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Combined effect of upstream surge chamber and sloping ceiling tailrace tunnel on dynamic performance of turbine regulating system of hydroelectric power plant

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ABSTRACT

Based on the nonlinear mathematical model of the turbine regulating system of hydroelectric power plant with upstream surge chamber and sloping ceiling tailrace tunnel and the Hopf bifurcation theory, this paper firstly studies the dynamic performance of the turbine regulating system under 0.5 times Thoma sectional area of surge chamber, and reveals a novel dynamic performance. Then, the relationship between the two bifurcation lines and the wave superposition of upstream surge chamber and sloping ceiling tailrace tunnel is analyzed. Finally, the effect mechanisms of the wave superposition on the system stability are investigated, and the methods to improve the system stability are proposed. The results indicate that: Under the combined effect of upstream surge chamber and sloping ceiling tailrace tunnel, the dynamic performance of the turbine regulating system of hydroelectric power plant shows an obvious difference on the two sides of the critical sectional area of surge chamber. There are two bifurcation lines for the condition of 0.5 times Thoma sectional area, i.e. Bifurcation line 1 and Bifurcation line 2, which represent the stability characteristics of the flow oscillation of "penstock-sloping ceiling tailrace tunnel" and the water-level fluctuation in upstream surge chamber, respectively. The stable domain of the system is determined by Bifurcation line 2. The effect of upstream surge chamber mainly depends on its sectional area, while the effect of the sloping ceiling tailrace tunnel mainly depends on the sectional area of surge chamber, type of load disturbance and ceiling slope angle. When the stable domain is determined by Bifurcation line 1, the combined effect of upstream surge chamber and sloping ceiling tailrace tunnel on stability equals to the linear superposition of their own effects play alone. When the stable domain is determined by Bifurcation line 2, the only way to improve the system stability is to increase the sectional area of upstream surge chamber.

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1. Introduction

In modern power system, hydroelectric power plant undertakes the major task of peak modulation and frequency modulation due to its characteristic of flexible operation [1]. Load frequency control of hydroelectric generating units is actualized by turbine regulating system [2–5], and the stability of the turbine regulating system is the prerequisite of the stable operation and high quality electricity supply of power system [6].

With the development of hydroelectric resources, more and more hydroelectric power plants with complicated layouts are being constructed. These hydroelectric power plants always have long penstocks, headrace tunnels or tailrace tunnels [7,8]. In the transient processes, huge water hammer pressure and strong instability will be caused by the extremely large flow inertia. In order to overcome the above problems, many pressure reduction facilities were proposed and applied into complicated hydroelectric power plants. Among the pressure reduction facilities, surge chamber and sloping ceiling tailrace tunnel are most widely used [9–13]. As a new and complicated type of pipeline layout, hydroelectric power plant with upstream surge chamber and sloping ceiling tailrace tunnel, which is the research object of this paper, has been proposed and designed during the hydroelectric construction.

Although the setting of surge chamber or sloping ceiling tailrace tunnel can decrease the flow inertia in the pipelines, new unfavorable factors are introduced into the turbine regulating system at the same time. For the hydroelectric power plant with surge chamber, the dynamic characteristics of turbine regulating system is significantly different from the case without surge

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Nomenclature

Q_y	discharge in headrace tunnel, m^3/s
h_y	head loss of headrace tunnel, m
T_{wy}	flow inertia time constant of headrace tunnel, s
c	wave velocity of free surface flow section, m/s
H_x	water depth at the interface of the free surface-pressurized flow, m
B	width of sloping ceiling tailrace tunnel, m
H	turbine net head, m
Z_y	change of water level of free surface flow section (relative to the initial level, positive direction is upward), m
N	turbine unit frequency, Hz
M_t	kinetic moment, Nm
e_h, e_x, e_y	moment transfer coefficients of turbine
T_a	turbine unit inertia time constant, s
K_p	proportional gain
F	sectional area of surge chamber, m^2
Q_t	discharge in penstock (i.e. turbine unit discharge), m^3/s
h_t	head loss of penstock, m
T_{wt}	steady-state flow inertia time constant of penstock, s
α	ceiling slope angle of sloping ceiling tailrace tunnel, tanα is the ceiling slope gradient, rad
V_x	flow velocity at the interface of the free surface-pressurized flow, m/s
g	acceleration of gravity, m/s^{-2}
λ	cross-section coefficient of tailrace tunnel
Z_F	change of water level of upstream surge chamber (relative to the initial level, positive direction is downward), m
Y	guide vane opening, mm
M_g	resisting moment, Nm
e_{qh}, e_{qx}, e_{qy}	discharge transfer coefficients of turbine
e_g	load self-regulation coefficient
K_i	integral gain, s^{-1}
T_F	time constant of surge chamber, s

