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Mechanism analysis and suppression method of ultra-low-frequency oscillations caused by hydropower units

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ABSTRACT

The ultra-low-frequency oscillation (ULFO) occurred in the hydro-dominant Yunnan power grid during its asynchronous interconnection with the China southern power grid in 2016, with the oscillation frequency at about 0.05 Hz. In view of this practical engineering problem, this paper analyzes the mechanism of this problem and puts forward the corresponding suppression measures. First, this paper utilizes the classical control theory to reveal the mechanism of the ULFO and analyze the effect of the governor parameters on the ULFO. According to the analysis, the ULFO will occur when the installed capacity of the hydro-power units is too large and the ratio of the hydro-power governor's proportional parameter to the integral parameter is too small. Secondly, a new method to tune the governor parameters is proposed, the parameters tuned by this method can avoid the recurrence of the ULFO under different operation conditions. Finally, simulation verifications are run in a three-machine system and the Yunnan power grid using PSS/E (Power System Simulator/Engineering). The simulation results verify the effectiveness of the analysis and the measure.

1. Introduction

With the proportion of clean energy increasing and the proportion of thermal power decreasing, the stability of power systems is reducing. This is because wind turbines and photovoltaic plants cannot provide the inertial support for power systems and the stability of the hydropower plant is relatively poor. This is a problem that power systems all over the world will face. Therefore, improving the stability of the power system with high penetration of clean energy is a prerequisite for humans to use clean energy on a large scale. At present, a large number of hydropower units are installed in the Yunnan power grid, which is an important sending terminal in the West-to-East Electricity Transmission Project. The Yunnan power grid is part of the synchronous network of the China southern power grid before 2016. In 2016, asynchronous interconnection tests were carried out between the Yunnan power grid and the rest of the China southern power grid [1]. During the tests, it is monitored that long time and large amplitude ultra-low-frequency oscillation (ULFO) with frequency of about 0.05 Hz occurred in the Yunnan power grid, seriously endangering the stable operation of the power systems. In fact, The ULFO not only occurred in China, but also in Turkey, Colombia and Nordic. The high penetration of hydropower increases the risk of the ULFO, and the use of hydropower will be limited if the ULFO cannot be solved from the root. In order to solve the problem of the ULFO and provide security for the large-scale use of hydropower, it is necessary to clarify the ULFO mechanism and propose an effective suppression measure.

There is an essential difference between the ULFO and the low-frequency oscillation, no oscillation between units is observed and all units have the same frequency in the ULFO. The ULFO is not a problem of the angle stability, but belongs to the category of the frequency stability. Since the oscillation frequency of the ULFO is lower than 0.1 Hz, the power system stabilizer cannot suppress the oscillation effectively. The cause of the ULFO in the Yunnan power grid has been proved to be hydro-power governors [2,3]. As for the stability analysis of hydroelectric generating units, a lot of research has been done by scholars. The dynamic characteristics of hydraulic turbine governors are introduced in detail in [4,6]. Ref. [7] uses the state space method to analyze the governor-turbine-hydraulic system stability. According to the analysis of [8], the ultra-low-frequency mode is a control mode of the governor system and its damping ratio is mainly influenced by the parameters of the PID controller. The governor power control mode has a better performance on stabilizing the low frequency oscillation caused by surge fluctuation [9]. Ref. [10] proposes a PI governor tuning criterion for the pumped storage hydro plants which can provide frequency support capacity in isolated power systems having significant renewable energy resources. The ULFO caused by hydropower generating units is reported in Columbia, Turkey and Nordic power grids before [11,13]. For the problem of Columbia power grid, Ref. [14] sets

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up a hydropower plant dynamic model and analyzes the dynamic characteristic of very low frequency oscillations in 0.05–0.08 Hz, finding out that the ULFO roots in the feed-forward controls of the governors. According to [12], the ULFO in Turkey is caused by the modification of the governor regulating speed. The fast control settings reduce the damping of frequency oscillations. According to the analysis of [15], the ULFO in the Yunnan power grid is a non-electromechanical oscillation mode, and optimizing the governor parameters can effectively improve the stability of the system. Ref. [16] simplifies the governor system controller model to a permanent speed droop coefficient, and analyzes the effect of the permanent speed droop coefficient and the load frequency factor on the system stability. While [8–16] have a profound analysis of ULFOs, it is still instructive to analyze the mechanism of ULFOs from different perspectives. When the ULFO occurs, emergency measures should be taken, and the operators need to adjust the governor parameters immediately. From this point of view, it is urged to provide an instructive guide for the operators to handle such problems.

According to [15], tuning governor parameters is an effective measure to solve the ULFO. There have been many methods for tuning governor parameters in existing literature. Many articles utilized intelligent algorithms to tune the PID parameters in governors, such as particle swarm optimization [17,18], genetic algorithm [19,20] and artificial fish swarm algorithm [21]. In [22,23], the traditional pole-placement method is used to adjust the governor parameters of the hydraulic turbine. Ref. [24] uses the relevant coefficient index to screen the ultra-low-frequency mode sensitive generators in a multi-machine system, and applies the particle swarm optimization to tune the PID parameters. Value set approach is applied to analyze the large-scale power system and tune the controller parameters in [25]. Ref. [26] gives a time domain solution for guide vane opening response and a response time formula using a widely adopted governor model. Although there is a lot of research in this area, this paper will propose a method that can both strictly guarantee the stability of the system in mathematics and facilitate its application in practical projects.

