Research on energy storage system participating in frequency regulation

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Abstract. With increasing penetration of renewable source in power system, higher requirements for power quality are put forward. Energy storage system represented by chemical battery and flywheel energy storage system is fast-ramping and responses quickly in frequency regulation market. It shows outstanding performance in frequency regulation comparing with the traditional frequency regulation resource. This paper reports a review of the energy storage system participating in frequency regulation, including frequency regulation market and energy storage technology. Also, it contrasts the frequency regulation characteristics and total costs between battery energy storage system (BESS) and flywheel energy storage system (FESS) both applied widely in the projects. The operation mode and Simulink modelling of energy storage system, along with the control strategy and capacity configuration, are also discussed through relative literature.

1. Introduction

Energy storage system has a wide range of applications in the smart grid, especially plays an important role in frequency regulation market. The energy storage system has variety kinds, including the traditional chemical battery, pumped storage, but also advanced flywheel energy storage, compressed air energy storage, supercapacitors energy storage and superconducting energy storage. How to achieve large-scale, secure and stable storage of electric energy is a critical issue. With the wind power, solar energy and other renewable energy connecting to the grid, it has more requirements for power quality.

At present, the main frequency regulation resources are thermal power units and pumped storage. While the thermal power units have to bear the task of adjusting the power peak. In the heating period, it also needs to bear the heating task. The location of pumped storage power station is limited by geographical location, water head, terrain and geology, etc. Compared with the conventional frequency regulation resources (FRR), energy storage resources such as chemical storage, flywheel energy storage, response and regulate quickly with a high accuracy. As the cost of batteries reduces and the frequency regulation compensation rises, the economic benefits of large-scale energy storage are even more substantial participating in the frequency regulation market.

Recently, many countries have attached great importance to energy storage technologies and applications. Xtreme Power, A123 and other companies have invested demonstration projects involving a variety of energy storage types, including lithium-ion batteries, ranging from 1MW/0.5MWh to 20MW/5MWh [1] [2]. Beacon Power participates in 20MW flywheel storage station for frequency regulation in Hazle, Unite States. From multiple sources [3] [4], the energy storage plants have been built mainly involved in frequency regulation in recent years. These projects shows it is potential that energy storage participating the frequency regulation.
2. Research Status Quo

2.1. Frequency regulation market
The United States has a relatively complete frequency regulation market. From 2007 to 2013, FERC issued Order 890, 755, 784 and 792 to guarantee the legitimacy of energy storage system participating in frequency regulation market and obtain reasonable compensation [5]. In particular, Order 755(2011) presents a new compensation method [6]. It compensates not only for the frequency regulation capacity, but also the frequency mileage and performance. By this way, the energy storage system can acquire more reasonable compensation because of their fast-ramping characteristic. Order 792 defines energy storage as small power equipment and has developed a rapid interconnection test. Besides, standard IEEE 1547 is applied for physical and electrical interconnections between utility and distributed generation.

Chinese frequency regulation market is undergoing reform. At present, there are no explicit standards about the energy storage system participating in the frequency regulation market, usually referring to the standards about the generator or generation management methods in the power market. The energy storage system mostly installed in the power plant is also part of generators’ AGC assessment. AGC assessment of generators can be based on “the two rules”. On June 7, 2016, the National Energy Administration issued the notice on “Pilot Project of Electric Power Storage Ancillary Service Compensation Mechanism (Market) to promote the Participation of Electric Storage Energy”, and started pilot projects about the energy storage system used for frequency regulation [7]. In November 2017, the National Energy Administration issued the "Work Plan for Perfecting Compensation Mechanism (Market) for Ancillary Services"[8]. These measures are conducive to energy storage system participating in the frequency regulation and energy storage system will receive more reasonable compensation.

2.2. Energy storage technologies
At present, the main frequency regulation resources are pumped storage and thermal power; Fast-ramping resources include chemical batteries, flywheel energy storage, superconducting energy storage, supercapacitors and compressed air storage. Among them, the superconducting energy storage, supercapacitors and compressed air technology are not mature enough to apply in projects. The comparison between FESS and BESS are as follows.

2.2.1. Characteristics comparison.
From the aspects below, we can learn the differentials between FESS and BESS.

- Depth of discharge (DOD): When the DOD is deep, such as 80%~100%, FESS can maintain its charge and discharge characteristics, while the lithium ion cannot. And the cycle number of lithium ion will decrease to a large extent.
- Temperature: FESS and lithium batteries have different operating temperatures. Lithium iron phosphate battery, for example, the charging temperature is 0 ~ 45 °C, discharge temperature is -20 ~ 75 °C [9]. In the operating temperature, temperature changes will not affect the performance of flywheel energy storage, but will affect the performance of lithium batteries. Lithium battery charge and discharge characteristics, self-discharge rate, depth of discharge are all affected by temperature.
- Service life: FESS’s design life is 20 years, while the lithium-ion battery 4 years. It is an advantage over the BESS.
- Discharge time: Flywheel energy storage battery is a high-power energy storage device, so that it cannot maintain long-term discharge. However, the lithium batteries are high-capacity device and can discharge for a relatively long time.
- Safety and environmental impact: FESS is safe, environment-friendly without any chemical substance. Lithium batteries have some security risks, which should be equipped with fire alarm and other related equipment.
The comparison between FESS and BESS can list in Table 1 below.

