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Modeling oscillation modal interaction in a hydroelectric generating system

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ABSTRACT

Global hydropower growth continues to accelerate with 25% of total capacity installed in just the last 10 years. This accelerating expansion and the important storage facility hydropower means it is increasingly important to understand the reasons for operational failures. This is a challenge because the major reason for failures involves the complex interaction of hydraulic, mechanical and electric subsystems. Historically, reliability modelling has been split in two directions, focusing on different sub-systems, and has not yet been unified. Here these approaches are unified with a novel expression of unbalanced forces. This model with operational data are validated and the important modes of oscillation in the shaft are identified. Finally, the mechanism of the first-order oscillation mode exciting a second-order mode is presented. This integrated and accurate mathematical model is a major advance in the diagnosis and prediction of failures in hydropower operation.

1. Introduction

Hydropower plants have been built in more than 160 countries, with a total of 27,000 hydro-turbine generator units [1]. China is leading the hydropower boom, followed by India, Europe, the United States and Japan [2]. These increases in hydropower capacity have been driven by concerns over climate change and energy security. Presently, it is one of the few technologies offering affordable storage over longer periods, making it a particularly important technology for security of supply [3]. Given these benefits, construction of further hydropower systems is expected to continue, and the growth rate to rise. The economic benefits [3] and carbon dioxide [4] mitigation of these generating systems are well known to the general public, but stability and safety requires attention, with several recent, high-profile failures, such as the accident at the Sayano-Shushenskaya Hydroelectric Power Plant [5]. Failures in hydropower units, at their best, result in capacity reductions and financial loss, and at their worst, injury and death. While operational information is being gathered to better govern hydropower systems (such as load-frequency regulation control methods [6] and refurbishment and uprating of hydro power units [7]), operational managers currently are unable to use this information practically because the underlying system failures are not well understood [8].

Hydropower generation offers a significant challenge to modelers and engineers because it involves sub-systems that interact in complex ways [9]. Historically, studies of these systems have been divided into two research directions: hydro-turbine governing systems [10]; and, shaft systems modeling of hydro-turbine generator units [11]. There are two main issues with these approaches. First, hydro-turbine governing system models attempt to provide stable services to the grid by controlling the speed of the turbine, but ignore shaft axis vibration; conversely, shaft oscillation modeling attempts to control vibrations rather than speed. Clearly these two models interact with each other, hence a general model coupling both viewpoints is increasingly urgent. Second, notwithstanding some early work [12], there have been no significant model developments which included complex water flow and the consequent impact on unbalanced hydraulic forces. This is despite the fact that plant failures caused by this force are very common, for example at the Three Gorges plant [13]. Additionally, with the rapid development of hydropower plants, the size of machined parts is becoming larger and, accordingly, manufacturing precision difficult to maintain. As the precision lowers, the influence of unbalanced forces becomes more important. A more accurate expression of the unbalanced hydraulic force is both important and timely.

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The hydro-turbine governing system consists of diversion penstock subsystems, hydraulic turbine subsystems, generator subsystems, and control subsystems. These systems can be described by linear and nonlinear mathematical modelling, and are usually expressed by transfer functions or differential equations. Differences in these model types are driven by differences in the penstock, hydraulic, and generator subsystems. For example, in the penstock system, the transfer function model contains a hyperbolic function from which, using a Taylor expansion, different order polynomials are obtained. The widely used expressions are the zero-order and first-order polynomials, which are named the rigid water hammer model and elastic water hammer model, respectively. In the generator model first- or second-order differential equations are used. Finally, the hydro-turbine governing system can be expressed by differential equations from which numerical results can be obtained using the canonical *Runge-Kutta* method. Linear models have been widely used in analyzing stability analysis and optimal controller design of the hydro-turbine governing systems. However, there are still many instability problems in operating turbine generator units, especially during transient processes. For example, the Sayano-Shushenskaya hydroelectric generator unit, or the largest power plant in Russian history, suddenly destroyed itself during load rejection and was thrown from its position by water pressure [5]. Seventy-five people died as a result of the catastrophe. All hydroelectric generators in the plant were badly damaged, the turbine hall building was destroyed, and electrical and additional equipment was significantly broken. Commonly, previous studies use simplified linear models, which poorly simulate the dynamical behavior of actual machines. This is especially true for the hydro-turbine governing system due to the complex nonlinear system coupling hydraulic, mechanical, and electrical subsystems. These issues are exacerbated by the scale and complexity of generators and turbines. Given this complexity, it is understandable that linear models present many problems when used in real world conditions.

