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Design of fuzzy sliding mode controller for hydraulic turbine regulating system via input state feedback linearization method

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A B S T R A C T

The HTRS (hydraulic turbine regulating system) plays an important role in hydropower electricity generating and safe operation of water turbine. In this paper, a novel approach to the LFC (load frequency control) is presented for the HTRS system. This approach combines sliding mode control with fuzzy logic control, where the robustness of the controller is guaranteed by a predefined sliding surface and chattering phenomenon is alleviated by the fuzzy logics. The dynamic model of a hydropower plant is developed with the consideration of inner perturbations and external noises of this system. Based on input state feedback linearization method, the relationship between reference output and control output is established. Simulations of an example HTRS system respect to the dynamical behaviors analysis without controller, fixed point stabilization, periodic orbit tracking and robustness test against random noises have been carried out by using the optimal PID (proportional–integral–derivative) controller, conventional SMC (sliding mode controller) and proposed FSMC (fuzzy sliding mode controller) for evaluating the validity and effectiveness of different controllers. The results indicated that the proposed FSMC controller was excellent from the standpoint of system performance and stability for LFC control of the nonlinear HTRS system with uncertainties.

1. Introduction

In recent years, the structure of generation unit systems has been changing dramatically. This is primarily due to the rapid development of some renewable energy sources, such as the hydropower energy, wind energy, etc. which supplement or often replace decommissioned coal-fired power [1]. In order to take full advantage of these sustainable energy sources, the reliability and efficiency of renewable energy generator plants become important topics in researches [2–4]. HTRS (Hydraulic turbine regulating system) is a control system of HGU (hydroelectric generator unit) that governs the rotor speed of water turbine according to the setpoint of output power and setpoint of speed [5]. The main task of HTRS system is to adjust the power output to the grid and to track the frequency of the grid in general. As the HGU typically operates in different status, such as starting, outage and operating in parallel with power grid, and the important parameters in HTRS system are dependent on time and working conditions, it is still a challenge problem to build a suitable prototype model and design proper control rules until now.

A lot of research efforts have been devoted to the modeling of HTRS system and its components over the past decades. For instance, a model was studied for a plant with severely leaky wicket gate in 2004 [6]. In 2005, a hill chart look-up table was added to the water turbine output power and another look-up table was added to transform the real gate position to ideal gate position in the equation and the first order filter block was used to include unsteady effects from gate movement [7]. A modification on the Kundur's turbine model was made in Ref. [8], where the novel model is obtained through the frequency response tests. Elastic and non-elastic models [9,10] for conduit system have been investigated in the long pipeline system and short pipeline system, respectively. Chen et al. [11] provided the nonlinear dynamical system model associated with a surge tank. Pennacchi et al. [12] developed water turbine model in accordance with the response of an actual Francis turbine. Various completely HTRS models were available in Refs. [13–15], etc. These models described the characters of complicated HTRS system in different ways and tried to

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approximate the real model exclusively, but it is interesting to note that most of these methods are based on the equilibrium point around stability region and keep a blind eye for the uncertain external noises and inner perturbations.

Accompanied with the development of HTRS system modeling, the controllers of the system have also experienced significant improvements. As we known, the power output of hydropower plant will vary with power network demand and produces variations in turbine rotational speed. The rotational speed of the turbine is checked by varying the wicket gate position which controls the flow through the turbine and subsequently torque. In the past, the wicket gate position was usually regulated with the PID (proportional–integral–derivative) controller due to its simplicity and ease of implementation in practice [16–18]. Integral, proportional and derivative feedback controller is based on the past (I), present (P) and future (D) error. Its use ensures a faster wicket gate position response by providing transient gain reduction/increase. However, the nonlinear nature of water turbine and the constantly varying load makes the gain schedule of PID controller difficult to design, which limits the operating range, thus many advanced control approaches have been developed for the nonlinear HTRS system in the recent years, such as fuzzy control [19], predictive control [20], and self-tuned control [21]. Unfortunately, most of the above controller designs were based on linear model and do not guarantee the robustness to the system perturbations due to the wear and tear. In this regard, SMC (sliding mode controller) is introduced into the controller design of HTRS system.

SMC controller is a quick and powerful variable structure approach that governing the nonlinear systems via a predefined switch sliding surface. There are numerous applications of SMC controller used in industries and the main advantage of this type of controller is its strong robustness against model uncertainties and parameter variations [22,23]. With the development of SMC techniques in practice, there gradually present the applications of SMC controller used in HTRS system [24–26]. However, a common drawback of conventional SMC controllers is the chattering phenomenon, due to the use of discontinuous sign function. Numerous techniques have been proposed to minimize chattering effect, such as selecting smooth approximation like *sat*, *tanh* and other continuous control laws to instead the sign function [22–24]. One of the most commonly used solutions is to combine FLC (fuzzy logic control) into SMC control [27,28], which overcomes the weakness of the sign function by the fuzzy logic so that the badly chattering phenomenon can be easily eliminated.

