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<th>Frequency regulation for a power system with wind power and battery energy storage</th>
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Abstract—With the increase of wind power penetration to a notable level in power systems, the requirement on frequency regulation services has increased accordingly in recent decades. Due to the limited ramp rate and economic factors of conventional generators, simply increase the capacity of conventional generators may not be an effective solution for providing frequency regulation services quickly. Large-scale battery energy storage system has been applied as a promising solution for frequency control in some renewable energy integration projects. In this paper, a control method is proposed for battery energy storage system to provide frequency regulation service. The control strategy to the energy storage system is indicated in the classical two-area AGC control diagram. The effects of the proposed battery control strategy for power system frequency control have been simulated and tested. The simulation results show that battery systems could be used as a tool in quick frequency control. The results also show the possibility of introducing battery energy storage system into real wind power generation projects.

Index Terms—AGC, battery energy storage system, frequency regulation, optimal sizing, and renewable energy integration

I. INTRODUCTION

Due to the “zero emission” characteristic of wind power generation, it has been regarded as one of the solutions to the global energy issues [1-5]. With the fast development of wind power generation technologies, the rated power of a single turbine has increased to 10MW in 2011. It is possible that in the near future rated power of an off-shore wind farm could exceed 1GW, which is similar to the largest conventional generators. In this case, the power output fluctuation of such a large wind farm may cause serious frequency stability problem to the system. Consequently, negative effects of wind energy system could not be neglected as previously. The connection between wind energy and power grid should be more flexible and stable.

Renewable energy integration issues have been widely discussed from various aspects. A system-wide approach is proposed for distributed generations based on the new IEC communication standard in [6]. In [7], a new control strategy for DFIG system is proposed to reduce the reserve requirement for power system. These works could optimize the allocation of system reserves. However, with the fast increasing of wind power capacity, more conventional generators need to be operated under frequency regulation modes. New technologies are expected to carry on the task of frequency regulation task for power grid.

Battery energy storage systems could inject or withdraw energy from the power grid through power conversion systems in seconds. The rated power and rated capacity of battery energy storage have reached hundred MWh levels with recent technology development. The large number of electrical vehicles in the future could provide distributed energy storages for power systems. It was proposed that battery energy storage system could be used for power system frequency regulation. A study on frequency regulation in an isolated power system has been carried out in [8]. The work supports the idea that battery energy storage system could be applied for frequency regulation. An optimization method for EV taking part in the frequency regulation service has been studied in [9]. An optimal control method of EV was proposed in this paper to provide frequency regulation service in order to obtain the maximal revenue. An optimal dispatching method for battery energy storage was studied in [10, 11]. The work focused on how to reduce power fluctuations of the wind farm outputs. In [12, 13], the battery energy storage system has been introduced into the control loop of AGC system. The dead band effect and generation rated constrains are considered. The work is focused on the application of energy storage system in the load frequency control.

In this paper, the application of battery for frequency regulation is studied. A control strategy is proposed for the battery energy storage system for the frequency control purpose. The results are obtained for different parameters based on the proposed method.

The organization of this paper is as follows. In Section II, the control diagram of AGC and battery energy storage system is presented. The historical data of wind power generation is provided in Section III. The simulation results of frequency regulation is presented and analyzed in section IV. Section V concludes.

II. AGC CONTROL SYSTEM WITH BATTERY ENERGY STORAGE

The classical two-area AGC control system with tie-line control has been developed and discussed since decades ago. The frequency control system for a multi-area power system
was proposed in [14]. The method has been widely applied in the modern power system. In [15], the dynamic models of two major turbines, steam turbine and hydro turbine, have been studied. The simulation accuracy of frequency regulation could be improved by applying dynamic models of generation turbines. With widely applications of lead-acid batteries in various industries, the possibility of introducing battery energy storage into power industry has been discussed [12]. Due to the limitation of present battery technologies, the application area of battery discussed in [12] was limited in load frequency control.

In this paper, we propose a control diagram to include battery energy storage system in power system frequency control. The modified diagram of classical two-area AGC control with energy storage system is shown in Fig.1. Symbols \( \Delta P_1 \) and \( \Delta P_2 \) represent the power fluctuation, which could be caused by renewable energy generation or load fluctuations. Symbol \( \Delta P_B \) represents the output power from energy storage system. Renewable energy generation could be considered in Area 1 and Area 2 through \( \Delta P_1 \) and \( \Delta P_2 \).

Based on previous works, the proposed control system of battery energy storage system is shown in Fig. 2. The control system includes three loops. 1) Item \( \frac{K_{pB}}{T_{\text{Charge}}s + 1} \) represents an auto balancing charging loop for the battery energy storage system. This loop could control the remaining energy of the energy storage around in the initial state, which is normally set to be 50%. 2) Symbol \( K_B \) represents the feedback gain of the frequency fluctuation in the power grid. Item \( \Delta P_{\text{cal}} \) represents the compensated power, which is caused by ramp rate limitations of generators. 3) Item \( \frac{1}{1 + sT_{\text{Conv1}}} \) represents the effect of the 1st order delay of DC-AC power converter in the battery energy storage system.

III. OPERATION DATA OF WIND POWER GENERATION

To study frequency regulation issues in a system with large capacity of wind power, the historical wind power generation data, which is shown in Fig. 3, is used.

It is shown in the figure that the wind farm output has a large power fluctuation. To study the impact of wind power
on power grid operation at different wind power penetration levels, the wind power profile in Fig. 3 is uniformed into per unit (p.u.) values.

