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Saturation characteristics for stability of hydro-turbine governing system with surge tank

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ABSTRACT

This paper aims to study the saturation characteristics for stability of hydro-turbine governing system with surge tank. Firstly, the mathematical model of hydro-turbine governing system under load disturbance is established, and the equivalent independent stability discriminants are presented. Then, the saturation characteristics for stability are analyzed. Using analytical stability discriminants and stable domain, the generation mechanism of saturation characteristics is revealed, and a distinguishing method of critical saturation state is proposed. Finally, the concept of saturation sectional area of surge tank is proposed. The distribution and partition for stability states is illustrated, and a combined tuning method of sectional area of surge tank and governor parameter is proposed. The results indicate that, for hydro-turbine governing system with surge tank, the fourth-order discriminant boundary is always the critical boundary of stable domain. The second-order and third-order discriminant boundaries determine the stable domain under saturation state. The equality for fourth-order discriminant has two real solutions when the system is saturated. The saturation sectional area of surge tank is the sectional area that makes the system reach critical saturation state. Domain C of the distribution and partition figure for stability states is the most favorable domain for the system stability.

1. Introduction

The hydropower station with surge tank is a kind of common layout for the development of hydroelectric energy [1]. Surge tank is an open standpipe or a shaft connected to the conduits of a hydropower station [2]. A surge tank reduces the amplitude of pressure fluctuations by reflecting the incoming pressure waves or by storing or providing water, thereby reducing acceleration or deceleration in the tunnel [3,4]. Nowadays, the surge tank is the most commonly used facility of pressure reduction for hydropower station.

Hydro-turbine governing system is the core control system of hydropower station. In the transient processes, the hydro-turbine governing system is a complicated feedback system. The modeling and dynamic characteristics of hydro-turbine governing system are two important aspects for the research. Many achievements have been obtained in that area. Li et al. [5,6] addressed the Hamiltonian mathematical modeling and dynamic analysis of a hydro-energy generation system in the transient of sudden load increasing, and studied the nonlinear modeling and dynamic analysis of a hydro-turbine governing system in the process of sudden load increase transient. Xu et al. [7,8] studied the stability of a hydro-turbine governing system under hydraulic excitations, and carried out the dynamic analysis and modeling of a novel fractional-order hydro-turbine-generator unit. Li et al. [9] conducted the fast-slow dynamical analysis of a typical complex engineering system coupling with hydraulic-mechanical-electric power. Yu et al. [10] studied the stability of governor-turbine-hydraulic system by state space method and graph theory. Konidaris et al. [11] presented a method for the study of oscillatory problems of hydraulic generating units equipped with Francis turbines.

For the hydro-turbine governing system with surge tank, the water level oscillation in surge tank is introduced. The stability of the water level oscillation in surge tank becomes the primary issue that affects the dynamic behaviors and safe operations of hydro-

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turbine governing system [12–14]. In 1910, D. Thoma proposed the famous Thoma's formula and described the concept of critical stable sectional area of surge tank [2]. The Thoma's formula shows that the water level oscillation in surge tank is unstable when the sectional area of surge tank is less than the critical stable value. To achieve a stable hydro-turbine governing system with surge tank, the sectional area of surge tank should be greater than the critical stable value. D. Thoma opens the study on the critical stable sectional area of surge tank, and the Thoma's formula is still adopted nowadays. Since the Thoma's formula was put forward, many scholars carried out more detailed and modified researches on the topic of critical stable sectional area of surge tank. Representative achievements are stated as follows: Calame et al. [15] studied the effect of turbine efficiency on the critical stable sectional area of surge tank. Dong [16] studied the effect of turbine characteristic and governor on the hydraulic and governor system. Li [17] analyzed the effect of governor parameters on the critical stable sectional area of surge tank. Guo et al. [18] proposed a novel formula of the critical stable sectional area of surge tank considering the fluid inertia in penstock and the characteristics of governor. Guo et al. [19] proposed a concept of critical stable sectional area of surge tank for primary frequency regulation and derived the analytical solution.

The summary of the above literature indicates that the previous researches mainly focus on the critical stable state of the hydro-turbine governing system with surge tank. In the practical applications, sectional area of surge tank should take a value which is greater than the critical stable value. Ref. [4] suggests that the sectional area of surge tank should take as 1.05–1.1 times of its critical stable value, i.e. the amplification coefficient of sectional area of surge tank should be 1.05–1.1. However, that recommendation is made based on engineering experience and lacks theoretical basis. In many cases, it is not reasonable to take the amplification coefficient as 1.05–1.1 [20,21]. Therefore, how to determine the amplification coefficient of sectional area of surge tank is still an unsolved problem. In the practical applications, only the empirical method and trial method can be adopted, which are work and time consuming.

