Case and mechanism analysis of low frequency oscillation caused by abnormal excitation system

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Abstract. This paper talks about a low-frequency oscillation event caused by the abnormal excitation system, and analyzes the mechanism of the oscillation. In view of the difficulty of finding the event cause, the theory of oscillation energy is used to locate the disturbance source in control device level. According to the oscillation waveform recorded by the wide area measurement system (WAMS), the source disturbance is located on the excitation system and confirmed on site. Finally, the physical mechanism of forced power oscillation caused by abnormal excitation system is explained, and the preventive measure is proposed.

1. Introduction

The power system is a nonlinear dynamic system, and the stability of its operation is a key issue. Since China’s energy and load centres are far apart, it is necessary to complete the power transmission through interconnection of regional power grids. At present, the scale of the power grid is getting larger and larger, and the operation mode is more and more complicated. The low frequency oscillation events caused by various reasons occur sometimes.

In [1], Su Y summarized the power oscillation events that occurred in the Southern Power Grid since 2008, and sorted out the causes of the oscillations. The main reasons include the weakly damped oscillation mode of the small group to the main network, the instability of the speed control system, the improper setting of primary frequency modulation parameters, and excitation system defects or abnormalities. By combining the negative damping mechanism [2] and the forced power oscillation mechanism [3], it’s pointed out in [4] that the main reason for the oscillation is the reduction of the damping and the introduction of external forced disturbance.

In recent years, several low frequency oscillation events related to the excitation system have occurred. Through simulation technology, Zhang J \textit{et al.} found the cause of abnormal power fluctuation of the Three Gorges hydropower station, that is, the wrong parameter setting of power system stabilizer (PSS) [5]. For the low-frequency oscillation event in [6], there is a defect in the PSS logic of the excitation system. For “12.2” low-frequency oscillation in Pingban Power Plant [7], the angular velocity input signal of PSS is shielded during the software upgrade process, which makes PSS cannot provide effective positive damping in the case of large disturbance. Duan J \textit{et al.} analyzed the influence of the current measurement in the excitation controller on the low-frequency oscillation [8], and pointed out that the influence of the current measurement on the low frequency oscillation is greater than that of the voltage measurement to some extent.
The energy function is a powerful tool for analyzing the stability of large power grids. At present, the energy function has made great progress in the stability domain [9]-[10], and it has become practical [11]. In [12], Chen et al. proposed a method for on-line calculation of oscillation energy flow based on WAMS data, which can avoid the difficulty in the construction of energy function. Further, the oscillation energy suitable for the control equipment level is derived in [13], which can locate the disturbance source in control systems of generator.

This paper introduces a low-frequency oscillation event caused by abnormal excitation system, and analyzes the oscillation mechanism. Using the waveform recorded by WAMS, the oscillation energy for the excitation and the governor system are calculated to locate the disturbance source. Combined with theoretical analysis, the abnormal stator current acquisition of excitation system is the cause of oscillation event.

2. Excitation system configuration

A power plant in Hunan Power Grid has two turbine generators with a rated power of 660 MW. One generator is connected to the grid via a 220kV substation, and the other generator is connected to a 500kV substation. The excitation system of the generators adopts self-shunt excitation system, and the specific model is the UNITROL 6800 microcomputer excitation regulator provided by ABB. The mathematical model of the excitation system is shown in Figure 1, and its PSS model is shown in Figure 2.

As can be seen from Figure 1, $U_g$ and $U_{ref}$ are the terminal voltage and terminal voltage reference value of the generator, $U_{ps}$ is PSS output value. The PSS output is superimposed on the PID output point to suppress the low frequency oscillation [5]. In Figure 2, PSS model of UNITROL 6800 is a typical PSS2B, whose input is active power and angular velocity deviation.

3. Low frequency oscillation event description

In 2018, the power oscillation occurred in the generator connected to the 220kV substation in the power plant. The WAMS of the dispatch center recorded the whole process of the low frequency oscillation event, which is shown in Figure 3. This power oscillation event exhibits an intermittent characteristic, and the oscillation amplitude increases to a maximum rapidly at a certain time, and then decays.

