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Effect analysis of generator governor system and its frequency mode on inter-area oscillations in power systems

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ABSTRACT

The governor system of a synchronous generator not only can influence the damping characteristics of inter-area oscillations but also introduces a special ultra-low frequency mode into the power system. This mode, called frequency mode, has a lower frequency than that of inter-area modes and would appear when the governor system regulates the rotor speed. In this paper, the influence of governor system on the damping characteristics of inter-area oscillations is investigated by using the torque analysis theory. Then the feature of the frequency mode and its influence on inter-area oscillations are analyzed by using a 4-machine 2-area benchmark system. The analysis results show that the frequency mode is a control mode of the governor system and its damping ratio is mainly influenced by the parameters of the proportional-integral-derivative (PID) controller used for the governor system. When the governor system makes the damping ratio of an inter-area mode negative and the dead band is taken into account, the inter-area oscillation will gradually become an equal amplitude oscillation in case the damping of the frequency mode is relatively strong, while the inter-area oscillation will appear like a beat frequency oscillation in case the damping of the frequency mode is relatively weak. Finally, simulation results of a practical large-scale interconnected power system validate the effectiveness of the above analysis results.

1. Introduction

Inter-area oscillation is one of the critical problems threatening the operation and stability of a large-scale power system [1–6]. It is generally agreed that inter-area oscillations may be caused by either using high-gain exciters or delivering heavy load across long tie-lines. In such condition, the generator exciters will provide negative damping torque to inter-area oscillations [7,8]. In the past several decades, the mechanical-hydraulic governor is widely applied for the generators. Since the response speed of such governor is quite slower than that of the exciter system, the effect of the governor system on the inter-area oscillation is usually ignored and only the effect of the exciter is considered in power system rotor angle stability analysis [9,10].

On one hand, recent studies have shown that governor system of a generator can influence the damping of inter-area oscillation significantly [11]. On the other hand, with the development and implementation of electro-hydraulic governor system [12], its influence on inter-area oscillation cannot be ignored as its response characteristic is significantly improved compared with the mechanical-hydraulic governor [13]. In [13], it is found that governor system of a hydro generator can provide negative damping to low frequency oscillation within a certain range of frequency. Governor systems may somehow provide positive damping to inter-area modes [14]. Ref. [15] shows that nonlinear operating point of valve control in the governor system can also evoke low frequency oscillations. Besides, damping controllers are designed and added to governor system to suppress low frequency oscillation in [16–18]. Currently, oscillation events caused by governor systems are quite common in a practical power system. A low frequency oscillation event caused by governor system providing negative damping torque in China is reported in [19]. Ref. [20] summarizes and analyzes 15 oscillation events occurred in the China Southern Power Grid between 2008 and 2012, it can be concluded that there are 6 events caused by the instability of governor system and 2 events caused by the instability of primary frequency control. Consequently, the effect of the governor system should be considered carefully in the stage of analyzing low frequency oscillations.

Governor system can also influence long-term frequency dynamics of a power system. Quasi-steady-state model is proposed for analyzing long-term voltage and frequency dynamics including governor system in [21], and simulation results show that governor system will

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introduce a new ultra-low frequency oscillation mode into the power system. This particular oscillation mode is called frequency mode in [22]. In [23], simulation results show that parameters of the PID governor controller have a significant influence on this ultra-low frequency oscillation. Ref. [24] demonstrates that power system stabilizers can enhance the damping of this mode to some extent. Refs. [25,26] reveal that dead band has a significant impact on the frequency response of power system. Field tests and oscillation events of this ultra-low frequency oscillation in practical systems can be found in [27–30]. In [28], an ultra-low frequency mode oscillation event in the hydro-dominant Columbian Power Grid is investigated. This oscillation has the frequencies in the range of 0.05–0.08 Hz and is caused by a feed forward control of the hydro governor system. Ref. [29] also reported an oscillation with the frequency of 0.05 Hz was observed in Turkish Power System, which is caused by improper parameter setting of the hydro governor. Analysis results indicate that the frequencies of these mentioned oscillations are usually lower than 0.1 Hz and all of them are caused by the governor systems. Therefore, it can be concluded that these ultra-low frequency oscillations are strongly correlated with turbine governors and the frequency of this frequency oscillation mode is relatively lower than that of the conventional inter-area modes.

The above references have investigated the influence of governor system on power system from following two aspects. One is that governor system may provide negative damping torque to inter-area modes. The other is that the governor system will introduce frequency mode oscillations into power grids. Furthermore, Ref. [31] has reported an oscillation event occurred in European power grid. The curve of the frequency oscillation is recorded and shown in Fig. 1. It can be found that there exists an ultra-low frequency mode oscillation (the oscillation frequency is about 0.015 Hz) oscillating together with the inter-area oscillation. This indicates that the ultra-low frequency oscillation may have influences on inter-area oscillations in the power grid. However, most of them investigate the characteristics of frequency mode only by numerical simulations and not by theoretical analysis. Moreover, the influence of frequency mode on inter-area oscillation has not been analyzed.