![Fig. 3 The historical data of wind farm](image)

**IV. FREQUENCY CONTROL CONSIDERING BATTERY ENERGY STORAGE AND WIND POWER FLUCTUATION**

**A. Case 1**

In Case 1, we will study the AGC system with wind power generation and battery energy storages located in one of the two areas.

Based on the block diagram described in Fig. 2, AGC with wind generation system in one area is shown in Fig. 4. The wind power signal is added at \( P_1 \). The control system of the battery energy storage system is the same as in Fig. 2.

![Fig. 4 The control diagram of AGC with wind power in one area](image)

Applying the historical wind power data shown in Fig. 3, the simulation results of frequency regulations are shown in Fig. 5 and Fig. 6.

![Fig. 5 Frequency deviations without energy storage](image)

![Fig. 6 Frequency deviations with energy storage system](image)

It is found in Fig. 5 that the highest frequency deviation without battery energy system is more than 1.5 Hz during the period of 24 days. In Fig. 6, it shows that the fast response characteristic of battery energy storage system could reduce the maximum frequency deviation to less than 0.12 Hz, which is less than 10% of the deviation without energy storage.

**B. Case 2**

In Case 2, we will study the scenario that wind power generations are located at different AGC control areas as battery energy storages.

The block diagram of the control system is shown in Fig. 1. Wind power generation is added in Area 2 at the point of \( \Delta P_2 \) in Fig. 1. The energy storage system is located in Area 1. The simulation results are shown in Fig. 9 to Fig. 12.
Fig. 9 shows the frequency fluctuations of two areas without battery energy storages, and wind power is in Area 2. The highest frequency deviations of two areas have exceeded 0.6Hz and 0.8Hz, respectively. This is lower than the frequency deviation in Case 1. The tie line, which connects two areas, could provide extra power for frequency regulation from the other area. Fig. 10 shows the simulation result with battery energy storage system installed in Area 1. The frequency deviation is to less than 0.02 Hz and 0.15 Hz, respectively. The fast response characteristic of energy storage system could reduce power deviations in both areas.

The power output of the energy storage system in Area 1 is shown in Fig. 11. The Fig. 11(a) shows that the maximum output power of the energy storage system under proposed control method is less than 0.7p.u.. The Fig. 11(b) shows the distribution of output power. The deviation is distributed between ±0.2 p.u., which is possible to be implemented with modern battery technologies.

The capacity requirement of the energy storage system is shown in Fig. 12. The required capacity of battery energy storage system is less than 0.06 p.u.hour in total. This means that if the energy storage system could maintain its output power at rated power for 4 minutes, the system could satisfy the capacity requirement for frequency regulation in a two-area system during a time period of 24 days.

C. Case 3

In Case 3, we will study the scenario that wind power generations are located in the same control area as battery energy storages.

The energy storage and wind power are located in Area 1 in Fig. 1. The results of frequency fluctuations without battery energy storage system are the same as Fig. 9, which just switches the sequence of Area 1 and Area 2.

The results in Fig. 13 show that the battery energy storage system could provide a better compensation result if the battery energy could be placed at the same area with wind power generation system. The frequency fluctuations in both areas could be controlled under 0.05Hz, which equals to half of the maximum frequency deviation in Fig. 10.

The result of battery energy storage system output is shown in Fig. 14, which is similar with the results shown in Fig. 11. The maximum output power has reached to 0.9 p.u., while the distribution of output power is almost the same as the result shown in Fig. 11.
The result of capacity requirement of battery energy storage system is shown in Fig. 15. The battery storage system locates in the same area as the wind power generation system. So the energy storage system could compensate much more power fluctuation than other cases. As a result, the required capacity is larger than the result shown in Fig. 12.

V. CONCLUSIONS

In order to reduce the frequency fluctuation, which is caused by wind power generations in power systems, a control method is proposed in this paper for battery energy storage system serving for frequency control. Three cases with different system configurations, including single area system, two area system with battery energy storage and wind power generation located in different areas, and two areas system with battery energy storage and wind power generation located in the same area, have been studied with the proposed control method.

The results support the idea that battery energy storage is suitable for providing frequency regulation services to compensate the fluctuation caused by wind power generations. Battery energy storages could significantly reduce frequency fluctuations in single-area and two-area power systems. In some cases, the frequency deviation could be reduced to less than 10% of the original one. As shown in the simulation results, the requirement to the battery energy storage system is possible to be realized using present battery manufacturing technologies.

To reduce the interactive charging/discharging fluctuations between conventional generators and battery storage systems, if the battery energy storage and wind power generation are located in the same area, the feedback gain $K_B$ should be reduced.

A 24-day power output profile of wind power generation has been applied to verify the effects of battery energy storage system. The time interval for the data is 10 seconds. Although the applied data is only for 24 days, by implementing an auto balancing charging/discharging control loop to the battery energy storage system, the proposed control method of battery energy storage could be applied in a real-time control system for a longer time period.

VI. APPENDIX

The nominal system parameters are:

- $T_{11}=T_{22}=0.3s$
- $T_{12}=T_{21}=0.08s$
- $T_{p1}=T_{p2}=24.0096s$
- $T_f=0.545s$
- $T_{charge}=100s$
- $K_{pf}=0.2$
- $A_{12}=1$
- $R_1=R_2=2.4$
- $K_{i1}=K_{i2}=0.1$
- $B_i=B_2=0.425$
- $K_{p1}=K_{p2}=1/D_1=1/0.00833=120.048$

Ramp Limitation of generators: 0.001 p.u. /s

In Case 1, $K_B=5$;
In Case 2, $K_B=150$;
In Case 3, $K_B=15$.

VII. REFERENCES