Study on Primary Frequency Control of Power Grid Based on Flywheel Energy Storage Technology

Jun Li*
State Grid Shandong Electric Power Research Institute, Jinan, China
*Corresponding author’s e-mail: lijun_sdu@hotmail.com

Abstract. The frequency regulation of power grid is the most valuable application direction of energy storage technology in the auxiliary services field. Through the analysis and comparison of different energy storage technologies, the energy storage principle of flywheel energy storage (FES), the design of motor controller and capacity selection method of FES system are introduced and analyzed in detail. With its strong short-time power capacity and easy change of adjustment direction, combined with conventional frequency modulation technology, it can be used as an effective auxiliary means of primary frequency control (PFC) to ensure grid frequency stability.

1. Introduction
With the continuous advancement of social modernization, energy crisis and environmental pollution bring more and more challenges to the sustainable development of society. Therefore, the development and utilization of new energy is highly valued by all countries in the world. Wind power plays an important role in the field of renewable energy with the advantages of abundant resources, large-scale development and relatively short construction period. However, the increase of wind power grid-connected capacity brings new difficulties and challenges to the frequency stability control of power system, which affects the safe and stable operation of the system. The premise of safe and stable operation of power grid is to ensure the stability of power grid frequency[1,2]. Under the new characteristics of new energy wide-area absorption and UHV AC-DC hybrid power grid, frequency control mode and control performance evaluation method should be changed.

At present, the third industrial revolution based on the change of renewable energy is in the process of development. Energy storage, as one of the five pillar technologies of the third industrial revolution, will play an important role in this industrial revolution[3]. Energy storage technology can adjust the mismatch between energy supply and demand in time, space, intensity and form. It is an important means of rational, efficient and clean utilization of energy, an important technical support for ensuring safe, reliable and high-quality power supply, and an important factor for promoting the transformation of energy production, consumption and development mode. For the application of power system, the basic technical characteristics of energy storage system are reflected in the power level and its operating time. The operating time of energy storage is a significant symbol different from the traditional instant and ready-to-use equipment of power system, an important embodiment of the value of energy storage technology, and a unique technical characteristic. The unique technical characteristics of energy storage will change the traditional mode of instantaneous balance between supply and demand of power system and play an important role in energy revolution[4,5]. Therefore, how to reasonably select the supporting type, energy storage capacity and control mode of energy
storage according to the frequency control characteristics of the power grid can contribute to the safe and stable operation of the power grid.

2. Grid-assisted Energy Storage technology Classification

Energy storage technology includes ontology technology and application technology, and ontology technology is the basis of energy storage technology. The energy storage body form can be divided into mechanical energy storage, electromagnetic energy storage, chemical energy storage and phase change energy storage according to the energy storage form. At present, chemical energy storage mainly includes electrochemical energy storage and hydrogen storage energy. Electrochemical energy storage includes typical secondary battery systems such as lithium ion batteries, flow batteries, lead acid batteries, and sodium sulfur batteries, as well as emerging ones. Secondary battery system (lithium sulfur battery, lithium air battery, etc.).

The basic technical characteristics of energy storage ontology are reflected in its power level and its energy action time, and the technical indicators of energy storage application requirements of power system are also power and energy action time. Among them, the action time of energy storage is the most important symbol, which is different from the traditional instant and ready-to-use equipment of power system, the most important embodiment of the value of energy storage technology, and the most important technical characteristics. Therefore, selecting the energy storage action time as the basis for technology division can better grasp the correlation between energy storage ontology technology and application requirements, better clarify the application space of different energy storage ontology technology, and guide the development direction of energy storage ontology technology and application technology.

