Development of the Control System for Fast-Responding Frequency Regulation in Power Systems using Large-Scale Energy Storage Systems

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Abstract

Energy storage systems (ESS) can be used to provide frequency regulation services in a power system to replace traditional frequency regulation power plants. Battery ESS, in particular, can provide "fast-responding frequency regulation," wherein the facility can respond immediately and accurately to the frequency regulation signal sent by the system operator. This paper presents the development and the trial run results of a frequency regulation control system that uses large-scale ESS for use in a large power system. The control system was developed initially for the 4 MW ESS demonstration facility in Jocheon Jeju Island, and was further developed for use in the 28 MW ESS facility at the Seo-Anseong substation and the 24 MW ESS facility at the Shin-Yongin substation to provide frequency regulation services within mainland Korea. The ESS facility in Seo-Anseong substation responds to a sudden drop in frequency via governor-free control, while the ESS facility in Shin-Yongin responds via automatic generator control (AGC).

Keywords: Energy Storage, Frequency Regulation, Power Systems, Control Algorithm

I. INTRODUCTION

Maintaining the frequency of a power system within an acceptable range and responding to sudden frequency drops are traditionally done by deploying thermal power plants to correct frequency deviations. In Korea, frequency regulation is performed by "governor-free" (GF) control, wherein turbine governors are to respond within 10 seconds and provide power for 30 seconds; and through automatic generation control (AGC), wherein a power plant must respond within 30 seconds and provide power for 30 minutes. These methods, however, are inefficient in that they require power plants to operate below their rated capacity to remain on standby until they are needed.

Using fast-responding facilities, like energy storage systems (ESS), to provide frequency regulation services have been determined to provide the exact amount of power at the exact time needed. This, in turn, allows power plants initially designated for frequency regulation to provide power at a constant rate to supply energy demands. Using energy storage systems in conjunction with traditional power plants can therefore increase the overall system efficiency [1].

Using ESS has also been determined to allow better integration of renewable energy resources with the power grid. Among the capabilities of ESS for grid applications are smoothing of output from renewable energy, frequency regulation, electric energy time-shift, and providing emergency power reserves [2]. The capabilities of ESS for providing these services have been demonstrated in the 4 MW/8 MWh lithium-ion battery ESS at the Jocheon substation on Jeju Island. The KEPCO Research Institute has developed different technologies for using the ESS facility to provide grid services, and one these technologies is a frequency regulation controller. After successful demonstrations were completed in 2014, frequency regulation controller (FRC) technology developed for the ESS facility in the Jocheon substation was used as a basis for developing the FRC at the new 54 MW ESS facilities in the Seo-Anseong and Shin-Yongin substations [3].

As stipulated in the "6th Basic Plan for Long-Term Electricity Supply and Demand" published in 2013 and the "2nd Energy Master Plan" published in 2014 both by the Ministry of Trade, Industry and Energy (MOTIE), Korea will have to increase the presence of renewable resources in its total power generation mix for up to 20% by 2027. This amounts to 32 GW of renewable generation capacity, wherein 17 GW will be for wind power generation. The increase in intermittent renewable energy resources then poses a challenge to maintain the system frequency of national grid, and using ESS is one way of meeting this challenge. Both policies published by MOTIE require the installation of 500 MW ESS in 2015, and the capacity will eventually be expanded to 2,000 MW by 2020. The frequency regulation controller developed in this study will be among the many technologies being developed under the ESS capacity expansion efforts [4][5].

This paper presents the development and trial run results of the frequency regulation controller for the 52 MW ESS facilities in Seo-Ansong and Shin-Yongin. Section 2 discusses the necessity for using ESS as a fast-responding resource in frequency regulation. Section 3 shows the 4 MW/8 MWh ESS facility at the Jocheon substation on Jeju Island. Section 4 discusses the 24 MW and 28 MW ESS facilities in Seo-Anseong and Shin-Yongin. This section includes the system setup as well as the control algorithm. Section 5 discusses the simulation results and actual results. In Section 6 is the conclusion of this paper.

