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Nonlinear dynamic analysis and robust controller design for Francis hydraulic turbine regulating system with a straight-tube surge tank

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A R T I C L E I N F O

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A B S T R A C T

The safety and stability of hydraulic turbine regulating system (HTRS) in hydropower plants become increasingly important since the rapid development and the broad application of hydro energy technology. In this paper, a novel mathematical model of Francis hydraulic turbine regulating system with a straight-tube surge tank based on a few state-space equations is introduced to study the dynamic behaviors of the HTRS system, where the existence of possible unstable oscillations of this model is studied extensively and presented in the forms of the bifurcation diagram, time waveform plot, phase trajectories, and power spectrum. To eliminate these undesirable behaviors, a specified fuzzy sliding mode controller is designed. In this hybrid controller, the sliding mode control law makes full use of the proposed model to guarantee the robust control in the presence of system uncertainties, while the fuzzy system is applied to approximate the proper gains of the switching control in sliding mode technique to reduce the chattering effect, and particle swarm optimization is developed to search the optimal gains of the controller. Numerical simulations are presented to verify the effectiveness of the designed controller, and the results show that the performances of the nonlinear HTRS system assisted with the proposed controller is much better than that with the commonly used optimal PID controller.

1. Introduction

Many hydropower plants have been built worldwide to utilize the energy of falling water or flowing water for electricity goal by various turbines, such as Francis turbine [1], Kaplan turbines [2], and pump-turbine [3]. An important part of a hydropower plant is the hydraulic turbine regulating system (HTRS), which is used to maintain the safety and stability of hydropower generating unit (HGU) [4]. The HTRS system is in nature a complex nonlinear, time-varying and non-minimum phase system, which involves the interactions among hydraulic system, mechanical system, and electrical system. More specifically, some important inner parameters in the HTRS system are dependent on the water head, and a number of certain nonlinear features like coupled characters among different devices and operational uncertainties have been observed in hydro system [5–7]. As these complicated properties, the control performances of the HTRS influence the working conditions of a hydro plant significantly. For instance, the oscillatory

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Nomenclature

Francis hydraulic turbine regulating system with a straight-tube surge tank

h_1 the water head at upstream penstock
h_2 the water head at surge tank outlet
h_3 the water head at downstream penstock
h_{f1} the water head loss at upstream penstock
q_1 the water flow rate at upstream penstock
q_2 the water flow rate at surge tank outlet
q_3 the water flow rate at downstream penstock
T_{w1} the water inertia time constant of downstream penstock
T_j the water storage time constant of surge tank
T_{w3} the water inertia time constant of downstream penstock
T_p the pilot actuator time constant of servo system
T_y the main gate time constant of servo system
m_t the incremental torque deviation
q the incremental turbine flow deviation
x_t the incremental turbine speed deviation
y the incremental guide vane/wicket gate position deviation
h the incremental turbine head deviation
e_h, e_y, e_x partial derivatives of the hydraulic turbine torque with respect to head, guide vane and turbine speed
e_{qh}, e_{qy}, e_{qx} partial derivatives of the hydraulic turbine flow with respect to head, guide vane and turbine speed
δ generator rotor angle relative deviation
ω_0 generator based angular speed
T_a generator mechanical time constant
D generator damping constant
m_e generator electromagnetic torque
P_e generator electromagnetic power
E_q' generator transient voltage of quadrature axis
V_s generator voltage of infinite bus system
$x_{d\Sigma}'$ generator direct axis transient reactance
x_d generator direct axis reactance
x_T short-circuit reactance of generator transformer
x_L the reactance of transmission lines
$x_{q\Sigma}$ generator quadrature axis transient reactance
x_q generator quadrature axis reactance
$d_1 \sim d_6$ the uncertain system state perturbation

FSMC controller and PID controller

$f(x)$, $g(x)$, d the composite equations in Eq. (27) of parameters of HTRS system
u_{eq} the equivalent control law (approaching item)
u_{sw} the switching control law (reaching item)
s the designed sliding mode surface
c a positive constant
η a positive constant lager than D_r
$\mathrm{sgn}(s)$ sign function
$\mathrm{sat}(s)$ a high-slope saturation function
μ_{fuzzy} the normalization value of fuzzy system
k_p the proportional adjustment coefficient
k_i the integral adjustment coefficient
k_d the differential adjustment coefficient

problems in HGU were reported to be closely related to the possible Hopf bifurcation and chaotic oscillation occurs in HTRS system [8]. Hence building a mathematical model of the HTRS system and carrying out the stability analysis of it are a necessary work.

The literatures review reveals that considerable research efforts have been devoted to the modeling of hydraulic system and its stability criteria. In [9], the authors studied the small disturbance stability of hydropower plants with complex conduits and a linear turbine model. In [10], there developed an interesting nonlinear and liberalized turbine models during the transient stability analysis in the free source Power System Analysis Toolbox (PSAT) software. In [11], the authors modeled the hydraulic turbine system in accordance with the response of an actual Francis turbine. Meanwhile, there are plenty of published papers about the models of some individual parts with respect to the HTRS system [12–14]. For instance, an elastic model and non-elastic model based on first-order differential equations for the conduit system have been established in [12,13]. As the capacity of the hydro-generator system becomes larger, and the water head becomes higher, especially the widely use of various surge tanks, the robustness and the stability of the nonlinear HTRS system meets some new challenges. Consequently, a number of improved mathematical models with partial nonlinear terms have been proposed in recent years [15–17]. These models described the characters of the HTRS system in different ways and tried to approximate the prototype system as much as possible, but it is noted that most of them are focused on the traditional regulation without concerning the system uncertainties, which are commonplaces for the nonlinear systems. With the development of nonlinear science and improvement of computer capacity in data processing, nonlinear dynamic analysis has gradually been used in many fields, such as vehicle system [18], rotor system [19], and power system [20], which has an advantage to the other stability analytical methods [19]. Therefore, it is natural to apply the nonlinear dynamic analysis method into the HTRS system with uncertainties.

On the other hand, to guarantee the unconditional stability, an innovative control method should be proposed when the system is operating in the undesirable states. The tracking control of nonlinear systems has been a well-established area in the last few decades. A widely applied tracking control approach is the sliding mode control because of its high robustness and availability [21]. However, after sustained researches on the sliding mode control, there found that the major drawback of this technique is the chattering effect, due to the use of discontinuous sign functions. Various techniques have been suggested to minimize this bad effect, such as selecting smooth approximations like *sat*, *tanh* and other continuous control laws instead of the sign function [22]. However, the practical implementations show that this simple-instead type sliding mode controller (SMC) is easy to excite the unexpected high frequency responses of the control systems [23]. To tackle this problem, fuzzy logic controller (FLC) is often used. Integration of SMC and FLC methods overcomes the weakness of one method over the other so that the guaranteed performance can be achieved. With the practical application of this hybrid fuzzy sliding mode controller (FSMC), many researchers have suggested different