Low-frequency oscillation suppression strategy considering dynamic power characteristics of energy storage system

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Abstract. Aiming at the problem of low-frequency oscillation in the weak power grid, a low-frequency oscillation suppression strategy considering the dynamic power characteristics of the energy storage system (ESS) is proposed in this paper. Firstly, the principle of low-frequency oscillation in the power system is analyzed by using a single machine infinite bus system. Secondly, considering the dynamic characteristics of the ESS output active power, a controller for the ESS to suppress low-frequency oscillation is designed, which can provide positive damping for frequency oscillation of the power grid. Finally, the simulation analysis and experimental results of an actual weak grid are carried out to verify the effectiveness and feasibility of the proposed method. The results show that the suppression effect of the low-frequency oscillations is related to the ESS location in the weak power grid.

1. Introduction

In remote areas, the power system often adopts chain connection mode, the grid structure is relatively weak, and the stability of the power grid is also relatively weak. Meanwhile, with the proposal of carbon neutrality and peak carbon dioxide emissions, the new energy in the power system will gradually become the main power supply, which will further deteriorate the stability of the system. It is easy to cause low-frequency oscillation in areas with a weak grid, and it seriously affects the safe and stable operation of the power grid [1-2]. Therefore, there is great theoretical significance and practical engineering value to study the suppression of low-frequency oscillation in weak power grid.

In the current development trend of regional power grid interconnection, low-frequency oscillation of power systems has become one of the important problems threatening the safe operation of the power system. Conventional methods of suppressing low-frequency oscillation include power system stabilizer (PSS) and the device of using flexible AC transmission systems (FACTS), et al [3-5]. The effect of using PSS to suppressing low-frequency oscillations depends on the mutual coordination of the parameters, but this method cannot adapt well to the changes in the operating state of the generator and the power system [6]. The FACTS device can smoothly change the power system damping, but it only provides reactive power support for the power system. The FACTS device to suppress low-frequency oscillation is the static synchronous compensator (STATCOM) of the parallel voltage source type. With the development of renewable energy power generation and power electronics
technology, the demand for flexible energy storage resources in power systems is increasing rapidly. Therefore, energy storage technology to stabilize system power fluctuations and suppress oscillation has become an effective method to improve the safety and stability of the power system.

At present, the advantages of the energy storage system (ESS) in suppressing power oscillation make it have a good application scenario. In [7], the generation, transmission and assignment of damping torque and influence of modal damping is studied based on the damping torque analysis method, the index and parameter configuration method of location and capacity for energy storage system are proposed, it can provide a reference for energy storage to suppress low-frequency oscillation of power grid. In [8], the physical mechanism of the energy storage system to suppress the low-frequency oscillation of the power grid is revealed, and when the energy storage system operates in the droop control and inertia control strategies, the parameters of the active power and damping coefficient in the speed control loop are adjusted, respectively. We can equivalently change the damping capacity and inertia level of the power system. In [9], the action path and mechanism of energy storage system active and reactive power modulation modes to suppress low-frequency oscillations were studied, and it proposed that the active power control mode has greater potential for increasing damping and higher stability; however, energy storage converters capacity limitation on different power modulation modes are not considered. The impact of capacity limitation. In [10], suppression strategy for low-frequency oscillations of power grid considering energy storage system converter capacity limit was proposed, but This document requires frequent switching to achieve low-frequency oscillation on the power grid, which is difficult to effectively apply to engineering practice.

Therefore, considers the dynamic characteristics of the ESS output power, and a control method for the ESS to suppress low-frequency oscillations is proposed in this paper. It can provide positive damping for system frequency oscillations. Then, a linearized mathematical model of a single-machine infinite bus system with the ESS is established. the action path of the ESS in suppressing low-frequency oscillation is analyzed by the damping torque analysis method. The damping torque analysis method is used to analyze the effect of the ESS on suppressing low-frequency oscillation. Finally, a weak current network is taken as an example to verify the correctness and effectiveness of the proposed method.

This paper is organized as follows: the topological structure of the ESS is presented in Section 2. Suppression strategies considering the dynamic power characteristics of the ESS are discussed in Section 3. In Section 4, the effectiveness and feasibility performance of the proposed method is examined in the weak network system. Section 5 is the conclusion.

2. The topological structure of the ESS

The ESS is mainly composed of the battery, DC capacitor, DC/AC converter and inductor. The structure is shown in Figure 1. $U_{DC}$ is DC voltage; L, C are filter inductor and filter capacitor, respectively; $i_{abc}$ is filter inductor current; $U_{oabc}$ is inverter output voltage; $i_{oabc}$ is output three-phase current; P, Q are the instantaneous output active and reactive power after low-pass filtering, respectively; $E_0$ is reference port voltage.