| Table 1. FESS and BESS characteristic comparison |
|-------------------------------------------------|
| **FESS**                                      | **BESS**                                      |
| Response time                                 | Full capacity within seconds                  | Fast response result in degradation          |
| Accurate output                               | Fast                                          | Fast                                         |
| Charge or dischage                            | None                                          | Avoid over discharging or over charging      |
| Depth of discharge(DOD)                       | Permit deep discharge                         | Avoid deep discharge                         |
| degradation                                   | None                                          | Degrate with cycles                         |
| cycles(100%DOD)                               | >100000                                      | <2500                                       |
| life                                          | 15-20 year                                    | About 4 years (it depends)                  |
| safety                                        | Safe                                          | Unsafe                                       |
| Environmental impact                          | Environmental friendly, no hazardous chemicals | Chemicals                                   |

2.2.2. Cost comparison.
The cost of energy storage system mainly includes the initial investment cost, operation and maintenance costs, replacement costs, recycling costs, the flywheel energy storage battery and lithium battery cost are as follows[10].

- The initial investment cost: When the capacity is certain, the battery has a lower initial investment cost, flywheel energy storage battery is about more than 1.5-2.0 times the initial investment cost of lithium batteries.
- Operation and maintenance costs: the energy storage system has to pay a lot for the operation and maintenance for the better characteristics. In contrast, flywheel energy storage operation and maintenance costs lower.
- Replacement costs: flywheel energy storage life is about 15-20 years, it need no replacement cost during its service life. While a lithium battery is about 4 years (it depends on specific kind). It means that it replaces every 4 years to maintain battery availability.
- The cost of recycling: lithium batteries need to be recycled due to the existence of chemical substances, and flywheel energy storage needn’t. As the flywheel storage system is mechanical structure without chemical substance.

Based on the different performance of frequency regulation and costs of FESS and BESS, it is important to choose the kind and certain capacity of frequency regulation resource.

3. Energy storage operation mode and Simulink Modelling
Energy storage operation mode can be divided into two kinds: independent energy storage frequency regulation station and joint operation mode. The flywheel storage frequency regulation station in Stephen is an example of independent operation mode. Joint operation mode requires energy storage system assist the traditional frequency regulation resource, such as thermal power units, hydroelectric units, photovoltaic, and wind power. According to the number of energy storage type, it can be divided into single energy storage and mixed storage operation mode. Energy storage systems usually assist the traditional thermal power plant to improve the quality of frequency in China.

The energy storage system is composed of energy storage system and Power Conversion System (PCS). The energy storage device is connected to the grid via a DC / DC, DC / AC, filter, and transformer [11], as shown in Fig. 1.
In terms of energy storage, taking BESS as an example, its model mainly includes a single element model and a PCS with a control method [12]. In the frequency regulation field, the product of the one-order inertial loop and the control gain is widely used to describe the behaviour of the BESS or FESS involved in the grid frequency regulation [13]. Besides, BESS can also described by external characteristic equivalent circuit [14].

4. Control strategy and capacity configuration

The control strategy of energy storage involved in the frequency regulation is to determine the control mode, timing and depth of action. Based on the regional grid, the ACE or ARR is calculated and then allocated. Literature [15] proposes that the discrete Fourier transform (DFT) for the change of frequency regulation demand is decomposed into low frequency and high frequency components. The energy storage system acts on high frequency components. Literature [16] compares the frequency regulation effect, energy storage state under the control of ARR and ACE. Energy storage system is priority or proportionate strategy. The literature [14] prioritizes energy storage systems (electric vehicles) participating in the AGC in Danish power system. The literature [17-18] distributes the ratio of the dynamic optimization between the flywheel and hydro-power unit based on AGC signal. Consider the thermal power units and energy storage device frequency regulation different internal characteristics to choose different distribution based on different scenarios. Literature [19] presents an optimal control strategy allocation considering suppression of reverse frequency regulation, dead-zone oscillation, over-discharge of energy storage device in the frequency regulation system composed of thermal power, VRB and VRLA.

Capacity configuration is to determine the degree of energy storage involved in the frequency regulation, that is, the capacity of energy storage and power. For independent or joint operation of energy storage frequency regulation station capacity configuration flow can describe as six steps:1) Get regional power grid frequency regulation historical data and control signals to determine the frequency regulation demand.2) Choose the energy storage kind based on the frequency regulation characteristics and conditions.3) Deploy the energy storage capacity and power.4) Find the constrains (technology: SOC, economy: costs and frequency regulation compensation).5) Analysis the results 6) Determine the optimal capacity. If the results in 5) cannot demand, it should return to the 2) or 3) until find the optimal capacity.

5. Conclusion

In order to promote the application of energy storage system in the frequency regulation market, we can promote it from the following aspects:

- A sound frequency regulation market, policies and compensation mechanisms are the preconditions for energy storage to participate in the frequency regulation market. The PJM market is a good example for energy storage system participating in frequency regulation market. The technical development and cost reduction can also promote.
- Discuss the modelling and operation mode of the energy storage system to determine the optimal objective function and configure the optimal capacity of the energy storage system.

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