Nonlinear models of the governing system were mooted some time ago [14], but were rarely used in solving actual problems owing to the lack of efficient theoretical analysis and computational tools. Studies on nonlinear models were revived in 1992 with the development of nonlinear system control theory and improvements in computation [10]. Since then, nonlinear system models have become a key interest in research [15]. Recent studies of the governing system are divided into two main themes. The first theme focusses on the coupling subsystem relationship and effect [16]. For instance, Riasi et al. investigated the effect of surge tank on the safe operation of power plant. The results showed that the surge tank decreases the pressure rise within the spiral case and turbine overspeed by 22% and 6%, [17]. The second theme is focused on model refinements (for example, the fractional-order model [18], the stochastic model [19], and the Hamiltonian model for single pipe [20] or multiple pipes [21]) and governor control methods (such as the testing measurements [22], the stalling-free control strategies [23], and the fuzzy-PID controller [24]). For example, Xu et al. introduced fractional calculus and utilized fractional stability theory to analyze dynamic operational stability [18]. Mesnage et al. proposed a real-life MPC scheme that considers realistic limitations on the actuator, leading to feasible, almost time-optimal control design [25]. Liang et al proposed a model of hydro-turbine governing system with a surge tank and designed a specified fuzzy mode robust controller [26]. Then, Guo et al established a nonlinear model of the hydro-turbine governing system considering the head loss [27], and surge tank [28], and proposed a corresponding primary frequency relation strategy. Zhang et al proposed an object-oriented approach to establish Matlab/Simulink platform for hydro-turbine governing system [29].

The shaft system of hydro-turbine generator units consists of the upper guide bearing, the generator rotor, the lower guide bearing, the water guide bearing, and the turbine runner. It is a typical, bearing-rotor rotational machine system upon which several forces act, including: the unbalanced magnetic force (of the generating inductor), the oil film force (the oil film used on the bearings), and the unbalanced hydraulic force (the mechanical forces of the water flow). By understanding the effects and interaction of each of these forces it is possible to predict the dynamic responses of turbines and diagnose possible unit failures [30]. Each of these forces has been previously investigated independently, and the major advancements in the first two forces are outlined in turn. The first formulation of the unbalanced magnetic force was used to analyze the effects of coupling misalignment on the vibrations of rotating machinery, such as the bladed disks [31] and hydraulic turbines [32]. A more generalized, force equation model was developed incorporating the actual air gap distribution inside the stator, regardless of the orbit type [33]. Recently, studies have focused on calculating the forces in different types of generator, such as the generator rotor [34], tidal turbine [35], and Francis turbine [36].

Three main contributions are concluded in this study. First, by using a novel expression of the unbalanced hydraulic force relative to the runner axis a general, unified model of the hydroelectric generating system is proposed. Second, the interaction of these subsystems and oscillation modes are obtained on the basis of this model. Finally, this model is validated against the existing theory (linear and nonlinear series methods) and operational data.

2. A unified model of a hydroelectric generation system

A hydroelectric generation system is composed of diversion penstocks (the hydraulic subsystem), hydraulic turbine generator units (the mechanic-electric coupling subsystem), and auxiliary equipment (the mechanical subsystem). The operating state of a hydraulic turbine is easily disturbed owing to the complex motion of water flowing in diversion penstocks, multi-operating mode conversion, etc. While it might be possible to control the shaft oscillations due to these disturbances, the turbine still needs to meet the requirements of electricity on the grid, such that the change in frequency of the turbine is limited (typically to within 0.5 Hz). With this in mind, the model unification with the canonical models are established from the literature for a hydro-turbine governing system [19] and a shaft system [37].

2.1. Hydro-turbine governing system model

Here a nonlinear mathematical model of the hydro-turbine governing system is adopted as [19]:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \dot{x}_3 = \frac{\pi^2}{T_{01}^2}x_2 + \frac{1}{Z_{01}T_{01}^3}\left(h_0 - fq^2 - h_{qT} - \frac{y_r^2}{y^2}q^2\right) \\ \dot{q} = -3\pi^2 x_2 + \frac{4}{Z_{01}T_{01}}\left(h_0 - fq^2 - h_{qT} - \frac{y_r^2}{y^2}q^2\right) \\ \dot{\omega} = \frac{1}{T_{ab}}(m_t - m_e - e_n\omega) \end{cases} \tag{1}$$

where T_{01} is the elastic time constant of the penstock system, $T_{01} = L/\upsilon$; L is the length of the penstock; υ is the speed of the surge pressure wave in the penstock; Z_{01} is the resistance value of the hydraulic surge in the penstock system, $Z_{01} = \upsilon Q_r/AgH_r$; Q_r is the rated flow of the hydro-turbine; H_r is the rated head of the hydro-turbine. g is the acceleration of gravity; A is the cross-sectional area of the penstock; h_0 is a difference of water head between the upstream and downstream; f_1 is the friction factor of the penstock; y_r is the rated value of the guide vane; m_t is the turbine torque; m_e is the electromagnetic torque of the generator; e_n is the is the accommodation coefficient; k_p is the proportional gain; k_i is the integral gain; k_d is the differential gain; y_0 is the initial condition of the guide vane; r is the load disturbance; x_1, x_2, x_3, and x_4 are the middle variables; q is the turbine flow; ω is the generator speed; y is the guide vane opening.