One objective of this paper is to provide a guide for the operators to adjust the PID parameters of the governors and suppress the ULFO immediately. Another objective of this paper is to provide a PID parameters tuning method which can guarantee the stability of the multi-machine system under different operation conditions. The contributions are summarized as follows:

(1) The Nyquist curve of the primary frequency regulation model is applied to reveal the mechanism of the ULFO. According to the analysis, the stability of the hydro-power units in Yunnan power grid is poor, and the larger the capacity proportion of the hydro-power units, the worse the power system stability.
(2) The effect of the governor PID parameters on the stability is analyzed using the Routh-Hurwitz criterion and we get the conclusion that the too small ratio of the hydro-power governor's proportional parameter to the integral parameter results in the occurrence of the ULFO.
(3) A new method is proposed to tune the PID parameters of the governors. This method guarantees the stability of the multi-machine system in strict mathematical relations. And when the operation condition of a system changes, the parameters calculated by this method still keep the system stable.

The remainder of this paper is organized as follows. Section 2 describes the models used for the analysis, including the hydro-power governor model, the thermal-power governor model and the primary frequency regulation models. Section 3 presents the mechanism analysis of the ULFO based on the transfer function of the multi-machine frequency regulation model. Section 4 proposes a new method to tune the governor parameters. Section 5 presents simulation results in a three-machine AC system and the Yunnan power grid to verify the effectiveness of the method. Section 6 provides the conclusions of this paper.

2. Model description

In this section, the governor systems will be introduced first, including hydraulic governor system and thermal governor system. Next, the primary frequency regulation models of the single machine system and the multi-machine system are given. This paper will use these models for the following studies.

2.1. The governor models

The hydraulic governor system consists of a turbine, a servo motor and a controller, and the commonly used models of them are given in Fig. 1a [27]. In Fig. 1a, K_P is the proportional gain, K_I is the integral gain, K_D is the derivative gain, b_P is the permanent speed droop, s is the Laplace operator, T_G is the constant of the servo system, and Tw is the water hammer effect time constant. The thermal governor model is shown in Fig. 1b, this model is based on the model IEEEG1. In Fig. 1b, K is the reciprocal of the permanent speed droop coefficient, T_a, T_b, T_c, T_{CH}, T_{RH} and T_{CO} are the time constants, F_{HP}, F_{IP} and F_{LP} respectively represent the high, medium and low pressure cylinder mechanical ratio coefficient.

2.2. The primary frequency regulation models

With the generator considered, the single-machine primary frequency regulation model is shown in Fig. 1c, here H is the inertia constant of the generator unit, D is the mechanical damping coefficient. The ULFO is different from the low-frequency oscillation and belongs to the problem of the frequency stability. The characteristics of the ULFO are that the oscillation frequency is very low, the speed of all the units is changed in the same direction, and there is no obvious oscillation between the units [28,29]. Because all units have the same rotor speed in the process of the ULFO, the multi-machine primary regulation model can be established as shown in Fig. 1d [12]. In Fig. 1d, S_i is the ith unit rated capacity, k_i is the ratio of the ith unit rated capacity to the grid total capacity, H_{ae} is the equivalent inertia constant of all the parallel units, H_i is the inertia constant of the ith unit, $\Delta\overline{P_e}$ is the equivalent electromagnetic power, D_S is the equivalent damping coefficient of the system. In addition, D_{ae} is the equivalent mechanical damping coefficient, D_i is the ith unit mechanical damping coefficient, K_{Lae} is the equivalent load frequency regulation effect coefficient, S_{Lj} is the jth load rated capacity, K_{Lj} is the jth load frequency regulation effect coefficient. The K_L value of a static load is given directly by the model parameter. As for the K_L value of a dynamic load, we can add a small frequency deviation Δf to the load bus and measure the load active power deviation ΔP_L. The K_L of the dynamic load can be calculated by $\Delta P_L/\Delta f$.

$$k_i = S_i \Big/ \sum_{i=1}^{n} S_i,\quad k_i = S_i/\sum_{i=1}^{n} S_i,\quad H_{ae} = \sum_{i=1}^{n} k_i H_i, D_S = D_{ae} + K_{Lae}$$

$$\Delta\overline{P_e} = \sum_{i=1}^{n} k_i \Delta P_{ei},\quad D_{ae} = \sum_{i=1}^{n} k_i D_i,\quad K_{Lae} = \sum_{j=1}^{m} S_{Lj} K_{Lj} \Big/ \sum_{i=1}^{n} S_i$$

3. Mechanism of the ULFO

In this section, we will study the ULFO mechanism using the Nyquist curve of the multi-machine primary frequency regulation model in Fig. 1d. Next, Routh-Hurwitz criterion is applied to study the effect of the governor PID parameters on the system stability. Then, a conclusion is drawn to help the operators adjust parameters. Finally, we will discuss the effect of the governor system nonlinear links on the ULFO.