II. BATTERY ESS FOR FAST-RESPONDING FREQUENCY REGULATION

Battery energy storage systems (BESS) will play a major role in the reliable and economic operation of power systems, especially in power systems with a high presence of intermittent renewable energy resources. Among the many applications of

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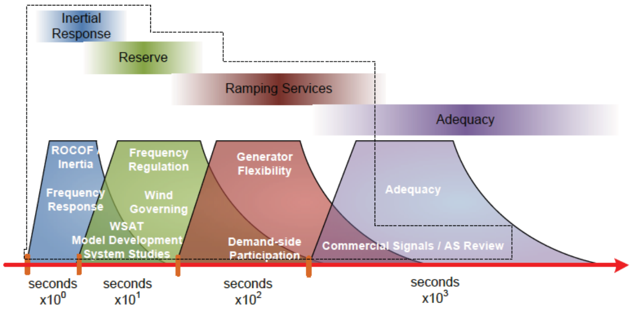

Fig. 1. Overview of proposed frequency control operations.

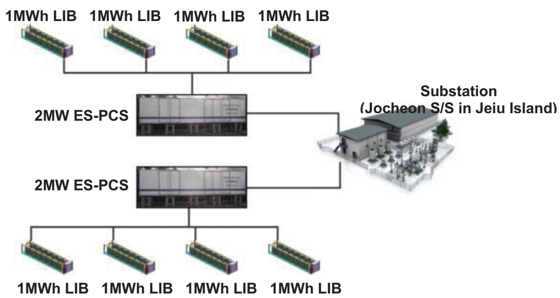

Fig. 2. Configuration of the 4 MW/8 MWh LiB system of the BESS facility at Jocheon, Jeju Island.

energy storage, one of the important applications that BESS can provide to power systems is frequency regulation [6]. The technical and economic benefits of using energy storage for frequency regulation are already being proven in the US, particularly in the PJM Interconnection in the United States, where regulatory policies and markets for energy storage are already in place [7]-[9].

Fast-responding frequency regulation systems are gaining greater importance in power systems of the future due to the increasing integration of renewable sources in power grids across the globe. This increase poses a threat in maintaining an inherent property of traditional power grids; it is often referred to as *system inertia*. System inertia is a property of a power system that is necessary in maintaining system stability. System inertia is due to the presence of rotating synchronous machines, mainly in the form of large thermal generators. Increasing the presence of renewable energy resources, like solar, that do not rely on rotating synchronous machines decreases the overall system inertia. This reduction in overall system inertia, however, can be mitigated by deploying fast-responding frequency regulation systems [10].

The system operator, EirGrid, in Ireland, for example, currently has plans in using fast-responding energy storage due to the increasing penetration of wind power in the Irish power grid. EirGrid defines fast frequency response as the additional increase in MW output from a generator or reduction in demand following a frequency event that is available within 2 seconds of the start of the event and is sustained for at least 8 seconds [11]. The additional energy that will be provided within the said period must be greater than any loss of energy within a time frame of 10 to 20 seconds. Shown in Fig. 1, is an overview of the proposed frequency control operations by EirGrid [12]. It can be seen that frequency response facilities should respond quickly after a sudden drop in system frequency. Other examples of system operators that currently have plans for integrating BESS for frequency regulation in their respective power systems are,

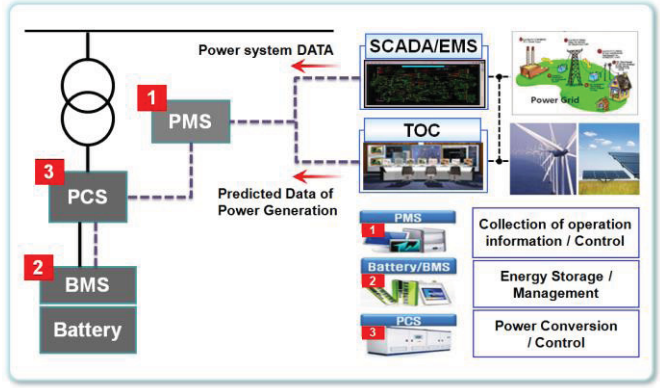

Fig. 3. The BESS configuration.

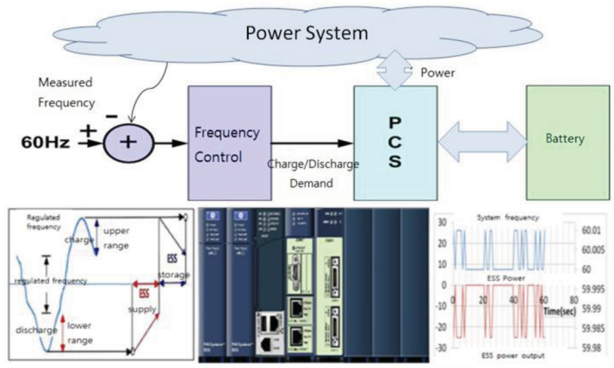

Fig. 4. Frequency regulation controller configuration.

