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Hamiltonian analysis of a hydro-energy generation system in the transient of sudden load increasing

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HIGHLIGHTS

- A novel Hamiltonian model of the hydro-energy generation system is established.
- The novel model is suitable for the transient of sudden load increasing.
- Six dynamic transfer coefficients are introduced.
- Dynamical characteristics of the generation system are investigated.
- The established Hamiltonian system has been proved.

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ABSTRACT

This paper addresses the Hamiltonian mathematical modeling and dynamic analysis of a hydro-energy generation system in the transient of sudden load increasing. First, six dynamic transfer coefficients of the hydro-turbine for the transient of sudden load increasing are innovatively introduced into the hydro-energy generation system. Considering the elastic water-hammer model of the penstock and third-order model of the generator, we established a dynamic mathematical model of the hydro-energy generation system in the transient of sudden load increasing. Moreover, from the point of view of the transmission and dissipation of energy of the system, we propose the hydro-energy generation system into the theory frame of the generalized Hamiltonian system. A novel Hamiltonian model of the hydro-energy generation system is established utilizing the method of orthogonal decomposition. Finally, based on the data of a real hydropower plant, numerical simulations and physical experiment are carried out, and the results indicates that the Hamiltonian system can reflect the essence of the nonlinearity of the hydro-energy generation system in the transient of sudden load increasing. More importantly, these methods and results will supply theoretical basis for designing and running a hydropower plant.

1. Introduction

The development of economy and technology puts forward higher request to the reliability of electrical power supply [1–5]. The stability of the power system is directly related to the safety, reliability and availability of the power system [2–8]. The hydro-energy generation system (HEGS), as an important part of the power system, affects the power transmission and safe operation of the hydropower plant [9–15]. In the actual operation, due to the flow inertia of the penstock, the disturbance of the stochastic load and the sudden changing of the load, the vibration and the self-excitation of the HEGS will become more prominent [16–27]. Therefore, it is important to study the dynamic characteristics of the HEGS.

The Hamiltonian system, which is an open generalized system, has the energy dissipation and energy exchange with the outside environment. It can better describe the energy dissipation, the energy produced from the interior of the system and the energy supplied from the environment [10,11,23]. The HEGS is a typical open system, which can better reflect the transmission and dissipation of energy [10,28–31]. From the point of view of the transmission and dissipation of energy, putting the HEGS into the

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Nomenclature

M_t	the mechanical torque of the hydro-turbine, N·m
Q	the hydro-turbine flow, m^3/s
H	the hydro-turbine head, m
n	the hydro-turbine speed, rad/s
a	the guide vane opening, rad
m_t	the relative value of the mechanical torque, p.u.
h	the relative value of the hydro-turbine head, p.u.
x	the relative value of the hydro-turbine speed, p.u.
q	the relative value of the hydro-turbine flow, p.u.
q_c	the relative value of the measured hydro-turbine flow
y	the relative value of the guide vane opening, p.u.
x_1, x_2, x_3	the intermediate variables
ω	the relative value of the generator rotor speed, p.u.
δ	the relative value of the rotor angle, rad
T_y	the engager relay time constant, s
T_r	the elastic water hammer time constant, s
D	the damping coefficient
h_w	the characteristic coefficient of the pipeline
T_{ab}	the mechanical starting time, s
P_m	the relative value of the output power of the hydro-turbine
P_{mc}	the relative value of the measured output power of the hydro-turbine
e_{mx}, e_{my}, e_{mh}	the relative values of the hydro-turbine torque as regards the hydro-turbine speed, the hydro-turbine guide vane and the hydro-turbine head, p.u.
e_{qx}, e_{qy}, e_{qh}	the relative values of the flow with respect to the hydro-turbine speed, the hydro-turbine guide vane and the hydro-turbine head, p.u.
k_p	the proportional adjustment coefficient
k_i	the integral adjustment coefficient
k_d	the differential adjustment coefficient
u	the output of the regulator
m_e	the electromagnetic torque of the generator
P_e	the electromagnetic power of the generator
E'_q	the transient internal voltage of armature
V_s	the voltage of infinite bus
x'_d	the direct axis transient reactance
x_q	the quartered axis reactance
E_f	the output of excitation controller, p.u.
H_1	the Hamitonian function for the hydro-turbine
H_2	the Hamitonian function for the generator
H	the Hamitonian function for the HEGS
$J(x)$	the anti-symmetric matrix
$P(x)$	the symmetric matrix
X_f	the exciting winding reactance
X_{ad}	the d axis armature reaction reactance

theory frame of the generalized Hamiltonian system is a new research approach to study the energy characteristics of the HEGS [23–40]. In previous studies, few published papers however focus on the investigation of the Hamiltonian model of the HEGS in large fluctuation processes. Most literatures address the Hamiltonian modeling in small fluctuation processes by utilizing the jump function or Gaussian function to indicate the dynamic characteristics and energy changing of the HEGS. According to Refs. [10,11,18,23–25,29], Table 1 is made to indicate the benefits and drawbacks of the existing Hamiltonian models of the HEGS. Apparently, these methods cannot better reflect the essence of the nonlinearity of the HEGS in large fluctuation processes. Therefore, establishing a proper Hamiltonian mathematical model of the HEGS and investigating the corresponding dynamic characteristics are of great significance for theory and industry practice.

Motivated by the above discussions, we have three advantages which make our approach attractive, comparing with the prior work. First, we creatively introduce six dynamic transfer coefficients of the hydro-turbine into the HEGS and consider the essence of the nonlinearity of the system, the dynamic mathematical model of the HEGS in the transient of sudden load increasing is established. Second, the mathematical model of the HEGS is converted to a novel Hamiltonian system by putting the HEGS to the theory frame of the generalized Hamiltonian system and using the method of orthogonal decomposition. Finally, we carry out numerical simulations and physical experiment based on the data of an existent hydropower plant. The detailed information of energy changing and the dynamic characteristics of the HEGS for the transient of sudden load increasing are exhaustedly investigated.

Table 1
Assessment of the existing Hamiltonian models of the HEGS.

Existing Hamiltonian models of the HEGS	
Benefits	Drawbacks
The model can better reflect the characteristics of the Hamiltonian system in the small fluctuation process	The Hamiltonian model cannot describe the characteristics of large fluctuation processes well
Some typical nonlinear elements including stochastic electrical load, hydraulic exciting force, etc., are considered	The more complex hydro electromechanical relation cannot be contained
The dynamic behaviors of the Hamiltonian system are researched by introducing random functions	The introduced random function cannot truly describe the dynamic change of the hydropower system with time

The rest of the paper is organized as follows. In Section 2, a novel Hamiltonian mathematical model of the HEGS for the transient of sudden load increasing is established. The established Hamiltonian system is detailed discussed in Section 3. A comparison between the numerical and experimental simulations has been made to prove the validity of the proposed model of the HEGS in Section 4. Section 5 gives some useful conclusions. Discussion in Section 6 closes the paper.

2. The Hamiltonian model of the HEGS in the transient of sudden load increasing

The HEGS composed of a control system and a controlled system as shown in Fig. 1 [15,23], contains the synchronous generator, the hydro-turbine, the governor and the penstock.

2.1. The joint model of the hydro-turbine and the hydraulic speed regulation system

2.1.1. Dynamic transfer coefficients of the hydro-turbine

Generally, we obtain the mathematical model of the hydro-turbine utilizing the internal characteristics method, external characteristics method or simple analytical method. Here, the internal characteristics method is used due to its high accuracy [6,18,19,29].

The mathematical model of the HEGS including the transfer coefficients of the hydro-turbine is shown in Fig. 2 [15].