In order to find the cause of the oscillation, the technicians conducted investigations from the power grid and the power plant respectively. It is verified by the dispatch control center that there is no disturbance on the power system when the oscillation occurs. However, the technicians did not find any obvious clues to the cause of the oscillation in the power plant.

![Figure 1. Mathematical model of the self-shunt excitation system.](image-url)
Due to the complexity of this low-frequency oscillation event, this section uses the oscillation energy to assist in the analysis, thereby reducing the fault range. According to Hamilton's realization, Li et al. analyze the internal energy structure of the generator [13], and split the transient energy into two components corresponding to the governor system and the excitation system, that is $W_{gov}^i$ and $W_{exc}^i$:

$$W_{gov}^i = \int (P_{ei} \Delta f_i + E_{int}^i)dt$$  \hspace{1cm} (1)$$

$$W_{exc}^i = \int (Q_{ei} \frac{\dot{U}_{ei}}{U_{ei}} + E_{ex} - E_{int}^i)dt$$  \hspace{1cm} (2)$$

with
\[ E_{ei} = \frac{(Q_{ei} + \frac{U_n^2}{x_q})P_e U_n^2 x_q}{P_e^2 + (Q_{ei} + \frac{U_n^2}{x_q})^2} \left[ (Q_{ei} + \frac{U_n^2}{x_q})\dot{P}_e - (Q_{ei} + \frac{2U_n\dot{U}_n}{2}) \right] \]  
\[ E_{int,ei} = \frac{P_e^2 + (Q_{ei} + \frac{U_n^2}{x_q})^2}{x_q} \]  
\[ P_{ei} = \frac{dP_{ei}}{dt} \]  
\[ Q_{ei} = \frac{dQ_{ei}}{dt} \]  
\[ U_n = \frac{dU_n}{dt} \]  

where \( P_{ei} \) and \( Q_{ei} \) are the active and reactive power of the \( i \)th generator, \( U_n \) is the terminal voltage amplitude of the \( i \)th generator, \( f_i \) is the terminal frequency, and \( x_q \) is \( q \)-axis synchronous reactance.

\( W_{we}^{ei} \) and \( W_{te}^{ei} \) reflect the \( i \)th generator’s contribution to the overall energy of the power system for a period of time, through the governor system and the excitation system respectively. According to the theory of oscillation energy, the potential energy flowing into the busbar is defined as negative in the network, and the potential energy flowing out of the busbar is positive. Therefore, the trend of \( W_{we}^{ei} \) and \( W_{te}^{ei} \) can be used as the criterion for determining whether there is a disturbance source in the two control systems. Using the generator busbar data recorded by WAMS, the disturbance source can be located on a specific control system. In this case, an oscillation waveform of 10s is used for analysis. The electrical components \( P_{ei}, Q_{ei}, U_n \) and \( f_i \) for oscillation energy calculation are shown in Figure 4.

**Figure 4.** Electrical components for oscillation energy calculation.
The oscillation energy for governor system is shown in Figure 5, and the oscillation energy for excitation system is shown in Figure 6. It can be seen that the non-periodic component of the oscillation energy for governor system is less than 0, indicating that the governor system extracts energy from the power system continuously, which is conducive to the stability of the grid. On the contrary, the non-periodic component of the oscillation energy for excitation system is greater than 0, indicating that the excitation system injects energy into the power system continuously, which is not conducive to the stability of the grid. Therefore, the disturbance source exists on the excitation system.

