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Dynamics analysis of time-delay hydro-turbine governing system with two time-scales

Bofan Wang[1], Junchen Dong [1], Quankun Li[1], Hengxu Li[1], Yang Chen[1], Jianglin Xia[2]
[1] *School of Mechanical Science and Engineering, Jilin University, Changchun, Jilin 130025, China*
[2]*School of Information and Computer Science, Nanjing Agricultural University, Nanjing, Jiangsu 210095, China*
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Abstract: Due to the existence of inertia and response time, time-delay always exists in the response of the guide vane opening and it may bring about multi time-scale effect. Therefore, time-delay modeling of hydro-turbine governing system with multi time-scale is addressed to investigate the dynamical behaviors of hydro-turbine governing system. The effects of the multi time-scale and time-delay on the dynamical behavior of the proposed system are analyzed. The fast-slow characteristic of the system is discussed via numerical simulations with the change of time-scale or time-delay. Results suggest that not only the time-scale but also the time-delay have significant impact on the dynamical behaviors of the hydro-turbine governing system.

Keywords: Hydro-turbine governing system, Time-delay, Fast-slow effect

1. Introduction

For a long time, the linear turbine model and the first order motor model are adopted to analyze the dynamic stability of hydro-turbine governing system, while ignoring the nonlinear dynamical action of the turbine [1, 2]. This approximate linear simplification has much limitation in application. It can only be acceptable for studying the performance of the turbine system with small fluctuations, and not applicable to the system with large disturbances which may lead to unreasonable results.

As the core part of a hydropower plant, hydro-turbine governing system has critical influence on the stable operation of it. The dynamical behaviors and the model of hydro-turbine governing system attracted researchers' interest and a lot of achievements have been gained. For example, novel nonlinear dynamical models of hydro-turbine governing system are established and the dynamical behaviors of the proposed model are investigated [3, 4]. Hamiltonian mathematical modeling of hydro-turbine governing system is applied to describe general open systems with the structure of energy dissipation and exchange of energy with the environment [5]. Takagi-Sugeno fuzzy system is used to establish the model of a micro hydro power plant [6]. The existing results are of great significance for the actual operation of hydropower station because they not only can explain many complex phenomena, but also can provide theoretical foundation for the safe and stable operation of the hydropower station system.

Under the action of water, machinery, electric and other factors [7-10], hydro-turbine governing system is a complex system. Although remarkable achievement has been made about hydro-turbine governing system, most of the results only consider single time scale. In fact, in real hydro-turbine governing system, there always exists time-relative non-autonomous factors, which can change the structure of the system and make it more complex. Therefore, multi time-scale hydro-turbine governing system is proposed and studied [11, 12].

In this paper, considering the time-delay between the slow variable and fast variable, time-delay is introduced into the multi time-scale hydro-turbine governing system and the dynamical behaviors of the system is investigated.

2. System Description

In Ref.[11], considering Francis turbine as the research object, dynamic model of hydro-turbine governing system is derived as

$$\begin{cases} \dot{\delta} = \omega_0 \omega \\ \dot{\omega} = \dfrac{1}{T_{ab}}(m_t - D\omega - \dfrac{E_q^{'} V_s}{x_{d\Sigma}^{'}} sin\delta - \dfrac{V_s^2}{2} \dfrac{x_{d\Sigma}^{'} - x_{q\Sigma}}{x_{d\Sigma}^{'} x_{q\Sigma}} sin2\delta) \\ \dot{m}_t = \dfrac{1}{e_{qh} T_w}[-m_t + e_{my} y - \dfrac{e e_{qh} T_w}{T_y}(-k_p \omega - \dfrac{k_i}{\omega_0}\delta - k_d \dot{\omega} - y)] \\ \dot{y} = \dfrac{1}{T_y}(-k_p \omega - \dfrac{k_i}{\omega_0}\delta - k_d \dot{\omega} - y) \end{cases}, \tag{1}$$

where the variables δ, ω, m_t, y denote the rotor angle, relative deviation of turbine speed, relative deviation of turbine output torque, relative deviations of the guide vane opening, respectively. The parameter denotations of system (1) are in given in Table 1, which are the same as those in Ref. [11] with intermediate variable

$$e = e_{qy} e_{mh} / e_{my} - e_{qh} \tag{2}$$

and

$$x_{d\Sigma}^{'} = \dot{x}_d + x_T + (1/2) x_L , \tag{3}$$

$$x_{q\Sigma} = x_q + x_T + (1/2) x_L . \tag{4}$$

Table 1 Parameter denotations of system (1).

Parameters	denotation	Units
ω_0	Initial value of relative deviation of turbine speed	p.u.
T_{ab}	Hydro-turbine inertia time constant	s
D	Generator damping coefficient	p.u.
E_q'	Transient internal voltage of armature	p.u.
V_s	Voltage of infinite bus	p.u.
$\dot{x}_d$	The direct axis transient reactance	p.u.
x_q	The quartered axis reactance	p.u.
x_T	The short-circuit reactance of transformer	p.u.
x_L	The transmission line reactance	p.u.
e_{qh}	Partial derivatives of the flow with respect to the hydro-turbine head	p.u.
e_{qy}	Partial derivatives of the flow with respect to the hydro-turbine guide vane	p.u.
e_{my}	Partial derivatives of the hydro-turbine torque with respect to hydro-turbine guide vane	p.u.
e_{mh}	Partial derivatives of the hydro-turbine torque with respect to the hydro-turbine head	p.u.
T_w	Inertia time constant of penstock	s
T_y	Engager relay time constant	s

For hydro-turbine governing system (1), due to the existence of inertia and response time, y is a slow variable while δ, ω, m_t are fast variables. It means that there is always a time-delay between y and δ, ω, m_t. Then the hydro-turbine governing system with time-delay can be introduced as

$$\begin{cases} \dot{\delta} = \omega_0 \omega \\ \dot{\omega} = \dfrac{1}{T_{ab}}(m_t - D\omega - \dfrac{E_q^{'} V_s}{x_{d\Sigma}^{'}} sin\delta - \dfrac{V_s^2}{2} \dfrac{x_{d\Sigma}^{'} - x_{q\Sigma}}{x_{d\Sigma}^{'} x_{q\Sigma}} sin2\delta) \\ \dot{m}_t = \dfrac{1}{e_{qh} T_w}[-m_t + e_{my} y - \dfrac{e e_{qh} T_w}{T_y}(-k_p \omega - \dfrac{k_i}{\omega_0}\delta - k_d \dot{\omega} - y)] \\ \dot{y} = \dfrac{1}{T_y}(-k_p \omega - \dfrac{k_i}{\omega_0}\delta - k_d \dot{\omega} - y(t-\tau)) \end{cases}. \tag{5}$$