![Figure 1. Topological structure of the ESS.](image-url)
3. Suppression strategy considering the dynamic power characteristics of the ESS

3.1. Mechanism analysis of low-frequency oscillation in power system

The third-order practical model is adopted, and the equivalent damping coefficient $D$ is used to replace the damping winding. The third-order mathematical model of the generator is given by

$$\begin{align*}
\frac{d\delta}{dt} &= \omega_0(\omega - 1) \\
T_e \frac{d\omega}{dt} &= M_m - M_e - D(\omega - 1) \\
T_{d0} \frac{dE_q^*}{dt} &= E_{fd} - E_q' - (x_d - x_d')i_d
\end{align*}$$

(1)

where, $T_j$ and $T_{d0}$ are the inertia time constant and the $d$-axis open-circuit transient time constant, respectively; $M_e$ and $M_m$ are the generator electromagnetic torque and the mechanical torque, respectively; $\omega$ and $\omega_0$ are the rotor speed and synchronous speed, respectively; $D$ is the damping coefficient; $\delta$ is the rotor angle; $E_q'$ and $E_q^*$ are $q$-axis transient electromotive force and $d$-axis excitation electromotive force, respectively; $x_d$ and $x_d'$ are $d$-axis synchronous reactance and $d$-axis transient reactance of the generator, respectively.

The stator winding voltage equation is given by

$$\begin{align*}
-u_d &= x_q' \cdot i_q \\
u_q &= E_q' - x_q' \cdot i_q
\end{align*}$$

(2)

where, $i_d$ and $i_q$ are the stator current shaft and shaft components, respectively; $u_d$ and $u_q$ are the $d$-axis and $q$-axis components of the stator voltage, respectively; $x_q$ are the $q$-axis reactance.

The electromagnetic power equation is given by

$$P_e = E_q' \cdot i_q - (x_q - x_q')i_q \cdot i_q$$

$$\Delta P_e = K_1 \cdot \Delta \delta + K_2 \cdot \Delta E_q'$$

(3)

Linearizing Equations (1) - (3), We can obtain the small disturbance model of the single-machine infinite bus system, where the linearized equation of the generator electromagnetic torque is given by

$$\Delta T_e = K_1 \cdot \Delta \delta + K_2 \cdot \Delta E_q'$$

(4)

The linearized equation of generator transient electromotive force is given by

$$\Delta E_q' = \frac{K_1}{1 + K_1 T_{d0} s} \Delta E_w - \frac{K_1 K_4}{1 + K_1 T_{d0} s} \Delta \delta$$

(5)

The linear equation of the generator terminal voltage is given by

$$\Delta U_w = K_1 \Delta \delta + K_4 \Delta E_q'$$

(6)

where $K_1, K_2, K_3, K_4, K_5$ is coefficient [10].

Combining the Equations (4) to (6), the model of the synchronous machine can be obtained, as shown in Figure 2. As shown in Figure 2, when the proportion of renewable power generation put into the power system is gradually increasing, the damping of the power will gradually decrease. Simultaneously, it will become a weak grid, and it is easy to cause low-frequency oscillation. When the power system is under heavy load, it may lead to negative damping. Then the system may have low-frequency oscillation under disturbance [11].
3.2. Control strategy for ESS to suppress low-frequency oscillation

When low-frequency oscillation occurs in the power system, the ESS dynamically adjusts the system frequency according to the active power and frequency deviation. The controller of suppresses low-frequency oscillation is shown in Figure 3.

\[
P_p = \begin{cases} 
  (\Delta \omega - \frac{1}{1+sT_p} + P_{ref} - P) \cdot \frac{K_p + \frac{K_i}{s}}{1 + sT_p} \cdot 1 & \text{if } \Delta \omega > \Delta \omega_0 \\ 
  0 & \text{if } -\Delta \omega_0 \leq \Delta \omega \leq \Delta \omega_0 \\ 
  (\Delta \omega + \frac{1}{1+sT_p} + P_{ref} - P) \cdot \frac{K_p + \frac{K_i}{s}}{1 + sT_p} \cdot 1 & \text{if } \Delta \omega < -\Delta \omega_0 
\end{cases}
\]

(7)

\[
P_{ES} = \begin{cases} 
  \text{sgn}(P_{ES}) \cdot P_{ES, \text{max}} & \text{if } P_{ES} \geq P_{ES, \text{max}} \\ 
  P_{ES} & \text{if } P_{ES, \text{max}} < P_{ES} < P_{ES, \text{max}} \\ 
  0 & \text{if } P_{ES} \leq P_{ES, \text{max}} 
\end{cases}
\]

(8)

where, \( P_p \) is the output power of the energy storage; \( \Delta \omega \) is the frequency deviation; \( K_i \) and \( K_p \) are the droop coefficient and the integral coefficient of the energy storage participating in the suppression of low-frequency oscillation; \( \Delta \omega_0 \) is the control dead zone of the energy storage to suppress the low-frequency oscillation; \( P_{ES, \text{max}} \) is the storage energy maximum energy power.