CAISO and ERCOT in the US, and National Grid in the UK [13]-[15].

III. THE BESS FACILITY IN JOCHEON, JEJU ISLAND

To explore the capabilities of using ESS for power grid applications, KEPCO implemented a demonstration project of a large-scale grid connected 4 MW/8 MWh Battery ESS (BESS) that uses Li-ion batteries. The 4 MW/8 MWh BESS is simultaneously connected to a 22.9 kV substation bus and distribution line in Jocheon, Jeju Island for offshore wind turbines. The operation strategies for the BESS that were developed are peak-shaving (or electric energy time-shift), frequency regulation, and wind energy output smoothing.

The demonstration project used 60 Ah battery cells and configured into 1.8 kWh modules, two of which make up a 3.6 kWh tray. One power rack consists of 16 trays (56.8 kWh capacity), a Li-ion Battery Management System (BMS) rack, and a switch gear. One container consists of 18 racks connected in parallel, amounting to a total of 1 MWh.

The BESS consists of a 4 MW PCS and 8 MWh batteries installed in Jocheon substation, Jeju Island. There are four 1 MW PCS configured to have a total capacity of 4 MW. Each 1 MW PCS is connected to two containers of 1 MWh batteries, with a total of 2 MWh capacity paired in one PCS. This amounts to a discharging duration of 2 hours. In addition, the BESS may charge and discharge power to and from the grid through the PCS as dictated by the power management system (PMS). The system configurations of the facilities are shown in Fig. 2 to 3.

Fig. 4 shows the BESS frequency regulation controller configuration, the power charge and discharge system (or the

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

IV. THE SEO-ANSEONG AND SHIN-YONGIN FR-ESS

Following the successful demonstrations performed at the 4MW/8MWh BESS facility of the Jocheon Substation located in Jeju Island, the construction of the FR-ESS facilities at the Seo-Anseong and Shin-Yongin Substations took place in October 2014, and the installation of the lithium-ion battery systems and the power conditioning systems (PCS) was completed in February 2015. The two newer ESS facilities use technology based on the technology developed for the demonstration facility on Jeju Island. Since April 2015, the ESS facilities have been in continuous operation to test and monitor the control algorithms and the ESS performance.

A. ESS System Configuration

The 28 MW Seo-Anseong FR-ESS facility performs governor response operations to regulate the system frequency. The 24 MW Shin-Yongin FR-ESS facility performs AGC operations by providing power depending on the AGC control signal it receives. Both facilities perform frequency regulation services under normal conditions to maintain the system frequency at 60 Hz.

The FR-ESS facilities are each connected to a 22.9 kV bus at each substation as shown in Fig. 5. The 22.9 kV bus is connected to the 440 V PCS via a step-down transformer. The PCS is also connected to the battery system (battery management system and lithium ion batteries) both electrically and via a communication line. The PCS communicates also with the frequency regulation controller (FRC), which determines the output of the battery system needed to maintain the required frequency level of 60 Hz. The FRC can be set to “manual mode” or “auto mode” via the human-machine interface (HMI), which also displays critical information such as the system frequency, individual battery state-of-charge (SOC) and temperature.

B. Frequency Regulation Algorithms

Under normal conditions where the system frequency fluctuates within the acceptable limits or the “dead band” (e.g., 59.97 Hz to 60.03 Hz), the 28 MW Seo-Anseong FR-ESS facility will charge or discharge energy to maintain a predetermined SOC. When the input frequency is less than the lower limit of the dead band, the batteries of the FR-ESS will discharge power; and when the input frequency exceeds the upper limit of the dead band, the batteries will be recharged.

Under abnormal or transient conditions when the frequency drops rapidly as shown in Fig. 6, the Seo-Anseong FR-ESS will immediately provide constant maximum power until it reaches a system frequency limit; after which, the FR-ESS will exit its control mode and gradually decrease its output power by a predetermined percentage for every second until its output reaches 0MW. The operation flowchart is shown in Fig. 7.

