to calculate frequency by measuring voltage and current from the distribution line and to assign a battery output target value in conjunction with the charging and discharging dispatch of the BESS. The simulated field test shown in Figs. 6-7 has an 8.3 ms time interval. It took 10120 ms (10.12 seconds) for controlling the BESS output using the target value when the controller is in the transient state of frequency variation. The target value is determined in accordance with the measured battery output from the power quality measurement devices which took 279 ms. Therefore that took a total delay of 10399 ms (10.4 seconds). It took the 400 ms from the start of discharging a battery until it reached 1000 kW.

Although a time delay occurred in the entire loop, it was confirmed that the control of the battery output is in accordance to the battery output target value. Also, the exit status mode control operates normally in order to eliminate the shock in the transient state when switching to the normal or steady state. The battery output target value of the transient state is a value controlled by the proportional gain as given in Eq. (3) [9]:

\[ M = K_c E \]  (3)

where \( M \) is the battery output demand; \( K_c \) is the controller proportional constant; and \( E \) is the error. During exit control mode operation Eqs. (3) and (4) are used:

\[ M = K_c E - M_r \]  (4)

where \( M_r \) is the exit mode control reduction bias. In Eq. (5) and the initial value of the \( M_r (M_{r0}) \) are calculated:

\[ M_{r0} = E_0 - R_s E_0 \]  (5)

where \( M_0 \) is the battery output when transient state ends; \( R_s \) is decreasing rate of exit control mode; and \( E_0 \) is the deviation between the battery output of
transient state and steady state when transient state is finished.

Fig. 11 shows the steady state frequency regulation with some delay time from the energy storage device to the battery output target value that is input to the console for operating the grid frequency.

Fig. 12 shows the frequency change rate within the transient criteria, between -0.0306 [Hz/sec] and -0.486 [Hz/sec], and the frequency change lasted for about 120 ms. Based on the duration of the transient state where in the corresponding frequency regulation control command is applied.

Power was transferred to PCS, at 180 ms until output target value (1000 kW) is reached and thus there will be a continuous rise of frequency and corresponding variability. Fig. 12 shows the generation delay time of 60 ms, which represents the time for the BESS to discharge power to the distribution line as commanded by the controller. In Fig. 12, it shows that 1000 kW 400 ms was spent to reach the output to 1000 kW, and it took 70 ms to measure the results directly from the controller. It was found that it took approximately 130 ms to generate the required battery output after frequency variation during the transient state. 130 ms contains the required process time for the control logic and 14 ms for the sweep controller.

With all the necessary tests done, the whole BESS system together with the frequency regulation controller is connected to the actual power system in Jocheon substation, Jeju Island. Previously frequency regulation of the actual system was only done for a short time (3 seconds) as shown in Fig. 13. Our latest data shows frequency regulation for 3 days. This is shown in Fig. 14. Real time communications are also done for the entire BESS frequency regulation control system and grid with corresponding actual battery charging and discharging dispatch.

It is necessary to control the supply time of the BESS power supply switch by three conditions [10]. First, it should be controlled within the dead-time of the generator to the frequency change time. Second, it must be able to ensure the supply time of about a few seconds for the supply switch to change from transient state to the normal state. Then it should be able to execute control that does not impact the system overall dispatch time. Considering the three conditions, the algorithm could be able to calculate the amount of frequency adjustment period required for the BESS to operate for the frequency regulation of the power system. If deployment is faster, there will be shorter supply time and will ease the requirement for longer feed time for deployment. Faster deployment time for operating an energy storage device gives a stable system with the capacity to operate for much less time in using the energy storage system. In this paper, the state of control mode was confirmed by the operation control of the supply switch. Future research could concentrate in determining deployment time for optimum performance of BESS.

It was therefore confirmed based from the simulation
test results that it is possible for a power system frequency regulation control operation to be applied for an energy storage device with a response time of 130 ms using commercially available programming languages and controller devices.

4. Conclusions

Based on the results, it is confirmed that simulation results for the power system frequency regulation used in this paper are similar to real-time operation of the power system frequency regulation in Jeju Island. It was confirmed that frequency regulation can be performed by the energy storage device, BESS with 4MW/8MWhr capacity. It was found out that the frequency control response is 130 ms to drive the BESS to correct the error of the frequency of the power system based on 60 Hz reference frequency.

Communication links between the different equipment, the control algorithm can be coded in the field control system and the drive to modify complement, was the most difficult part of the screen for the operation control of the new system operation during the development processing subsequent development speed and reliability of data for the energy storage device. Development of a communication system with, was considered to be pursued in parallel from the initial research and development is suitable for the latest control algorithm development.

Rate response to the frequency of the energy storage device error will accelerate more total reduction of the energy storage capacity required for the follow-up frequency of the power plant operation roles. We expect to be able to replace the role frequency tracking operation is also less with plant capacity by studying the factors identified in this paper, and shorten the time delay element.

All of these findings and results on implementing the frequency regulation control of the total BESS to the actual grid marks a significant milestone to the commercialization of large scale BESS for the power system in Republic of Korea.

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