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Stability analysis of governor-turbine-hydraulic system by state space method and graph theory

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ABSTRACT

The coefficient matrix of the state equations is essential for stability analysis of the governor-turbine-hydraulic (GTH) system by the state space method. With plant layout becoming more and more complicated, it is important to derive the state matrix quickly and accurately. Based on the stability analysis theory of the GTH system, this paper investigates regular features of the state equations that describe small fluctuations in the state variables of the system. The equations for unsteady flow in the pipeline system are conveniently given by using graph theory. By specifying the order of the state variables and using matrix transformation, an innovative method for solving the coefficient matrix of the state equations is established, and the stable region of the system can be given with the eigenvalue method. The proposed method is used to analyze the stability of a practical hydropower station during small fluctuation, which is also verified in the hydraulic transient model of hydropower system on the basis of characteristics method.

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1. Introduction

Hydropower is a major renewable energy resource, which is widely utilized all over the world. With the rapid exploitation of hydropower resources in China, a lot of hydropower stations are constructed and the gross installed hydropower capacity of China ranked first in the world [1]. Stable operation of hydro-units of a large scale hydropower station has great influence on the safety of units [2] and even the whole power system [3]. So it is an important issue on the design of a hydropower generation system to ensure its stability and regulating quality. It is generally considered that the GTH system of a hydropower station is steady when the units are connected to a large power grid under a small disturbance condition. However, small and mini hydropower stations are mostly isolated from national grid, which make a significant contribution to energy needs [4]. In addition, with the application of the high-voltage direct current (HVDC) transmission technology, large power stations may be in an islanding condition as well. Particularly, some hydropower stations in west China are diversion-type stations with a fairly long headrace tunnel and a surge tank, and the stable issue is more prominent [5]. Regarding these hydropower stations, the GTH system should be designed to be stable in isolated operation during design process.

Governor-turbine-hydraulic system is complex because of strong couplings of hydraulic, mechanical and electrical system, which is an important application area for control engineering [6]. The schematic of hydropower plant and GTH system are illustrated in Fig. 1. Fang [7] introduced the basic models for hydraulic turbine and control system. The speed oscillations following a load change are stable or unstable depending upon the values of the parameters of waterway system, hydro-unit and governor, so that, the sensitivity analysis of such parameters would help to optimize system design or the turning of governors.

There are in general two approaches to analyze the stability of GTH system. One is numerical simulation in time domain [8]. Although the numerical simulation method can be taken as many nonlinear factors of the system as possible, the mathematical model is complex and programming is also very difficult. The results are affected by numerical errors, particularly in a small disturbance condition, which might result in wrong judgments. In addition, it is not convenient to optimize system parameters or the turning of governors. The second one uses the automatic control theory. The state space method and the transfer function method have been widely used for studying the stability and performance of the GTH system.

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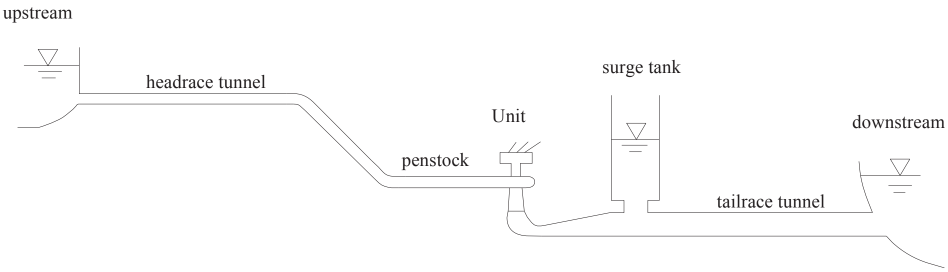

