Development of Frequency Control Performance Evaluation Criteria of BESS for Ancillary Service: A case study of Frequency Regulation by KEPCO

Hyeondeok Jo[1], Jeonghyeon Choi[2], Kofi Afrifa Agyeman[3] ,Sekyung Han[*]
Department of Electrical Engineering
Kyungpook National University
South Korea
chd998@gmail.com

***Abstract*— In order to evaluate system frequency regulation ability of BESS, we propose a system equivalent model that can reconstruct the system environment using frequency characteristics. This equivalent model is designed to reflect the relationship between the characteristics of various generator units and the system frequency, and each parameter is parameterized by the actual frequency and the demand power. For the validity of the model, the output power of model and the output power of optimal power flow was compared and verified. In the case study, we verified that we were able to evaluate contribution of Frequency Regulation BESS using the model in actual grid and mentioned various applications.**

***Index Terms*-- Battery energy storage system (BESS), Primary frequency control (PFC), Frequency regulation**

I. Introduction

The power system has metamorphosis in recent years, as a result of the steady growth of renewable energy sources like solar, geothermal, and wind power in the generation mix. Although this brings great advantage as result of its natural eco-friendliness, however, unlike, generators, the uncontrollability of RE poses a major challenge to system operators. BESS, on the other hand, is greatly welcomed by system operators because of its advantage of its large energy storage functionality [1].

The enormousness of BESS applications includes, but not limited to: intermittency compensation of renewable energy, frequency regulation, transient stability, voltage support, frequency compensation, frequency regulation, load leveling, spinning reserve, uninterruptable power supply (UPS), and improvement of energy. Although it is most actively developed due to its colossal applications, expensive initial investment cost and limited lifetime are still obstacles to its commercialization. However, many such projects are still on-going for frequency regulation, because of its economic viability [2]. Fast response due to BESS is suitable for frequency regulation and has proven to be superior to existing generators in recent research [3]. For this reason, the Korea Energy Power company (i.e. KEPCO) is in the process of employing 500MW of BESS for the system frequency regulation until 2017.

For similar reasons, many countries around the world are conducting research on introducing BESS for frequency regulation, but the uncertainty in evaluating how much BESS contributes to frequency security still remains unsolved. This is because of the characteristics of the power system changing instantaneously [1], [4], [5]. Even if the frequency is improved after BESS input, there is no confident in attributing that as an effect of BESS.

Therefore, in order to evaluate the contribution of BESS, a simulation that mimic the grid environment should be implored. In order to simulate a real system, various information such as parameters for a huge number of system parameters are required. It is also very difficult to obtain numerous parameter information and to prove that the simulated system environment is the same as the real system.

This paper proposes an equivalent system model that mitigate these problems. Using the proposed model, we can obtain the power fluctuation that influences the actual frequency variation by inputting the frequency. When the BESS operation is added to the inverse transform model, the influence of the factor on actual system frequency can be grasped. The remaining of the paper is arranged as follows: In section 2, the principle concept of system frequency-power characteristics is discussed. In Section 3, we describe the configuration of the equivalent model and verify the validity of the model. In Section 4, we evaluate the frequency contribution of the BESS

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for frequency regulation in Korea through the system equivalent model proposed in this paper.

II. System Frequency-Power Characteristics

The system frequency is the heartbeat of the grid. It's indicates the balance between power supply and demand of the system. System frequency fluctuations are caused by supply-demand imbalance on the grid. Frequency fluctuations occurs at the instance of sudden power fluctuation.

Generally, load fluctuation can be divided into three components. Small variation of up to a few minutes is called cyclic component. Short-period fluctuation component of a few minutes up to several tens of minutes called fringe component. Several tens of minutes or more of the long-period fluctuation component is called sustained component. System operators aiming to power balance analyze demand power patterns and meteorological factors, and establish a power supply plan to cope with sustained component. However, since it is impossible to predict cyclic and fringe component that have no uniform pattern, the system operator implements a governor control by providing a spinning reservoir. Therefore, long-term fluctuation factors that can respond in real-time are not involved in the frequency, but the fluctuation factors corresponding to the self-control and governor control of the system after the power fluctuation are unfolded on the frequency [6].

System frequency and demand power shows high correlation at every instance in time. As shown in Figure 1, at any given time period, system frequency depicts an inverse proportion with demand power. This is as a result the frequency falls when the demand power rises and the frequency rises when the demand power falls.