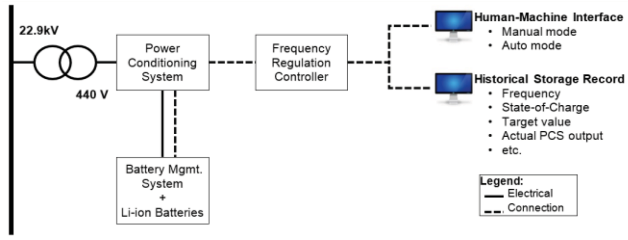

Fig. 5. FR-ESS configuration at the Seo-Anseong and Shin-Yongin substations.

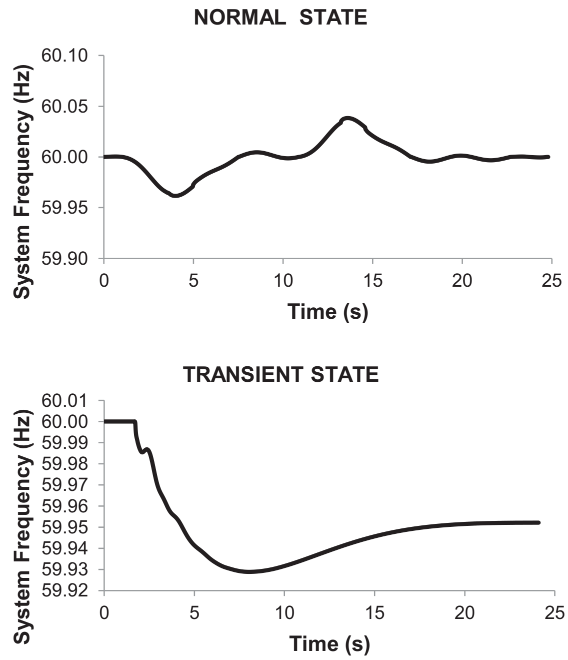

Fig. 6. Normal and abnormal states of the system frequency.

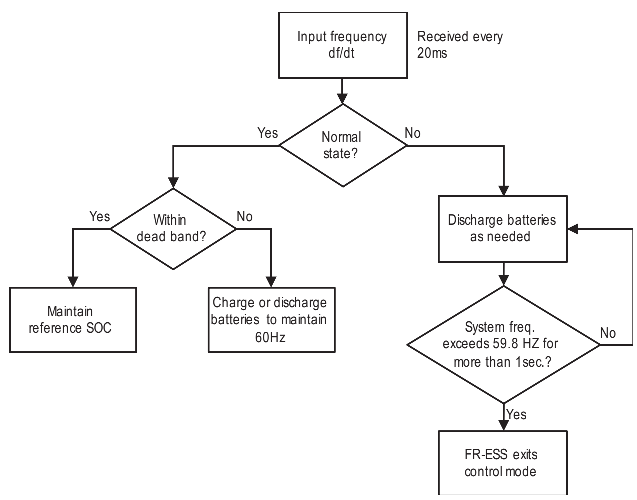

Fig. 7. Seo-Anseong FR-ESS algorithm flowchart.

V. RESULTS

A. Simulation Results

Simulations for the Shin-Yongin and Seo-Anseong facilities

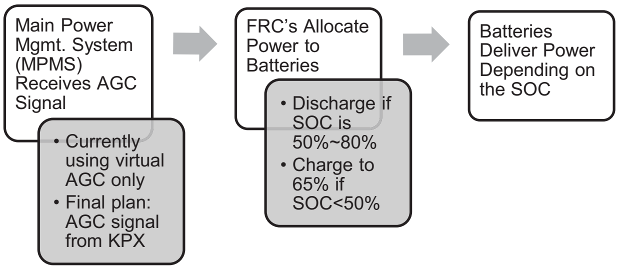

Fig. 8. AGC Operation of the Shin-Yongin FR-ESS.