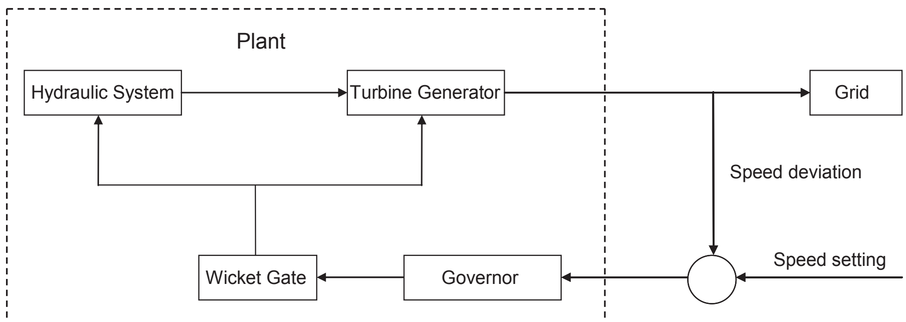

Fig. 1. Schematic of hydropower plant (a) general layout; (b) GTH system.

Chaudhry [9] used the Routh-Hurwitz stability criterion to analyze the stability of the GTH system. Hagihara et al. [10] established the stable region of turbine-generator units with proportional integral differential (PID) governor by using the root locus method. Thorne et al. [11] applied the state space method and eigenvalue analysis to examine the effects of system parameters on the stability boundaries of single hydro unit connected to a large power system. Kishor [12] used the state space hydro plant model with inelastic and elastic water column effect to simulate the regulation of turbine speed with the linear quadratic approach. Chen et al. [13] introduced a nonlinear model based on state equations to study the nonlinear behaviors of GTH system and a fuzzy sliding mode governor was designed. Load rejection transients were simulated with a nonlinear model of a hydro-turbine governing system in [14], and the stable regions were presented by analyzing the coefficient matrix of the system. Zhou et al. [15] utilized a higher-order elastic model of pipe flow in state equations. Xu et al. [16] introduced fractional order calculus to the state space model of GTH system and the stability was studied. Guo et al. [17] studied the regulation quality for frequency response of turbine regulating system of an isolated hydroelectric power plant, and the expressions of coefficients in overall transfer function was derived. Yang et al. [18] proposed a linear state space model of the hydro-turbine governing system with an open tailrace channel, and Guo et al. [19] used the Hopf bifurcation theory to study the stability of the system. Donaisky et al. [20] studied the hydraulic amplifier of a governor and the frequency control performance of the hydropower plant is improved. Martínez-Lucas et al. [21] investigated the performance of the frequency control of isolated power systems including a hydropower plant. Based on the transfer function model of the GTH system, a lot of methods for improving the setting performance of the system parameters were presented, such as the robust control methods [22], improved particle swarm optimization algorithm [23], adaptive grid particle swam optimization [24], improved gravitational search algorithm [25], fuzzy sliding mode control [26].

However, most of the GTH system used in the literature are simple, including a turbine-generator unit, a single penstock and an upstream reservoir. Even though the system is simple, the authors spent a lot of time to derive the coefficient expressions of the state space model, which is very complex and easy to make mistake. But in a practical hydropower plant, the GTH system is much more complex (i.e. multi-unit, hydraulic coupling and surge tanks), let along multi-hydropower plants connection. When the system is complicated, both the state space model and the transfer function model are not easy to establish and it is also difficult to judge the stability of a nonlinear and multi-variable system with the automatic control theory directly.

The state space method is used to analyze the stability of the GTH system under small disturbance in this paper. The coefficient matrix of the state equations that describe the small fluctuations in the state (dependent) variables of the system is essential for stability analysis of the GTH system. As we have discussed before, how to get the coefficient matrix of the state equations accurately and quickly is significant in stability analysis of a rather complicated GTH system with fewer simplifications.

Inspired by the above discussions, this paper investigates the regular features of the state equations that describe the small fluctuations in the GTH system, and the equations for unsteady flow in the complex pipeline system are conveniently given by using graph theory. By specifying the order of the state variables and using matrix transformation method, an innovative method for solving the coefficient matrix of the state equations is established. With this method, the stability region of the system can be given by using the eigenvalue method, which can be used for optimizing the system parameters or the turning of governors. Then, the proposed

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