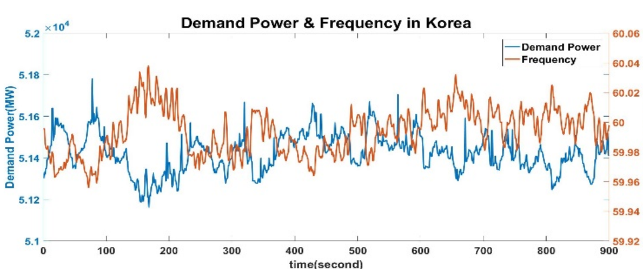

Figure 1-Frequency and Demand Power in Korea

In this paper, we propose an equivalent system model that can take advantage of these system frequency-power characteristics. From Figure 1, fringe and cyclic components appear intrinsically on system frequency, so it is reasonable to calculate power fluctuations using a frequency in the absence of long-term power fluctuations. Therefore, knowledge about known parameters such as: system frequency and power system scale, makes it easier to estimate demand power without the consideration of the entire parameters of the grid model.

III. System Equivalent Dynamic Model

Now, before discussing the equivalent system dynamic model, let's talk about the leveling effect. In generally, the fluctuation of a wind farm distributed over a large area is less than N times the fluctuation of a wind turbine. The reason for this is that the leveling effect is caused by the difference in wind speeds blown by each wind turbine [7]. This leveling effect is maximized as the correlation of the wind blowing to the generator is low. Likewise, the leveling effect also appears in demand power or supply power.

A. Model configuration

There are various types of generators committed on the grid at every unit commitment session. Generators such as steam turbines, gas turbines, pumping-ups power, photovoltaic and wind turbines, are increasingly involved in the generation mix in recent years. In view of this, it seems quite impossible to construct an equivalent model which abstracts the very fabric of these units. As such, the purpose of this equivalent model is not to involve all the characteristics of each generator, but to propose a part that frequency controls demand power fluctuation due to cyclic and fringe component.

The configuration of the equivalent model is chosen as a common model that can explain the basic characteristics of several generators. As shown in Figure 2, the configuration of the equivalent model includes governor, Rotating mass and load, and prime-mover characteristics for Primary frequency control [8]–[10].

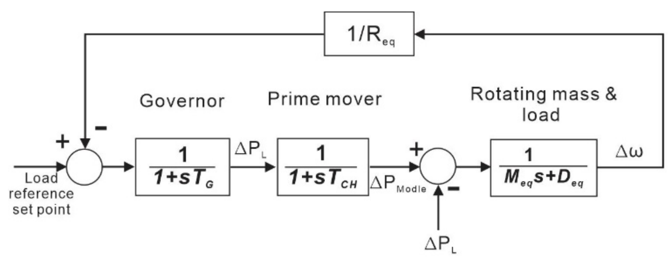

Figure 2-Block diagram of governor, prime mover, and rotating mass **[8]**

In general, the block diagram of Figure 2 can be simplified to a single transfer function, as is the feedback structure of rotating mass and load expressed in a single feedforward manner. The transfer functions of the governor and the prime mover can be expressed simply as a single transfer function through multiplication, and the prime mover and the governor can be described as one transfer function. In addition, if per unit is used, the transfer function of the system equivalent model can be simplified as follows:

$$\frac{\Delta\omega(s)}{\Delta P_L(s)} = \frac{\frac{-1}{M_{eq}s + D}}{1 + \frac{1}{R_{eq}}\left(\frac{1}{1 + sT_G}\right)\left(\frac{1}{1 + sT_{CH}}\right)\left(\frac{1}{M_{eq}s + D}\right)} \quad (1)$$

We can easily obtain the inverse transfer function by summarizing the system equivalent dynamic model as one transfer function. In this paper, we call this inverse-transfer function a system inverse-equivalent dynamic model. On the contrary, the equivalent model that can estimate the frequency based on the demand power, and vice-versa.

The parameters required for the system equivalent model are obtained by integrating the existing system factors into one, as results, estimation based on the data is remains necessary. Each parameter was estimated by the Least squares method and consisted of optimal parameter values.

The proposed system equivalent dynamic model estimate the cyclic and fringe components of demand power based on the frequency fluctuation. However, a sustained component not included in the frequency cannot be estimated through the proposed model. Therefore, it is necessary to confirm the scale of the power system by referring to the Generator power data and the demand power data that was calculated using optimal power flow, and confirm whether the data is low in the sustained component.

B. Model Validation

In this paper, a complex power system model is represented by one equivalent model. Although we consider only the frequency control related to the short-term, minute power fluctuations, we need to verify the model because many elements are composed of equivalent models.

The frequency and demand power data used for verification were obtained from KPX, which institute is responsible for SO (System Operation) and MO (Market Operation) in Korea. This demand power data was recorded by calculating the optimal power flow using data obtained from SCADA. The time period of the data is 5 minutes, and the type of data in which the sustained component is small and the cyclic & fringe component have large fluctuation is selected.

