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Nonlinear modeling and dynamic analysis of hydro-turbine governing system in the process of load rejection transient

Hao Zhang, Diyi Chen *, Beibei Xu, Feifei Wang

Institute of Water Resources and Hydropower Research, Northwest A&F University, Yangling, Shaanxi 712100, PR China

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ABSTRACT

This article pays attention to the mathematical modeling of a hydro-turbine governing system in the process of load rejection transient. As a pioneer work, the nonlinear dynamic transfer coefficients are introduced in a penstock system. Considering a generator system, a turbine system and a governor system, we present a novel nonlinear dynamical model of a hydro-turbine governing system. Fortunately, for the unchanged of PID parameters, we acquire the stable regions of the governing system in the process of load rejection transient by numerical simulations. Moreover, the nonlinear dynamic behaviors of the governing system are illustrated by bifurcation diagrams, Poincare maps, time waveforms and phase orbits. More importantly, these methods and analytic results will present theoretical groundwork for allowing a hydropower station in the process of load rejection transient.

1. Introduction

With the development of hydroelectric power industry, special attentions need to be paid to ensure the stability and safety of water turbine generator in the process of operation [1–6]. As we all know, hydraulic turbine governing system (HTGS) is one of the most important parts of hydropower plant, which plays a key role in maintaining safety, stability and economical operation for the hydropower plant [7–14]. Therefore, the study of the governing system becomes a necessary and important issue.

Transition process makes up of two phases: large fluctuation process and small fluctuation process. Most published papers have focused on the modeling of hydro-turbine governing system in the process of small fluctuation and not suitable to describe large fluctuation process [15–25]. However, turbine characteristic is very complex with violent changes of parameters in the process of large fluctuation. Therefore, the research of hydro-turbine needs attention in the process of large fluctuation.

Motivated by the above discussions, we have three advantages which make our approach attractive comparing with the prior works. Firstly, a novel nonlinear dynamic mathematic model of a hydro-turbine-generator unit system is established, which is more accordance with the actual project. Secondly, as a pioneering work, nonlinear dynamic transfer coefficients are introduced to the above system. Thirdly, the nonlinear dynamical behaviors of the above system with six nonlinear dynamic transfer coefficients are studied in detail.

The rest of the paper is organized as follows: in Section 2, a novel nonlinear dynamic mathematical model of a hydro-turbine-generator unit is established. Section 3 analyzes the nonlinear dynamical behaviors of the presented system in the process of load rejection transient. Section 4 closes the paper.

2. Mathematical model of hydro-turbine governing system

2.1. Linear mathematic model

The structure of Francis turbine unit governing system is shown in Fig. 1.

For Francis turbine, the dynamic characteristics [26–30] can be described as

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

where the M_t, Q, H, n and a denote the mechanical torque of turbine, turbine flow, turbine head, rotate speed and guide vane opening, respectively. The corresponding relative deviation are m_t, q, h, x and y, respectively. Considering the guide vane opening a has an asymptotically linear relationship with main servomotor stroke y, we replace a with y and acquire the dynamic characteristics expression of hydro-turbine.

$$\begin{cases} m_t = e_{mw}x + e_{my}y + e_{mh}h \\ q = e_{qw}x + e_{qy}y + e_{qh}h \end{cases}, \tag{2}$$

* Corresponding author. Tel.: +86 181 6198 0277.
E-mail address: diyichen@nwsuaf.edu.cn (D. Chen).

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Nomenclature

M_t	mechanical torque of the turbine, N m	β_0	runner intermediate flow surface angle, rad
H	turbine head, m	α	guide vane discharge angle, rad
N	turbine/rotor speed, rad/s	b_0	guide vane height, m
A	guide vane opening, m	F	runner outlet area, m^2
Q	turbine flow, m^3/s	r_0	runner intermediate flow surface radius, m
m_t	turbine torque relative deviation, p.u.	D_0	guide vane pitch circle diameter, m
q	incremental turbine flow deviation, p.u.	L	guide vane width, m
x	incremental turbine speed deviation, p.u.	Z_0	number of guide vane
y	incremental guide vane/wicket gate position deviation, p.u.	Y	guide vane angle, rad
h	incremental turbine head deviation, p.u.	D_1	runner diameter of hydro-turbine, m
T_w	water starting time, s	e_{mx}, e_{my}, e_{mh}	partial derivatives of the hydro-turbine torque with respect to head, guide vane and turbine speed, p.u.
T_{ab}	mechanical starting time, s	e_{qx}, e_{qy}, e_{qh}	partial derivatives of the flow with respect to head, guide vane and turbine speed, p.u.
T_y	engager relay time constant, s	e_n	synthetic self-regulation coefficient
m_{g0}	load torque disturbance	k_p	proportional adjustment coefficient
r	frequency disturbance	k_i	integral adjustment coefficient
u	regulator output	k_d	differential adjustment coefficient
z	intermediate variable		
β	normal angle of guide vane, rad		

