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Dynamic modeling and energy distribution analysis in a hydroelectric generating system considering the stochastic turbine flow

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ABSTRACT

This study focuses the energy distribution of a hydroelectric generating system. Understanding the way energy distribution is important for researchers because it determines many of the macroscopic attributes, such as conversion efficiency, dynamic characteristics, et al. Historically, energy modeling has been split into two directions, focusing on stability analysis and its control, and has not yet been studied from the viewpoint for the stochastic turbine flow. Here we established a novel stochastic model to analyze the energy distribution of the hydroelectric generating system. We verified this model with the monitored data from *Nazixia* hydropower station of China. We also show how the stochastic turbine flow affects the energy losses of the system. The result shows that the one with the highest influence is the hydraulic impact losses in spiral case (more than 60%), and the hydraulic friction loss first keeps 19% as the stochastic intensity changes from 0.01 to 0.5, then increases to 20% when the stochastic intensity reaches 0.6.

1. Introduction

China is leading to a hydroelectricity power boom, followed by India, Europe, the United States, and Japan. Hydroelectricity power plants have been built more than 160 countries, with a total number of 11,000 plants equipped with 27,000 hydro-turbine generator units at the end of 2008, from the report of International Hydropower Association [1]. The 2015 United Nations Climate Change Conference held in Paris, France, promised the raise of global warming not greater than 2 °C compared to pre-industrial levels [2]. In China, the capacity of hydropower is planning added from 200 to 380 GW by 2020 [3]. These plants are constructed at sites along other international rivers, including 13 on the Salween or Nujiang, and 20 along the Brahmaputra [1]. In 2016, the number of small hydroelectricity power plants in Brazil was 475 with a total installed capacity of 4799 MW, and it is estimated that the installed capacity will be approximately 6500 MW in 2020. [4]. Renewable HGSs (Hydroelectric generating systems) are under construction all over the world to ensure the enforcement of stricter energy and environmental policies. Obviously, the economic benefits and carbon dioxide mitigation of these generating systems are well known to the general public [5–9], but the energy losses in HGSs are still not well studied.

The conversion efficiency is an important index to evaluate the utilization ratio of hydropower. The hydro-turbine efficiency is the main factor affecting the conversion efficiency of HGSs, considering that the generator efficiency roughly remains unchanged over time [10,11]. Its value is affected by the internal energy losses and stochastic perturbation. The internal energy losses include the hydraulic impact loss in spiral case, the hydraulic friction loss of spiral case, the hydraulic loss of leakage flow, the hydraulic loss of the penstock, the local hydraulic loss at stay ring and hydraulic loss of the straight pipe at the inlet of the spiral case [12–14]. The stochastic change of turbine flow causes the change of these energy losses and then directly affects turbine efficiency due to its stochastic characteristic [15,16]. When the hydro-turbine generator set is running at low efficiency for a long time, it not only affects the utilization ratio of hydropower but also causes serious cavitation erosion and even the violent vibration, which threatens the safe and stable operation of the HGS [17–20]. Recently, researchers have performed a number of studies on the relative problem. For example, Borkowski et al. presented a complete small

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Nomenclature

c	constant of the spiral case
d	height of guide vane
D_t	damping coefficient of synchronous generator
E_f	output of excitation controller
E_q'	internal transient voltage
f	coefficient of the loss in the penstock
h	relative deviation of the hydro-turbine head
h_0	gross head of hydropower station
h_w	hydraulic loss of the hydro-turbine
h_{wj}	hydraulic loss at the stay ring
h_{ww}	hydraulic loss of spiral case
h_{ww1}	hydraulic friction loss of spiral case
h_{ww2}	hydraulic impact loss of spiral case
h_{wz}	hydraulic friction loss of the straight pipe at the inlet of the hydro-turbine
K	speed torque of the spiral case
k_v	coefficient of volume loss
l	length of the straight pipe
P_e	electromagnetic power of the generator
P_m	output power of hydro-turbine
Q	hydro-turbine flow
q	relative deviation of the hydro-turbine flow
r_d	radius of the stay ring
T_y	major relay connecter response time
T_j	inertia time constant of the generator
$T_{d0'}$	time constant
T_{01}	elastic time constant of the penstock
u	control signal input
U_s	voltage of infinite power system
v	speed of the water flow in the spiral case
v_1	flow speed in the straight pipe
v_{rb}	water flow speed of the spiral case in the radial direction
$X_{d\Sigma}$	d-axis reactance
$X_{q\Sigma}$	q-axis reactance
$X_{d\Sigma'}$	d-axis transient reactance
y	relative deviation of the guide vane opening
y_0	initial incremental deviation of the guide vane opening
y_r	deviation of incremental guide vane
Z_{01}	resistance value of the hydraulic surge
γ	density of water
δ	relative deviation of the rotor angle
ζ_i	coefficient of the hydraulic impact loss
ζ_k	hydraulic loss coefficient
λ	coefficient of the hydraulic friction loss
ω	relative deviation of the angular speed
ω_B	basic value of the angular speed
ΔP_h	power of the hydraulic loss
ΔP_f	power of the mechanical loss
ΔP_v	power of the volume loss