The purpose of the verification is to confirm that the demanded power graph obtained from the model is similar to the demanded power graph obtained from the optimal power flow calculation in KPX.

In Figure 3, the blue line shows the power trend obtained from the equivalent model, and the orange line shows the power trend obtained from the optimal power flow calculation in KPX. Figure 3 shows that demand power converted based on frequency deviation and demand power obtained by the KPX draw a similar trend, except for few errors.

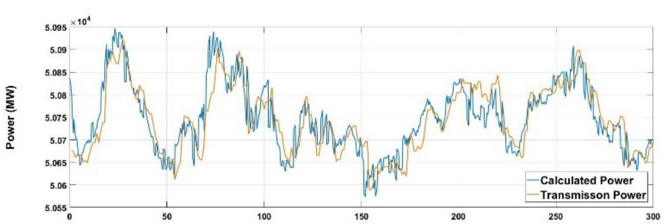

Figure 3-Comparison of demand power obtained by equivalent model and demand power obtained by power algae calculation

It should be noted that the optimal power flow method also involves errors. Taking this into consideration, the demand power obtained by the equivalent dynamic model is valid and is meaningful as a value indicating a direct relationship with the actual frequency.

The value of the demand power obtained through the equivalent dynamic model is that the actual frequency is output when the equivalent model is input. Using this procedure, the frequency contribution of the BESS for frequency adjustment can be checked.

IV. Case Study

As mentioned earlier, it is important to evaluate the contribution of BESS to the current system in Korea. Considering the wear of the battery, BESS participating in the frequency regulation is undervalued as compared to its role. BESS has a higher contribution than the existing control mechanisms for Frequency regulation, but it is difficult to verify the frequency contribution real time due to the dynamic system environment. In view this, we can evaluate the system frequency contribution, by quantifying the response of the system equivalent dynamic model with/without the usage of BESS whiles maintain the system configuration and set of parameters.

As shown in Figure 4, the general framework of the system comprises of measured frequency and regulated frequency as its input and output respectively. The inverted equivalent model, equivalent model and BESS control model form the core operating model of the system. In this regard, we built a simulation based on this case study. In this simulation, the measured frequency as well as measured demand for the same time span was obtained from Korea Power Company. The data obtained for the simulation is 1-hour period at an internal of one second.

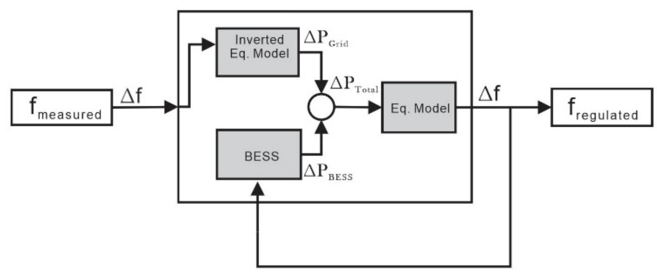

Figure 4- System framework

As shown in Figure 5, at the core of this system resides our control models: inverted equivalent dynamic model, equivalent dynamic model and the BESS control model. The simulation was developed in MATLAB / Simulink and operated based on the operational dynamics of KEPCO.

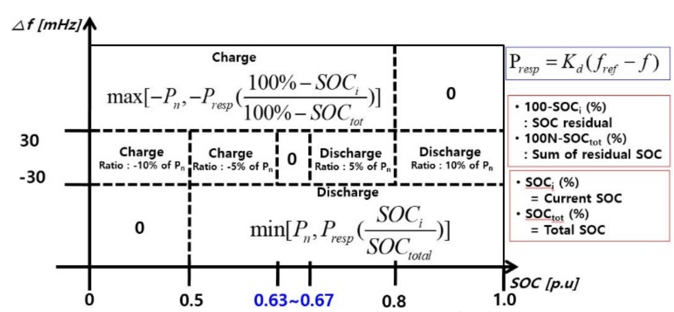

Figure 5-BESS steady-state operational algorithm for frequency regulation **[11]**