The amplification coefficient of sectional area of surge tank is the most important hydraulic parameter for the design of surge tank and is directly related to the safe operation and construction investment of the hydropower station. When the sectional area of surge tank is greater than the critical stable value, the selection of the amplification coefficient is mainly based on the dynamic behaviors of hydro-turbine governing system. Lai et al. [22] and Guo et al. [23] studied the effect of sectional area of surge tank on stability of the hydro-turbine governing system. The results in Refs. [22,23] indicate that when the sectional area of surge tank is greater than the critical stable value, the stability of the hydro-turbine governing system cannot be improved effectively by increasing the sectional area of surge tank. There is an upper limit value of the stability with respect to the sectional area of surge tank. From the above existing achievements, it can be known that there is a saturation phenomenon for the stability of the hydro-turbine governing system with surge tank. The stability of the system keeps unchanged when the sectional area of surge tank is greater than one value. From the perspective of stability, the increase of sectional area of surge tank is a waste of investment of the surge tank when the system is already saturated.

The saturation phenomenon for the stability is a significant reference for the selection of the amplification coefficient of sectional area of surge tank. However, the previous researches only simply describe the saturation phenomenon by using an engineering example. The following important questions still remain open. What are the characteristics of the saturation phenomenon for stability? What is the generation mechanism of the saturation phenomenon and how to reveal the generation mechanism using an analytical method? How to determine the value of sectional area of surge tank that makes the system saturated? The above questions become the biggest obstacle for the design and operation of the hydro-turbine governing system with surge tank. To overcome the above obstacle, this paper aims to study the saturation characteristics for stability of hydro-turbine governing system with surge tank. The motivation and innovation of this paper are as follows:

(1) Analyze the saturation characteristics for stability of hydro-turbine governing system with surge tank by using analytical method. Reveal the generation mechanism of the saturation phenomenon and provide an analytical method to judge the critical saturation state of the system.
(2) Determine the value of sectional area of surge tank that makes the system saturated. Propose a convenient and practical method to tune the amplification coefficient of sectional area of surge tank. Provide a guidance for the design and operation of practical hydropower station with surge tank, which can achieve a both stable and economical hydro-turbine governing system.

The novelties of the present paper are outstanding and definite. Ref. [18] only proposed a novel formula of the critical stable sectional area of surge tank, and didn't involve the issue of saturation characteristics for stability and saturation sectional area of surge tank. Critical stable sectional area of surge tank and saturation sectional area of surge tank are two totally different concepts. Compared with Ref. [18], the analysis of the saturation characteristics for stability of hydro-turbine governing system with surge tank and saturation sectional area of surge tank are the novelties of the present paper and are original. Ref. [22] studied the effect of sectional area of surge tank on stability of the hydro-turbine governing system and presented the saturation phenomenon for the stability. However, the saturation characteristics for stability and the generation mechanism of the saturation characteristics were not analyzed. The concept of the saturation sectional area of surge tank was not proposed. Compared with Ref. [22], the analysis for the saturation characteristics and the generation mechanism of the saturation characteristics are the novelties of the present paper. The concept of the saturation sectional area of surge tank is original.

The paper is organized as follows. In Section 2, for the hydropower station with surge tank, the mathematical model of the hydro-turbine governing system is established and the overall transfer function under the operating condition of load disturbance is derived. The equivalent independent stability discriminants for the system are presented. In Section 3, the saturation characteristics for stability of the hydro-turbine governing system are analyzed. The analytical expressions of the stability discriminants are derived. The relationship between saturation characteristics and stability discriminants is described based on stable domain, and the saturation phenomenon for stability is clarified. The generation mechanism of the saturation characteristics is revealed and a distinguishing method of the critical saturation state is proposed. In Section 4, the concept of the saturation sectional area of surge tank is proposed and the calculation procedure is described. Based on the saturation sectional area of surge tank, the distribution and partition for stability states of hydro-turbine governing system with surge tank is illustrated, and a combined tuning method of sectional area of surge tank and governor parameter is proposed. In Section 5, the benefits and drawbacks of the study are revealed. In Section 6, the conclusions are given.