Motivated by the above discussions, a novel mathematical model of HTRS system with the considerations of inner perturbations and external noises is presented, and the input state feedback linearization method is used to construct the relationship of reference output and control output. To ensure the stability of this model, an ingenious controller combining fuzzy logic control and sliding mode control is proposed, where the robust behavior of HTRS system with controller is guaranteed, and the chattering phenomenon can be attenuated. Compared with PID controller and a common used SMC controller for an example HTRS system simulation, the designed FSMC (fuzzy sliding mode controller) controller has a desirable response output. Furthermore, the dynamical analysis is introduced to study the stability of HTRS system, such as bifurcation maps, Lyapunov exponents, phase diagrams, power spectrums, etc. Many interesting phenomena have been observed.

The rest of the paper is organized as follows. Section 2 briefly introduces the modeling of HTRS system with uncertainties. In Section 3, input state feedback linearization method of HTRS system, FSMC controller design, and the robustness analysis are discussed in details, where the application of FSMC controller in HTRS system is formulated and constructed in Section 4. The comparative simulations are designed and the results are discussed in Section 5. The conclusions are summarized in Section 6 and acknowledgment is given in the end.

2. Model of HTRS system

A simple scheme of hydropower station plant is shown in Fig. 1. The entire system model can be constructed by combining individual dynamic models of conduit penstock, electric-hydraulic servo system, water turbine and generator set [5,18].

As showed in Fig. 1 for a hydropower station system, running water from the reservoir flows into the scroll casing after passing through diversion system, and promotes the turbine to rotate. Then the power generator is driven for the joint of the shaft coupling. In order to keep the frequency, wicket gate positions are regulated by the oil-servo controlled by the speed governor. In this section, a kind of affine model of HTRS system is studied and sections of the model are illuminated, respectively.

2.1. Conduit penstock model

According to the hydromechanics theory, the head and flow equation between two sections of conduit system can be deduced as [11]:

$$\begin{bmatrix} H_p(s) \\ Q_p(s) \end{bmatrix} = \begin{bmatrix} \cosh(r\Delta x) & -z_c\sinh(r\Delta x) \\ -\sinh(r\Delta x)/z_c & \cosh(r\Delta x) \end{bmatrix} \begin{bmatrix} H_q(s) \\ Q_q(s) \end{bmatrix} \quad (1)$$

where subscripts q and p are the symbols of upstream and downstream section of penstock in Fig. 1, respectively. $\Delta x = L$ means the penstock length, r and z_c are the composite equations of parameters of the penstock. $r = \sqrt{MCs^2 + RCs}$, $z_c = r/(Cs)$.

M, R, C among the equation can be written as:

$$M = \frac{Q_0}{gAH_0}, \quad C = \frac{gAH_0}{v^2 Q_0}, \quad R = \frac{fQ_0^2}{gDA^2H_0} \quad (2)$$

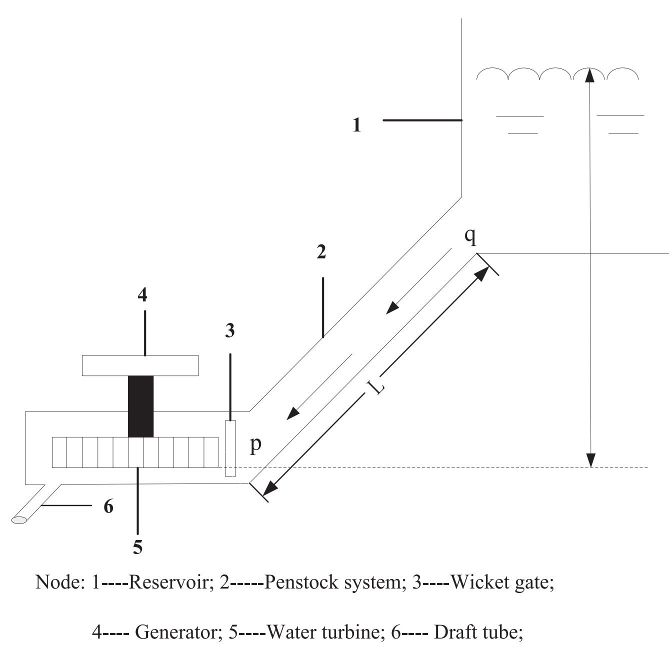

Fig. 1. A simple scheme of hydropower station plant.