A. BESS operational algorithm

The BESS operation algorithm applied in this case study mimic the actual operation of BESS control operation by KEPCO. The BESS operation control strategy is applied differently depending on the current state of the system frequency: steady state, transient state, exit state, and recovery state. In Korea, high frequency quality is maintained, and most of the operation state is in steady state and recovery control state. The case study was also operating under steady and recovery control conditions. Figure 5 illustrates the control algorithm in both steady state and recovery state. The steady state control mode operates when the system frequency is out of the ± 0.03Hz range (i.e. dead band) of the rated frequency (i.e. 60Hz) and the BESS charges and discharges according to the degree of deviation. In order to minimize the life cycle of the battery, the algorithm recommends operating frequency regulation at a specific State of charge (SOC) range. In the recovery control state, the SOC of the battery is shifted to a specific spot. The battery charges up to 10% of rated output when SOC falls below 50%, and discharges up to 10% of rated output when SOC rises above 80%. In addition, when the SOC is out of the range: 63% ~ 67%, it charges and discharges up to 5% of the rated output, and moves to a specific SOC section [11]. The BESS operation data implemented in the simulation and the operation data of the BESS participating in the actual system are compared with each other to confirm their exactness at the same time instance. The aftermath of the simulation shows, that the BESS operation data implemented by the simulation and the operation data of the BESS participating in the actual system are when compared, matched precisely.

Table 1 - System Equivalent Dynamic Model parameters at example

Parameter	Quantity	Value
$\boldsymbol{P_{base}}$	System Power base	50840MW(fixed)
$\boldsymbol{M_{eq}}$	Angular momentum inertia	7.0
D	Load damping coefficient	0.156
$\boldsymbol{T_G}$	Governor time constant	1.41
$\boldsymbol{T_{CH}}$	Charging time constant	1.31
$\boldsymbol{R_{eq}}$	Equivalent Droop rate	0.1077

B. Results analysis

The system equivalent dynamic model parameters used in the simulation are shown in Table 1. These parameters were estimated by the Least Squares Method mentioned above.

In Figure 6, the blue graph represent unregulated system frequency whiles the orange represent regulated system frequency with the introduction 500MW BESS.

Between 1300 and 1450 seconds, the system frequency was significantly out of the dead band, so the BESS discharged according to the degree of deviation. After 1450 seconds, it can be seen that the system frequency of BESS is little higher than the existing frequency because it operates the recovery control mode to recover the lowered SOC due to the previous discharge.

Using the system equivalent model in the above simulation, the power system environment can be reconstructed, and the effect of the operational factor on the system can be grasped. Using this case study, the appropriate capacity of BESS for frequency regulation can be selected, and the operation algorithm of BESS can be evaluated and improved.

V. CONCLUSION

In this paper, we propose the system equivalent dynamic model that can reconfigure the past system environment by utilizing the fact that the power balance state of the system can be grasped by the frequency. In other words, if we know the scale and frequency of the power system, we propose a system equivalent dynamic model that can calculate the demand power that affects the actual frequency, not the demand power obtained by the optimal power flow. For the validity of the proposed model, we were comparing the demand power data obtained by inputting the frequency to the proposed model and the demand power data obtained using optimal power flow by the system operator. The utility of the proposed equivalent model is to invert the demanded power back to obtain the same frequency again. In the case study, the frequency contribution of BESS was verified by adding 500MW of BESS for Frequency regulation which is operated in the actual system in the system environment reconstructed at the actual frequency in Korea. As a result, it is expected that BESS will be evaluated rationally, which is undervalued due to lack of verification. The proposed model can be used not only to estimate the appropriate capacity of BESS for Frequency regulation but also to consider large - scale renewable energy employ. This is expected to accelerate the diffusion of new and renewable energy. In the future paper, we will verify the performance of BESS in transient state due to power plant outages.

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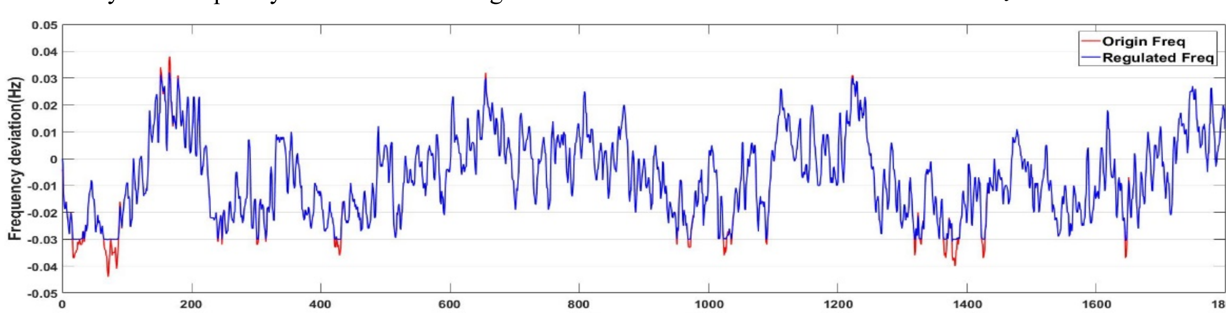

Figure 6-Frequency improvement due to employ 500MW BESS

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