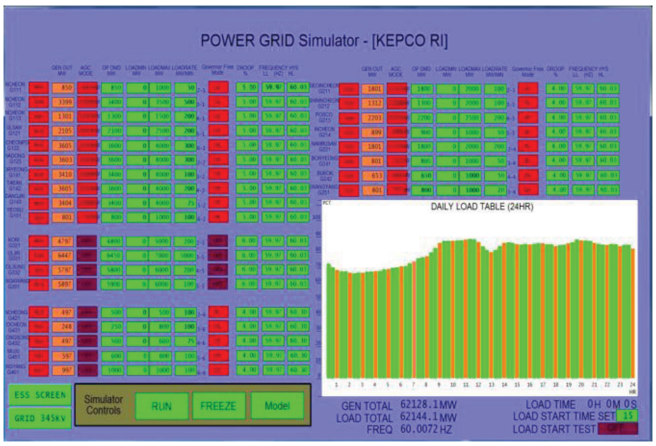

Fig. 9. Interface of the Power Grid Simulator.

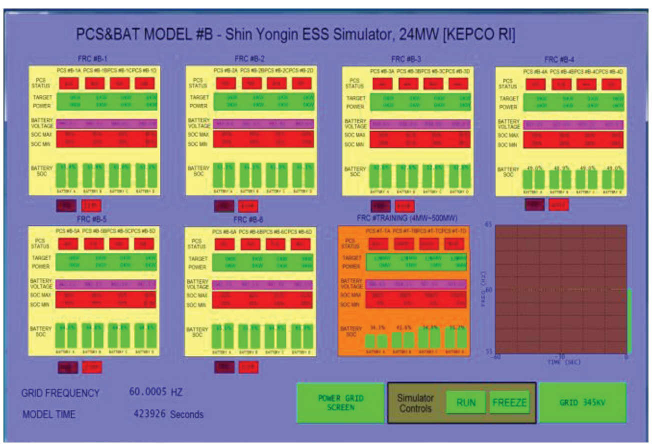

Fig. 10. Interface of the PCS & Battery Model.

were conducted in KEPCO Research Institute using a virtual system that simulates the output of individual generator units connected to the power grid of mainland Korea, as well as the status of each battery. With this virtual system, the output of each generation can be changed as needed to test the frequency control algorithms. Fig. 9 shows the user interface of the Power Grid Simulator. In this screenshot, the status and output of each generator is shown; and from here, they can be individually turned on or off and controlled to deliver a different amount of output power. Fig. 10 shows the user interface of the PCS & Battery Model, wherein the current status of each battery and the corresponding PCS is shown. The output displayed in this screen will be dependent on the status of the generators in the Power Grid Simulator.

Fig. 11 shows sample simulation results from the 28 MW FR-ESS at Seo-Anseong Substation for when the system

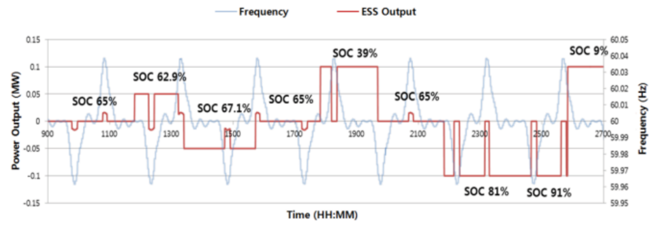

Fig. 11. Sample simulation results at the 28MW Seo-Anseong FR-ESS facilities.

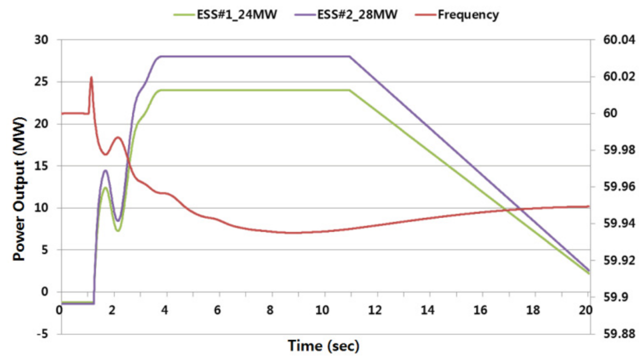

Fig. 12. Response of the FR-ESS at the Seo-Anseong and Shin-Yongin substations during a transient state.

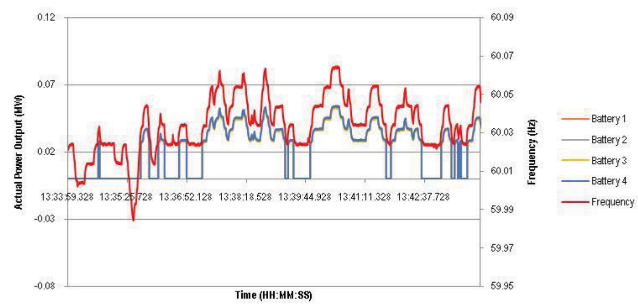

Fig. 13. Frequency regulation results of the Seo-Anseong ESS facility.