To address the above problem, this paper further investigates the influence of frequency mode on inter-area oscillation. The model of a typical hydraulic governor system is used and analyzed in the common frequency model of the system [21]. The analysis results are validated through a 4-machine 2-area benchmark system and a practical large-scale interconnected power system, respectively. Note that although only hydraulic turbine governor systems are investigated here, the analysis method used in this paper can also be applied for analyzing the thermal turbine governor systems.

Compared with the previous results, the main contributions of this paper are listed as follows,

- The frequency mode oscillation is theoretically analyzed by using the common frequency model of the power system. It more clearly reveals the inherent characteristics of the turbine governor system. The parameters of the governor system how to influence the damping of inter-area oscillation and the frequency mode oscillation can be obtained quantitatively.
- The influence of dead band and frequency mode on inter-area oscillations is also investigated. Analysis results show that inter-area mode oscillating with frequency mode may cause a variation in the damping ratio of the inter-area mode and make the inter-area oscillation like a beat frequency oscillation.
- The above analysis results are validated through the 4-machine 2-area system and a practical interconnected power system, respectively. Simulation results verify the correctness of the analysis results.

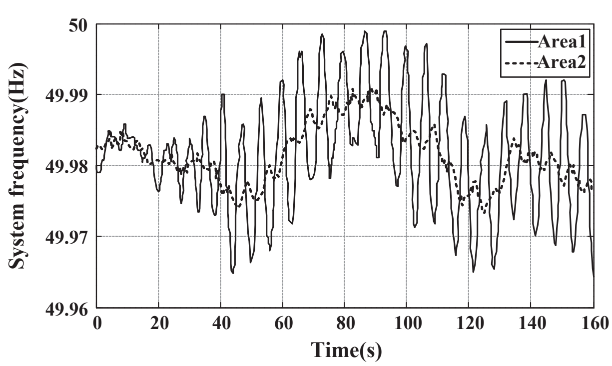

Fig. 1. Frequency oscillation curves recorded in European power grid.

The rest of the paper is organized as follows. Section 2 analyzes the characteristics of frequency mode and gives a brief explanation of the influence of electro-hydraulic governor system on inter-area oscillation. In Section 3, the influence of the frequency mode and dead band on inter-area oscillation is investigated by using the 4-machine 2-area system. The correctness of the above analysis results are validated through a practical large-scale system in Section 4. Conclusions are drawn in Section 5.

2. Basic influence analysis of governor system on frequency mode and inter-area oscillation

2.1. Frequency mode and its characteristics

For convenience of analysis, a typical hydraulic turbine governor system shown in Fig. 2 is used for analysis [17,32], where ω is the rotor speed of the generator, ω_0 is the rotor speed reference. K_p, K_i, K_d are the proportional, integral and differential parameters of the governor PID controller, Y is the opening degree command of the governor system, T_B and T_y are the time constant of pilot servo and gate servo, b_p is the adjustment factor of valve opening degree, T_w is the water hammer time constant, INT_{max} and INT_{min} are the maximum and minimum output of the integral in PID controller, respectively, P_m is the mechanical power of the turbine governor system. Assuming that the investigated hydraulic turbine has a short penstock and the operating point of the generators have not changed significantly during the oscillations, the ideal hydro turbine model can be suitable for studying frequency mode in an interconnected power system.

Since frequency oscillations relate to the total inertia and the regulating capacity of the whole system, it is analyzed by using the common frequency model of the entire system shown in Fig. 3 [14]. P_l is the load of the system, T_J is the time constant of rotor inertia, D is the damping coefficient. TG_i indicates the turbine governor system of the generator i. The model consists of multiple generators with turbine governor system. The mechanical power deviation of each turbine governor system is added to reflect the total regulating capacity of the governors. An equivalent machine with the total inertia of the generators is used to calculate the frequency of the whole system.

Stability of this system and influence of PID parameters on frequency mode oscillation can be investigated via the open loop frequency characteristics of the system. The system is open looped from point A depicted in Fig. 3, and the transfer function of the open loop system is represented as Eq. (1), where the dynamics of the pilot servo is neglected because T_B is much less than other time constants.

$$H(s) = -\frac{1}{\sum (T_J s + D)} \sum \left(\frac{(K_d s^2 + K_p s + K_i)(1 - T_W s)}{(b_p K_d s^2 + (1 + b_p K_p)s + b_p K_i)(1 + T_y s)(1 + 0.5 T_W s)} \right) \quad (1)$$

To analyze the characteristics of $H(s)$, $H(s)$ is divided into three