Energy Conversion and Management 108 (2016) 478–487

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Hamiltonian modeling of multi-hydro-turbine governing systems with sharing common penstock and dynamic analyses under shock load

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

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

ARTICLE INFO

Article history:
Received 14 May 2015
Accepted 17 November 2015
Available online 7 December 2015

Keywords:
Hydro-turbine governing systems
Common penstock
Hamiltonian model
Shock load
Randomness

ABSTRACT

This paper focuses on the Hamiltonian mathematical modeling and dynamic characteristics of multi-hydro-turbine governing systems with sharing common penstock under the excitation of stochastic and shock load. Considering the hydraulic-coupling problem in the common penstock, we propose a universal dynamic mathematical model of the multi-hydro-turbine governing system. Then, the proposed model is fitted into the theoretical framework of the generalized Hamiltonian system, utilizing the method of orthogonal decomposition. The dissipation energy, the produced energy and the energy supplied from the external sources are derived from the Hamiltonian model and compared with the physical energy flow. Furthermore, numerical experiments based on a real hydropower station demonstrate that the Hamiltonian function can describe accurately the energy variation of the hydro-turbine system in the transient process and in the stable process. Moreover, in order to deal with the randomness and mutability of the electrical load, we introduce a Gaussian function and a jump function to the control signal of the PID controller to analyze the dynamic characteristics. In addition, the intensity of the shock load is discussed when the system loses its stability. The proposed approach can be used for improving the stability of hydropower stations.

1. Introduction

During the last 30 years, China's economy has continuously rised with an annual GDP growth rate of 8–10% [1]. Correspondingly, the power consumption has shown a bulge from 2952 billion kilowatt-hours in 1980 to 55,233 billion kilowatt-hours in 2014 [2,3]. While these changes have improved the living standard of millions of Chinese residents, it has faced different challenges, including the increase of the difference between peak load and valley load of electric power system and the intensity of electrical load with increasing randomness and mutability [4–8]. In China, 23% of the electric energy is produced by means of hydropower stations. The present hydropower stations are primarily made up of a hydro-turbine set with a penstock, multi-hydro-turbine sets with sharing common penstock and multi-hydro-turbine sets with sharing multi-penstocks. For multi-hydro-turbine sets with sharing common penstock, the variability of the electrical load is one of the most important factors affecting the stability of a hydro-turbine governing system in the process of operation. [9,10]. These systems, which inevitably involves mechanical dynamics, hydrodynamics, electromagnetic field and electrical dynamics, are essentially complex nonlinear, time-variant and non-minimum phase systems [11–15]. Therefore, the study of such systems is a necessary and challenging task. Fortunately, there are some contributions about the modeling of a hydropower station [16–23]. For example, Nagode and Skrjanc [16] presented a dynamic modeling of a Francis turbine with a surge tank and the control of a hydropower plant. Kishor et al. [17] studied the effect of the elasticity of the water column in the penstock of a hydro power plant. Zhang et al. [18] developed a stochastic transient model for water conveyance systems in hydropower plants. However, there are few contributions to the modeling of multi-hydro-turbine governing systems with sharing common penstock. Moreover, the variability of the electrical load and its effect on the system stability are often not considered.

The generalized Hamiltonian control system, which is an important branch of nonlinear science, can be used to describe general open systems with possessing the structure of energy dissipation and the exchange of energy with the environment [24–26]. In recent years, its structure matrix and damping matrix provide more information for system parameters with the development of the theory of the generalized Hamiltonian system [27–29]. Obviously, it has opened a novel line of attack for exploring dynamic behaviors of complex systems [30–33].

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

http://dx.doi.org/10.1016/j.enconman.2015.11.032
0196-8904/

Multi-hydro-turbine governing systems with sharing common penstock are complex water-electro-mechanical coupling systems with coupled energy production, transportation and dissipation. Such systems play a key role in maintaining safety, stability and economical operation for the hydropower stations. Therefore, it is surely a novel route to study the dynamic behaviors and the energy flow of the governing system by means of the generalized Hamiltonian models.

The paper proposed a novel and flexible approach to model a multi-hydro-turbine governing system with sharing common penstock. Then, utilizing the method of orthogonal decomposition, a Hamiltonian mathematical model is derived. Numerical experiments have allowed to verify that the generalized energy flow of the Hamiltonian model is consistent with the actual physical energy flow of multi-hydro-turbine governing systems. Moreover, we innovatively introduce a Gaussian function and a jump function to the control signal of the PID controller to analyze the dynamic characteristics of the hydro-turbine governing system under stochastic and shock electrical load. Finally, the intensity of shock load with randomness when the hydro-turbine governing system loses its stability, namely the regulate limit of the PID controller is discussed.

The rest of this paper is organized as follows: Section 2 introduces the dynamical mathematical modeling and Hamiltonian mathematical modeling. In Section 3, numerical simulations along with detailed discussions are presented. Dynamic characteristics of the hydro-turbine governing systems under the excitation of electrical load are analyzed in Section 4. Finally, the conclusions are summarized in Section 5.