According to the demand of power system, the action time of energy storage can be divided into three categories, below minute level, minute level to hour level and above hour level. Among them, the minutes below level applications include improve the power-angle of system stability, the support of wind turbines low voltage across, offset voltage drop, etc., in these cases need energy to support for a short period of time, requires the change of the energy storage can be based on the system to make automatic, rapid response, requires the ability to charge and discharge of energy storage is of high power, applicable techniques include: super capacitor, superconducting magnetic energy storage, flywheel energy storage, etc[7,8]. Applications ranging from minute to hour include smoothing fluctuations in renewable energy generation, tracking planned output, and secondary frequency regulation. In these applications, the energy storage is required to be capable of continuous charge and discharge for several minutes or even hours, and the state of charge and discharge can be changed frequently. The energy storage technology used is mainly electrochemical energy storage. Applications above the hour level include peak cutting, load adjustment, reduction of wind abandon, etc. In these applications, the energy storage is operated for several hours, days or longer, which requires the energy storage to have large-scale energy handling capacity. Energy storage technologies that are easy to form a considerable scale, have little environmental impact and are economical should be selected, including pumped energy storage, compressed air energy storage, molten salt heat storage, hydrogen energy storage, etc.

3. Principle of FES

Flywheel energy storage system (FESS) is an energy storage system that stores energy in the form of rotational kinetic energy by accelerating the rotor(flywheel) to extremely high speeds. When the energy is released, according to the principle of energy conservation, the rotation speed of the flywheel will be reduced. When energy is stored in the system, the speed of rotation of the flywheel increases accordingly.

A flywheel is a round, circular, or cylindrical rigid body that rotates about its axis of symmetry. When a rigid body rotates around a fixed axis, all points on the rigid body move in a circle around the same straight line (rotating axis), while the position of the axis itself remains unchanged in space [9,10]. Suppose the rigid body rotates at an angular velocity w around the axis, and the rigid body is
regarded as a system of particles composed of n mass elements. If the mass of each mass element is \( m_i \), then the kinetic energy of the rigid body can be obtained

\[
E_k = \sum \frac{1}{2} m_i v_i^2 = \sum \frac{1}{2} m_i (\omega r_i)^2 = \frac{1}{2} \omega^2 \sum m_i r_i^2
\]

(1)

The moment of inertia of a rigid body about its axis is defined as

\[
J = \sum m_i r_i^2
\]

(2)

The rigid body with continuous mass distribution is

\[
J = \int r^2 \, dm
\]

(3)

So the kinetic energy of the rotating rigid body is

\[
E_k = \frac{1}{2} J \omega^2
\]

(4)

During the acceleration of the flywheel, the angular velocity increases from \( \omega_1 \) to \( \omega_2 \), the angular displacement increases from \( \theta_1 \) to \( \theta_2 \), and the work done by the external torque \( M \) on the flywheel is transformed into the kinetic energy increment of the flywheel.

When the rotation speed is \( \omega \), the instantaneous power for increasing energy storage or decelerating energy is

\[
P = \frac{dW}{dt} = M \frac{d\theta}{dt} = M \omega
\]

(5)

\[
P = \frac{dE_k}{dt} = J \omega \frac{d\omega}{dt}
\]

(6)

Therefore, the balance between the inertial characteristics of the flywheel shafting and the shifting characteristics and the external moment is

\[
M = J \frac{d\omega}{dt}
\]

(7)

4. Motor Controller Design of FES

The charging control of the FESS adopts the double closed loop control strategy of speed and current. The current control adopts the vector control strategy based on \( I_d = 0 \). The charging control block diagram of the flywheel energy storage system is shown in Figure 1.

![Figure 1. The charging control block diagram of FESS](image-url)
composite control is proposed by referring to the intelligent composite control strategy. The specific process is, start the flywheel motor; when the motor speed is lower than the minimum working speed, it runs in the way of constant torque. Between the lowest working speed and the highest working speed of the motor, constant power mode is adopted. After reaching the maximum working speed, the flywheel is kept running with low power. Flywheel charging control strategy is shown in Figure 2.

![Flywheel charging control strategy](image)

**Figure 2. Flywheel charging control strategy**

5. **Capacity Selection of FESS**

The PFC has the characteristics of high frequency of action and small amplitude of motion. Therefore, the selection of the existing chemical battery such as lithium iron phosphate for the frequency modulation compensation will cause rapid decay of the battery life. Therefore, the selection of the FES device for PFC compensation is one practical solution.