**Figure 5.** Oscillation energy for governor system.

**Figure 6.** Oscillation energy for excitation system.

5. Determination of oscillation mechanism

With the oscillation energy theory, the power oscillation disturbance source is concentrated on the excitation system. After several days of field observation, the technicians found the fault point, as shown in Figure 7. For the UNITROL 6800, the CCM collects the generator terminal voltage $U_g$ and current $I_g$ through the secondary circuit of the potential transformer (PT) and current transformer (CT). It is found that B phase of the CT secondary circuit has intermittent grounding condition, which will cause the stator current collection to be abnormal. That is, the stator current collected by the excitation regulator is unbalanced, and the amplitude of the B phase decreases intermittently.
Figure 7. Fault point diagram of excitation system.

Under normal conditions, the active power based on the ideal $U_g$ and $I_g$ is as follows:

$$ P_e = u_{ga}(t)i_{ga}(t) + u_{gb}(t)i_{gb}(t) + u_{gc}(t)i_{gc}(t) $$

$$ = \frac{3}{2} U_1 I_1 \cos(\phi_u - \phi_i) $$

with

$$ \begin{align*}
    u_{ga} &= U_1 \sin(\omega_1 t + \phi_u) \\
    u_{gb} &= U_1 \sin(\omega_1 t + \phi_u - \frac{2}{3} \pi) \\
    u_{gc} &= U_1 \sin(\omega_1 t + \phi_u - \frac{4}{3} \pi)
\end{align*} $$

and

$$ \begin{align*}
    i_{ga} &= I_1 \sin(\omega_1 t + \phi_i) \\
    i_{gb} &= I_1 \sin(\omega_1 t + \phi_i - \frac{2}{3} \pi) \\
    i_{gc} &= I_1 \sin(\omega_1 t + \phi_i - \frac{4}{3} \pi)
\end{align*} $$

where $U_1$ and $I_1$ are the primary amplitude of generator terminal voltage and current, $\omega_1$ is the electrical angular frequency. $\phi_u$ and $\phi_i$ are the initial phase angles of generator terminal voltage and current. Theoretically speaking, the instantaneous value of active power has no pulsation.

When the intermittent grounding in Figure 7 appears, the instantaneous power calculated by the excitation regulator is no longer a constant value. Suppose the amplitude of B phase current changes alternately with an oscillation frequency $\omega_D$ and initial phase angle $\phi_D$, and then B phase generator current can be expressed as:
$i_b = [I_i \cos(\omega_i t + \phi_D)] \cdot \sin(\omega_i t + \phi_I - \frac{2}{3} \pi)$ \hspace{1cm} (11)

And the instantaneous active power of the generator is

$$P_e = \frac{3}{2} U_i I_i \cos(\phi_e - \phi_I) + \frac{1}{2} U_i I_i \left[ \cos(\phi_e - \phi_I) - \cos(2\omega_i t - \phi_e + \phi_I) \right] \cdot \cos(\omega_i t + \phi_I) - 1$$ \hspace{1cm} (12)

It can be seen from (12) that there is a periodic component in the instantaneous value of the active power. At the same time, as one of the PSS input signals in Figure 7, the fluctuating active power will trigger the PSS. Inevitably, the PSS output $U_{pss}$ will contain a periodic component and affect the excitation control voltage $U_e$. Therefore, there is a perturbation component of the certain frequency in the entire voltage control loop in Figure 7.

In general, PSS output $U_{pss}$ can suppress power oscillation by affecting the terminal voltage $U_p$. But for this case, the PSS provides a superimposed channel for abnormal current acquisition, and a forced power oscillation occurs.

6. Conclusions

In this paper, a low-frequency oscillation event caused by the abnormal excitation system is studied, and the oscillation mechanism is analyzed. With the theory of oscillation energy, the low frequency oscillation disturbance source is located on the excitation system. The intermittent grounding of the CT secondary circuit causes the active power calculation abnormality, and triggers the forced power oscillation event through the PSS link.

As the main means of suppressing low-frequency oscillations, PSS becomes the boosting force under abnormal conditions. From this case, the correctness of data collection is the basis of equipment control. Therefore, in the daily operation and maintenance of the generator, the secondary circuit of the excitation system should be checked regularly to ensure the stability of control system.

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