hydropower plants (SHP) solution based on an innovative generation unit to maintain the high efficiency of energy conversion systems [21]. Cordova et al. proposed a system for the performance evaluation and energy optimization of the real-time operation at Itá Hydropower Plant, and this computational tool is very useful for the efficient use of hydro resources [22]. Quaranta and Revelli proposed the big power losses, which are the dissipation of the stream kinetic energy against the blades and the hydraulic losses in the headrace. The results showed that a better design of the inlet and blades geometry may improve the efficiency of the wheel [23]. Qian et al. first calculated the energy losses and analyzed the general characteristics of the inner energy losses within the hydro-turbine [24]. There is, however, little research focuses on the energy conversion of the HGS considering the stochastic characteristics of the turbine flow. In actual operations, this uncertainty existing in the power system is inevitable [25]. Therefore, it is very necessary to study the influence of stochastic turbine flow on the distribution characteristics of energy loss for the HGS.

There are several methods to investigate dynamical problems of the stochastic system, such as Monte Carlo method [26], stochastic finite element method [27,28], and orthogonal polynomial approximation method [29,30]. Among these methods, the orthogonal polynomial approximation method is used not only to the problem of stochastic response evolution, but also to stochastic bifurcations and chaos studying of the stochastic system [31,32]. In recent years, the Chebyshev polynomial approximation method has been widely used to study stochastic bifurcations and chaos in some classical dynamic models. For example, Fang et al. use the method of Chebyshev polynomial approximation for reducing the stochastic system into its deterministic

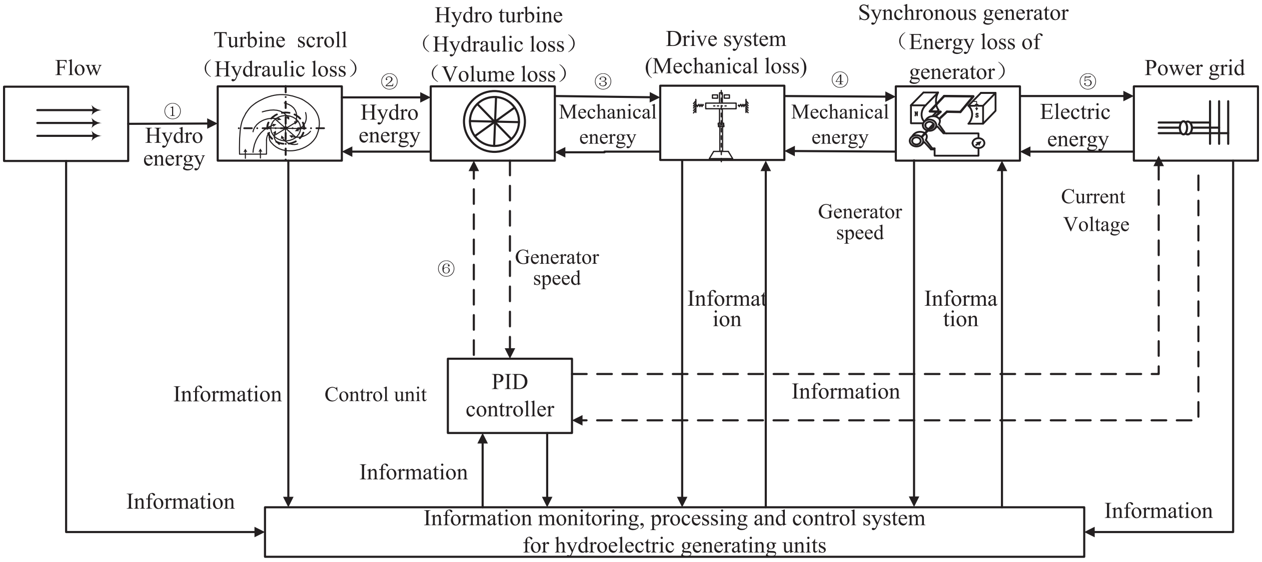

Fig. 1. The schematic diagram of energy conversion of HGS.