5.1. **PFC assessment criteria**

The grid-connected power plants of various regional power grids in China have basically the same regulation for PFC. The grid assesses the integral electricity contribution index of the first 60s of the unit during frequency fluctuations. For example, the northwest regional power grid stipulates that the primary frequency pass rate is not less than 60%. Shandong Power Grid regulations are not less than 70%. As shown in Figure 3, the primary frequency pass rate is equal to the ratio of the actual integrated power of the unit to the theoretical integrated power, that is, the ratio of the integral area A formed by the theoretical power curve 2 to the integral area B formed by the actual power curve 3.

![PFC integral electricity contribution index calculation chart](image)

**Figure 3. PFC integral electricity contribution index calculation chart**

5.2. **Capacity selection method for FESS**

According to the statistics of the twelve month grid frequency of the unit, the upper and lower limits of the unit frequency are determined. Then, the power variation range that the unit needs to compensate is obtained. Since the price of the FES device increases with the increase of the capacity, it is necessary to make a reasonable compensation capacity selection according to the performance of the unit's PFC. In actual engineering, the average value is selected as the power variation. The integral
electricity contribution value within 60s is calculated according to the average value, and the theoretical integral electricity contribution value is obtained. The theoretical integral electricity contribution value is multiplied by the integral electricity contribution index to obtain the capacity value of the FES.

The statistical analysis of the grid frequency of one 300MW unit that frequency exceeds ±0.05Hz in 12 months. It is found that the power grid frequency is less than 50Hz for most of the time. As shown in Figure 4, since the frequency of the unit generally fluctuates within ±0.1Hz, the capacity of FES is calculated according to the frequency deviation value. Corresponds to ±0.1Hz frequency fluctuation, the unit needs to provide 8MW PFC power compensation. Since the integral electricity contribution index of this power grid is not less than 70%, the capacity of the FES can be 5.6MW.

![Figure 4. Statistics of the twelve month grid frequency of one unit](image)

6. Conclusion

Through the analysis and comparison of different energy storage technologies, the energy storage principle of FES and the design of motor controller are introduced and analyzed in detail. In this scheme, FES is selected as an effective auxiliary means of PFC, which can select reasonable FES compensation capacity according to the frequency index under various working conditions and coordinate with the unit. Utilizing the quick response and accurate tracking capability of FESS, the frequency modulation performance of the unit can be improved and the rotary reserve capacity required by the power grid can be reduced. At the same time, through the reasonable selection of energy storage device capacity, the power plant can make full use of FES device to carry out frequency modulation compensation, and reduce the unit action amplitude.

References

[1] Bowden G J, Barker P R, Shestopal V O, etal. (1983) The Weibull distribution function and wind power statistics. Wind Engineering, 7(2):85-98.

[2] LIN Li, Tian Xinyu. (2017) Analysis of deep peak regulation and its benefit of thermal units in power system with large scale wind power integrated. Power System Technology, 41(7):2255-2263.

[3] Chen H, Cong N T, Yang W, Tan C, etal. (2009) Process in electrical energy storage system— a critical review. Process in Natural Science, 19(3):291-312.

[4] Edgardo D C, Pecaslopes J A. (2004) Optimal operation and hydro storage sizing of a wind hydro power plant. International Journal of Electric Power & Energy Systems, 26(10):771-778.

[5] Tatsuto Kinjo, Tomonobu Senjyu. (2006) Output levelling of renewable energy by electric double-layer capacitor applied for energy storage system. IEEE Transactions on Energy Conversion, 21(1):221-227.

[6] Baker J. (2008) New technology and possible advance in energy storage. Energy Policy, 36:4368-4373.

[7] Genta G. (1985) Kinetic energy storage: theory and practice of advance flywheel systems.
London & Boston: Butterworths.

[8] Tarrant C. (1999) Revolutionary flywheel energy storage system for quality power. Power Engineering Journal, 13(3):159-163.

[9] Gowayed Y, et al. (2002) Optimal design of Multi-direction composite flywheel rotors. Polymer Composites, 23(3):433-441.

[10] Yamanchi Y, et al. (2006) Development of 50kWh-class superconducting flywheel energy storage system. International Symposium on Power Electronics, 36:484-486.