2. Hamiltonian mathematical modeling of multi-hydro-turbine governing systems with sharing common penstock

2.1. Hamiltonian mathematical modeling of multi-hydro-turbine systems

To illustrate effects of the hydraulic coupling problems on the multi-hydro-turbine governing systems with sharing common penstock, a general layout of a hydropower station is shown in Fig. 1. From Fig. 1, water from the upstream of the hydropower station flows through the water conveyance tunnel and the long penstock before arriving at the bifurcation point between the long penstock and the several pipes. Then, it from the bifurcated pipes comes through the scroll casing and pushes the runner of the hydro-turbine forward for rotate continuously. Obviously, the running state of the hydro-turbine generator set is determined by the flow in the pipe. As the flow in the common penstock keep unchanged, the running states of other hydro-turbine generator sets depend on the flow of the i-th pipe.

In this paper, the mathematical equations of the i-the pipe can be described as [33]

$$\begin{cases} \dot{x}_{1i} = x_{2i} \\ \dot{x}_{2i} = x_{3i} \\ \dot{x}_{3i} = -\pi^2/T_{01}^2 x_{2i} + h_{qi}/Z_{01}T_{01}^3 \end{cases}, \tag{1}$$

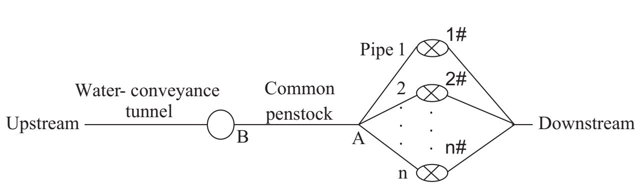

Fig. 1. The general layout of a hydropower station with common penstock and several bifurcated pipes.

where the meaning of each variables are shown in Table 1.

The first order derivative of the flow of the i-the pipe can be written as

$$\dot{q}_i = -3\pi^2 x_{2i} + \frac{4}{Z_{01}T_{01}} h_{qi}. \tag{2}$$

The relative of the head of the i-th bifurcated pipe becomes

$$h_{qi} = h_0 - \sum_{i=1}^{3} h_{qiT} - f_T q_T^2 - \left(f_{pi} + \frac{y_{ri}^2}{y_i^2}\right) q_i^2. \tag{3}$$

The nonlinear output power of the i-th hydro-turbine can be described as [12]

$$P_{mi} = A_t h_{ti}(q_i - q_{nl}) - D_t y_i \omega_i. \tag{4}$$

The basic task of the hydraulic servo system is providing motive force to govern the guide vane so as to regulate the output power of the hydro-turbine and the frequency of the generator. As for the PID controller, it is the heart of the hydraulic servo system. Here, the structure of the hydraulic servo system with PID controller is presented in Fig. 2.

From Fig. 2, the mathematical equation of the i-th hydraulic servo system with the PID controller can be written as

$$\dot{y}_i = \frac{1}{T_{yi}}\left(k_{pi}(r_i - \omega_i) + k_{ii}\int (r_i - \omega_i)dt + k_{di}(r_i - \dot{\omega}_i) - y_i\right). \tag{5}$$

Combining the pipe system, the hydro-turbine system and hydraulic servo system into an organic unity, the mathematical

Table 1
Variables of two units.

Symbol	Quantity
x_{1i}	State variable of the pipe i, p.u.
x_{2i}	State variable of the pipe i, p.u.
x_{3i}	State variable of the pipe i, p.u.
T_{0i}	Elastic time constant of the pipe i, p.u.
h_{qi}	Water head of the pipe i, p.u.
Z_{0i}	Impedance of surge, p.u.
q_i	Flow of the hydro turbine i, p.u.
h_0	Gross head of the hydropower station, p.u.
h_{qiT}	Pressure of the common penstock, p.u.
f_T	Coefficient of pressure loss of the common penstock, p.u.
f_{pi}	Coefficient of pressure loss of the pipe i, p.u.
y_{ri}	Deviation of incremental guide vane/wicket gate position
y_i	The incremental deviation of the guide vane opening, p.u.
q_{nl}	Flow of the operation of a system with no load
D_t	Damping coefficient of the generator i
h_t	The hydro-turbine head, p.u.
A_t	Coefficient scale, p.u.
ω_i	Deviation of relative angular speed
k_{di}	Differential adjustment coefficient
k_{pi}	Proportional adjustment coefficient
k_{ii}	Integral adjustment coefficient
u	Control signal of the PID controller
r	Reference input, p.u.
T_y	Major relay connecter response time, s
P_{mi}	Output power of the hydro-turbine i, p.u.
m_{ti}	The incremental torque of the hydro-turbine, p.u.
H_1	Hamiltonian function of unit 1, p.u.
H_2	Hamiltonian function of unit 1, p.u.
i	The number of the pipe, p.u.
ω_B	Nominal angular speed of generator i, rad/s
δ_i	Rotor angle of the generator i, rad
D	Damping factor of the generator i, p.u.
m_{gi}	Nominal torque of generator, p.u.
E_q'	Internal transient voltage, p.u.
T_{d0}'	Transient time constant of axis d, p.u.
Us	Voltage of the infinite power system
E_f	Output of the excitation controller, p.u.
H_r	Nominal head
Q_r	Nominal flow
N_r	Installed capacity
n_r	Nominal speed