chamber because of the influence of water-level fluctuation in surge chamber [10,14,15]. For the hydroelectric power plant with sloping ceiling tailrace tunnel, there is a reciprocating interface movement of the free surface-pressurized flow in the tailrace tunnel [16–18]. As a result, the operational characteristics of the turbine regulating system of hydroelectric power plant with sloping ceiling tailrace tunnel are significantly different and much more complicated than those of hydroelectric power plant with pressurized tailrace tunnel. When the surge chamber and sloping ceiling tailrace tunnel are both set in a hydroelectric power plant, the turbine regulating system is affected by the interaction and mutual superposition of the surge chamber and sloping ceiling tailrace tunnel, which will be a great challenge for the optimal design and stable operation of this kind of hydroelectric power plant.

For the dynamic performance of turbine regulating system under the independent effect of surge chamber or sloping ceiling tailrace tunnel, many research achievements have been obtained. (1) For the hydroelectric power plant with surge chamber: Zhao et al. [19] found that the wave form of frequency response of turbine regulating system with surge chamber shows a characteristic of head wave and tail wave. Then, the fluctuation characteristics of head wave and tail wave and the effect of system parameters on the wave form were analyzed by numerical simulation [19–21]. By solving the fluctuation equation of tail wave, the fluctuation characteristics of tail wave and its relationship with regulation quality were analytically studied [22,23]. Guo et al. studied the regulation quality for frequency response of turbine regulating system of isolated hydroelectric power plant with surge chamber [24], and then investigated the time response of the frequency of hydroelectric generator unit with surge chamber under isolated operation based on turbine regulating modes [25]. (2) For the hydroelectric power plant with sloping ceiling tailrace tunnel: The nonlinear analytic mathematical model of turbine regulating system with sloping ceiling tailrace tunnel was established and the stability under load disturbance was analyzed in [26]. The operational stability and dynamic control of the unit of hydroelectric power plant with sloping ceiling tailrace tunnel were analyzed by using the MATLAB [27].

However, for the turbine regulating system of hydroelectric power plant with upstream surge chamber and sloping ceiling tailrace tunnel, the combined effect mechanism of upstream surge chamber and sloping ceiling tailrace tunnel and their coupled influence on system stability has not been studied. Although the nonlinear mathematical model of turbine regulating system of hydroelectric power plant with upstream surge chamber and sloping ceiling tailrace tunnel was proposed in [28], only the effect of the governor parameters on the stability were studied. Moreover, the sectional area of upstream surge chamber was selected as 1.5 times Thoma sectional area, which means that the sub-system of the upstream surge chamber is stable. As a result, the effect of the upstream surge chamber on the dynamic performance of turbine regulating system was not revealed. In the process of practical applications, the design and optimization of upstream surge chamber and sloping ceiling tailrace tunnel are more important because they have a greater impact on the stability of turbine regulating system than the governor. The analysis of the combined effect of upstream surge chamber and sloping ceiling tailrace tunnel is the key to overcome the challenge of the stability of turbine regulating system for this kind of hydroelectric power plant. Then the optimization methods of the upstream surge chamber and sloping ceiling tailrace tunnel need to be proposed based on the combined effect mechanism, with the objective of improving system stability. Those are the motivations of this paper.

This paper aims to reveal the combined effect of upstream surge chamber and sloping ceiling tailrace tunnel on the dynamic performance of turbine regulating system. To achieve this goal, this article is organized as follows. In Section 2, the nonlinear mathematical model of the turbine regulating system with upstream surge chamber and sloping ceiling tailrace tunnel and the Hopf bifurcation theory are briefly presented. Note that: the detailed introduction of the model and the Hopf bifurcation theory can be found in [28]. In Section 3, the dynamic performance of the turbine regulating system under load disturbance and 0.5 times Thoma sectional area are analyzed, and a novel dynamic performance is revealed. In Section 4, the relationship between the two bifurcation lines on the PI parameter plane and the wave superposition of upstream surge chamber and sloping ceiling tailrace tunnel is studied. The effect mechanisms of the wave superposition of upstream surge chamber and sloping ceiling tailrace tunnel on the system stability are investigated, and the methods to improve the system stability are proposed. In Section 5, the whole paper is summarized and conclusions are given.

2. Mathematical model and Hopf bifurcation analysis of turbine regulating system

2.1. Mathematical model

The pipelines system of hydroelectric power plant with upstream surge chamber and sloping ceiling tailrace tunnel is shown in Fig. 1.

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