where $e_{mw} = \frac{\partial m_t}{\partial x}$, $e_{my} = \frac{\partial m_t}{\partial y}$ and $e_{mh} = \frac{\partial m_t}{\partial h}$ denote partial derivatives of the hydro-turbine torque with respect to head, guide vane and turbine speed, respectively. $e_{qw} = \frac{\partial q}{\partial x}$, $e_{qy} = \frac{\partial q}{\partial y}$ and $e_{qh} = \frac{\partial q}{\partial h}$ denote partial derivatives of the flow with respect to head, guide vane and turbine speed, respectively.

2.2. The dynamic characteristics of penstock system

When the elasticity of water and tube wall shows no significant effects on the water hammer, we consider it as rigid water

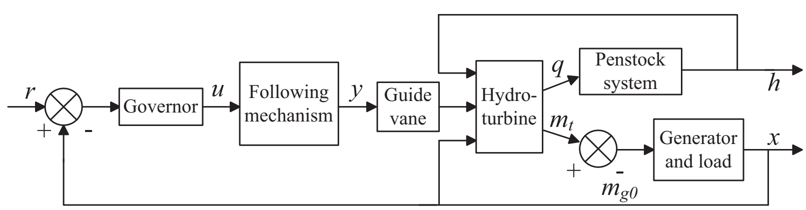

Fig. 1. Governing system structure diagram of Francis turbine unit.

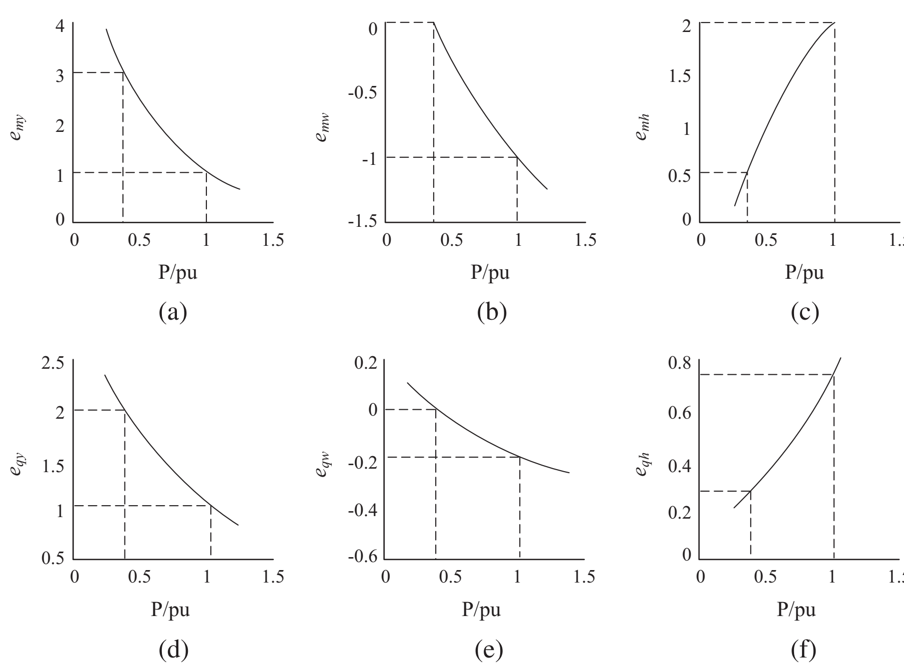

Fig. 2. Curves of hydro-turbine transfer coefficient.