When the frequency deviation is within the dead zone, the output active power of the ESS is zero. When the frequency deviation exceeds the positive dead zone, the ESS outputs active power to the power grid. When the frequency deviation exceeds the negative dead zone, the ESS absorbs active power from the power grid. The dead zone is conducive to the decision of the depth of action of the ESS participating in low-frequency oscillation, including the size and direction of the ESS active power. At the same time, to reduce the demand for the ESS capacity in the process of suppressing low-frequency oscillations, the limiting loop is set up to limit the energy storage active power.

When the rotor speed is 1, the torque per unit value is approximately equal to the power per unit value, then the synchronous torque coefficient and damping torque coefficient of the system are [10]:

\[
\begin{align*}
  K_p &= K_1 + K_{p2} \\
  K_D &= D + K_{D2}
\end{align*}
\]

(9)
4. Simulation analysis
The simulation analysis and experimental results of a real weak power grid are carried out to verify the effectiveness and feasibility of the proposed method in this paper. Schematic diagram of high voltage interconnected a real weak power grid A and power grid B as shown in Figure 4. The voltage level of the power grid is 550kV. This power grid includes real weak power grid A and power grid B. The power grid adopts a chain connection mode. We can connect an energy storage system in A2 substation, A3 substation, A6 substation, A7 substation. The rated capacity of the ESS is 100MVA. The output voltage of the ESS is 10 kV. After passing the transformer, the rated voltage of the ESS is increased to 550 kV, and then it was connected to the power grid. We can use the PSASP (power system analysis synthesis program) for simulation verification.

![Schematic diagram of high voltage interconnected a real weak power grid A and power grid B.](image)

**Figure 4.** Schematic diagram of high voltage interconnected a real weak power grid A and power grid B.

![The power angle curves of generators without ESS.](image)

**Figure 5.** The power angle curves of generators without ESS.

We set up a failure on the B11 side of the transmission B11-B16. And we chose the power angle of generator GA1#1_GB8#1, GB12#01_GB8#1, GB2#1_GB8#1, GA1#1_GB2#1, GA1#1_GB5#1, GB2#1_GB5#1, GB9#1_GB5#1, GB8#1_GB5#1, GB12#1_GB2#1 and GB12#1_GB9#1. The power
angle curves of generators without ESS are as shown in Figure 5. As shown in Figure 5, the power angle of generator GA1#1_GB8#1, GA1#1_GB2#1 and GA1#1_GB5#1 have a large oscillation, and at the 40s, the power angle of the generators is still oscillating. Secondly, to obtain the power angle curve damping ratio and oscillation frequency. Similarly, the power angle curve of a typical generator GA1#1_GB2#1 was also selected for analysis. Prony analysis results are listed in Table 1, we can know the power angle of GA1#1_GB2#1 has a low-frequency oscillation with an oscillation frequency of 0.52Hz. The damping ratio is approximately 0.0116. This oscillation severely restricts the transmission capacity of the transmission line A7-B25.

When the ESS project is put into production, the power angle curves of generators without ESS are as shown in Figure 6. As shown in Figure 6. ESS put into A2 substation and A3 substation to suppress low-frequency oscillations effect is superior ESS put into A6 substation and A7 substation. Similarly, the power angle curve of GA1#1_GB2#1 was selected for analysis. In Table 1, the damping ratio is approximately 0.0352, 0.0333, 0.0126, 0.0073; the frequency is approximately 0.512, 0.511, 0.552, 0.517. It can be seen that the suppression of the low-frequency oscillations effect is related to the ESS location. When it is close to the position of the generator, the effect is the best.

![Figure 6. The power angle curves of generators after ESS put into the power system.](image)

![Table 1. Prony analysis results.](image)

| Working condition       | frequency (Hz) | damping ratio |
|-------------------------|----------------|--------------|
| without ESS             | 0.5222         | 0.0116       |
| ESS put into A2 substation | 0.512         | 0.0352       |
| ESS put into A3 substation | 0.511         | 0.0333       |
| ESS put into A6 substation | 0.552         | 0.0126       |
| ESS put into A7 substation | 0.517         | 0.0073       |
5. Conclusions
Considering the problem of low-frequency oscillation in the weak grid structure, a low-frequency oscillation suppression strategy considering the dynamic power characteristics of the ESS is proposed in this paper. Firstly, the principle of low-frequency oscillation in the power system is analyzed. Meanwhile, considering the dynamic characteristics of the ESS output power, a controller of the suppressing low-frequency oscillation is power. Finally, the simulation analysis and experimental results of the actual weak grid are carried out to verify the effectiveness and feasibility of the proposed method. We can connect an ESS in A2 substation, A3 substation, A6 substation, A7 substation. The results show that the suppression low-frequency oscillations effect is related to the ESS location. When it is close to the position of the generator, the effect is the best.

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