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Research paper

Dynamics analysis of the fast-slow hydro-turbine governing system with different time-scale coupling

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ABSTRACT

Multi-time scales modeling of hydro-turbine governing system is crucial in precise modeling of hydropower plant and provides support for the stability analysis of the system. Considering the inertia and response time of the hydraulic servo system, the hydro-turbine governing system is transformed into the fast-slow hydro-turbine governing system. The effects of the time-scale on the dynamical behavior of the system are analyzed and the fast-slow dynamical behaviors of the system are investigated with different time-scale. Furthermore, the theoretical analysis of the stable regions is presented. The influences of the time-scale on the stable region are analyzed by simulation. The simulation results prove the correctness of the theoretical analysis. More importantly, the methods and results of this paper provide a perspective to multi-time scales modeling of hydro-turbine governing system and contribute to the optimization analysis and control of the system.

1. Introduction

Hydro-turbine governing system (HTGS) is the core part of a hydropower plant with a critical influence on stable operation of the power plant. With the increase of the head and capacity of the hydropower unit, the vibration and stability of the HTGS have been highlighted and concerned [1–3].

Multi-time scale dynamics is an important part of nonlinear dynamics. It reveals the nonlinear essential characteristics of multi-time scale objects from the perspective of dynamics. The fast and slow are not only from the fast-slow effect in the real time, but also from the scale effect in geometry. For example: The coupling between the relative slow translations and high-speed rotations in aircraft is a typical fast-slow model [4]. The rapid metabolic processes and slow genetic changes in biological cells are also fast-slow behaviors [5]. The fast and slow are reflected in the change rates of state variables by the conversion of dimensionless in modeling process.

For the HTGS, bifurcation and chaos phenomena may cause the sustained vibrations of the hydropower unit [6–8]. To study and avoid these phenomena, many researchers have conducted numerical simulation and experiment on the dynamical behavior of the hydro-turbine governing system. For example, the lateral-torsional coupling effects on the nonlinear

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Notation

N	Hydro-turbine speed, rad/s
M_t	Kinetic moment, N m
Y	Guide vane opening, rad
T_{ab}	Hydro-turbine inertia time constant, s
T_y	Engager relay time constant, s
T_w	Inertia time constant of penstock, s
D	Generator damping coefficient, p.u.
e_{qh},e_{qy}	Partial derivatives of the flow with respect to head and guide vane, p.u.
e_{mh},e_{my}	Partial derivatives of the hydro-turbine torque with respect to head and guide vane, p.u.
u	Regulator output
e	Intermediate variable
m_t	Relative deviation of turbine output torque, p.u.
ω	Relative deviation of turbine speed, p.u.
k_p	Proportional adjustment coefficient, p.u.
k_i	Integral adjustment coefficient, s^{-1}
k_d	Differential adjustment coefficient, s

dynamic behavior of a rotating flexible shaft-disk system have been investigated by Khanlo et al. [9]. The nonlinear dynamic behavior of a hydro-turbine governing system in the process of sudden load increase transient has been studied by Li et al. [10]. Chen et al. [11] have studied the stability of a hydro-turbine system with the effect of surge tank. The generalized Hamiltonian theory for the hydro-turbine system has been proposed by Zeng et al. [12].

Nevertheless, most of the work so far is based on the condition that all the variables of the HTGS are at the same time-scale. The HTGS involves different time-scale in operation because the response rate of the mechanical system is significantly lower than that of the hydraulic system. The multi-scale coupled effects lead to complex dynamical behaviors, such as bursting oscillation and chaos [13]. These phenomena will seriously influence the safe and stable operation of the hydropower station. Moreover, due to the time-lag between mechanical system and hydraulic system, it is difficult to obtain a precise model of the HTGS at the same time-scale and the performance as well as security of the HTGS cannot be achieved. Therefore, the modeling and analysis of the HTGS at multi-time scales are needed urgently.

This paper studies the dynamic characteristics of the HTGS with different time-scale coupling. The dynamical behavior and evolution mechanism of the HTGS are investigated by means of numerical simulation. Moreover, the general rules of the HTGS with different scales are revealed. The results of this paper can provide theoretical guidance for the optimal design and control of the HTGS.

Motivated by the above discussions, this paper has three advantages which make the approach attractive comparing with the prior works. First, a fast-slow mathematical model of the HTGS is established by rescaling the hydraulic servo system. Second, the fast-slow dynamical behaviors of the HTGS are analyzed in detail with different time-scale. Finally, the influences of the time-scale of the HTGS on the stable regions of the PID parameters are discussed by means of numerical simulation.

The rest of this paper is organized as follows. In Section 2, the fast-slow model of the HTGS is established by rescaling the hydraulic servo system. Section 3 analyzes the effect of the time-scale on the fast-slow effect of the HTGS, and the stable regions of the PID parameters are investigated by using numerical experiments. Section 4 closes this paper.

2. Fast-slow model of the HTGS

In the condition of rigid water hammer, the Francis turbine is chosen as the research object. Considering the slow change of the guide vane, the HTGS is rescaled and transformed into fast-slow system.

The dynamic characteristics of a Francis hydro-turbine [14] can be described as

$$\begin{cases} M_t = M_t(H, N, Y) \\ Q = Q(H, N, Y) \end{cases}, \tag{1}$$

where M_t, Q, H, N and Y denote the mechanical torque of the hydro-turbine, the hydro-turbine flow, the hydro-turbine head, the hydro-turbine speed and the guide vane opening, respectively.

By using Taylor series expansion, Eq. (1) is obtained as

$$\begin{cases} \frac{M_t - M_{t0}}{M_{tR}} = \frac{\partial \frac{M_t}{M_{tR}}}{\partial \frac{n}{n_R}} \frac{n - n_0}{n_R} + \frac{\partial \frac{M_t}{M_{tR}}}{\partial \frac{Y}{Y_{\max}}} \frac{Y - Y_0}{Y_{\max}} + \frac{\partial \frac{M_t}{M_{tR}}}{\partial \frac{H}{H_R}} \frac{H - H_0}{H_R} \\ \frac{Q - Q_0}{Q_R} = \frac{\partial \frac{Q}{Q_R}}{\partial \frac{n}{n_R}} \frac{Y - Y_0}{n_R} + \frac{\partial \frac{Q}{Q_R}}{\partial \frac{Y}{Y_{\max}}} \frac{Y - Y_0}{Y_{\max}} + \frac{\partial \frac{Q}{Q_R}}{\partial \frac{H}{H_R}} \frac{Y - Y_0}{H_R} \end{cases}, \tag{2}$$