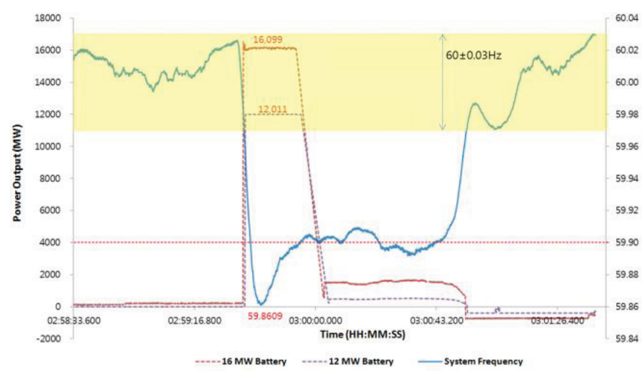

Fig. 14. Frequency response of the Seo-Anseong ESS facility during an emergency event on August 8, 2015.

frequency (blue line) is under normal conditions. The graph shows the state of the battery SOC (red line) over time. When the system frequency is less than the lower limit, the SOC drops (battery discharges); and when the system frequency exceeds the upper limit, the SOC increases (battery charges).

Fig. 12 shows the response of the the Seo-Anseong (purple line) and Shin-Yongin (green line) FR-ESS facilities during a transient state when the system frequency (red line) suddenly drops. It may be observed that both the FR-ESS systems stop delivering maximum output power after approximately 11 seconds and gradually decrease their output over time.

B. Actual Results

Shown in Fig. 13 is a sample of actual frequency regulation data obtained at the Seo-Anseong ESS facility. The data shown was taken from 13:33:34 to 13:33:44 in the afternoon of July 20, 2015. The dead band was set at 59.97 Hz to 60.03 Hz. It may be seen from the figure that when the frequency was above 60.03 Hz, batter numbers 3 to 4 where in a charging state. When the frequency was within the dead band, the batteries were neither in a charging or a discharging state.

At 2:59 a.m. on August 8, 2015, Unit 2 (950 MW) of the Hanbit nuclear power plant halted its operations due to an emergency situation. As the unit went off-line, the system frequency dropped. As shown in Fig. 14, the Seo-Anseong ESS facility responded by providing a full output of 28 MW when the frequency dropped to 59.97 Hz. This continued for 19 seconds until the frequency increased past 59.90 Hz for 1 second. This signaled the ESS to exit the control mode. Although the 28 MW is minimal compared to the 950 MW that had to be compensated for by the whole system, the Seo-Anseong ESS facility was able to show its quick responsiveness during the event.

On the other hand, no data from actual events is available yet from the Shin-Yongin ESS facility. As of present time, the Shin-Yongin substation has been shut down while its main building is undergoing repairs after an emergency situation occurred on July 31, 2015. All operations of the substation, including the operation of the ESS facility, have been temporarily halted. Prior to the said event, the ESS facility has been operating under a testing phase using only a virtual AGC signal.

VI. CONCLUSION

Based on results obtained from real-world conditions at the Seo-Anseong ESS facility and from simulations performed at both the Seo-Anseong and Shin-Yongin ESS facilities, the Li-ion battery energy storage systems were proven to be capable of providing fast-responding frequency control services for the power grid of mainland Korea. During emergency situations when the system frequency rapidly decreases, the ESS facility at the Seo-Anseong substation can provide governor-free response, whereas the ESS facility at the Shin-Yongin substation can provide AGC response. In addition, both facilities are capable of providing real-time frequency regulation services.

KEPCO is currently leading the construction of eight additional ESS facilities all over mainland Korea, with the goal of reaching a total ESS capacity of 200 MW in 2016 for use in the power grid. These facilities will use Li-ion battery technology, as well as the same frequency regulation control algorithms used at the Seo-Anseong and Shin-Yongin substations.

Future studies will include: the development of frequency regulation control systems and simulation models that consider the integration of renewable energy sources; and energy storage systems that use technologies other than Li-ion battery systems.

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