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Modelling and Control of a Hydropower Plant in Dealing with the Speed Control Problem of Synchronous Generators

Thi-Mai-Phuong Dao
Department of Electrical Engineering Technology, Hanoi University of Industry, Hanoi, Vietnam
Corresponding Author : daophuong@haui.edu.vn

ABSTRACT

Maintaining the rotational speed of synchronous generators in a hydropower plant is a vital control strategy in power system stability and operation. It is because such rotational speed is proportional to the output frequency of the synchronous generator, thereby it strongly affects the stability of the electric power grid. This paper presents a study regarding the modelling and control of a hydropower plant to maintain the generator speed. This study is divided into two main parts. A well-used model of an isolated hydropower plant is established in this study at first; then two controllers including conventional PI and intelligent fuzzy logic regulators are investigated to speed control of the generator. Simulations implemented in MATLAB/Simulink package demonstrate effectiveness and feasibility of the proposed speed controllers.

Keywords: Hydropower Plant, Rotational Speed Control, Mathematical Model, Pi Regulator, Intelligent Fuzzy Logic Controller

I. INTRODUCTION

As the most traditional power plants, hydroelectric power systems have been widely growth in every country around the world. It is clear the hydroelectric plants annually contribute a large amount of electricity to the countries. This is why study on stability and operation of the hydropower plants still plays an important role in control strategies of electric power grids [1-2].

This paper has selected a way to go in deep to the hydropower plant's control and stability. The study starts with the modelling of a hydropower plant. Such a hydroelectric facility typically includes several major components: penstocks, speed governors, pilot actuators, main inlet valves embedded servo motors, hydro-turbines and synchronous generators. These components are integrated to form an entire power plant. There is no doubt that these components are difficult to mathematically model due to their nonlinearities [3-4]. One of the most methods to tackle this problem is to linearize these component around an equilibrium. Although this method normally leads to an approximate model, it is useful in designing of the control strategies for such a hydroelectric facility. This study implements the modelling by means of such a linearization.

After the mathematical modelling, the system is then applied control strategies in order to maintain the rotational speed of the synchronous generator. It is noted that this control problem is directly related to the load-frequency control of a hydropower facility since the speed is proportional to the frequency of the generator [5-9]. Two speed controllers are investigated in this paper, including PI and fuzzy logic regulators. The PI regulator is treated as a conventional speed controller. Meanwhile, the fuzzy logic counterpart can be called as an intelligent controller. Numerical simulation results obtained by using MATLAB/Simulink environment prove the feasibility of the proposed controllers in dealing with the speed maintaining of the synchronous generator.

II. MODELLING OF A HYDRO-POWER PLANT

An isolated hydro power plant as shown in Figure 1 typically includes three major parts indicated below [3]:

(1) Speed governor consisting of pilot actuator and main gate servo;
(2) Turbine and penstock;
(3) Generator and load.

The penstock that is normally made of steel carries water under high pressure down from the hydroelectric reservoir to the hydro-turbine. It is the one of the most essential component of a hydroelectric facility, allowing water to move to the hydro turbine. According to [1], the penstock which is supposed to be short enough can be approximately modelled as follows:

$$\frac{\Delta H(s)}{\Delta U(s)} = -\left[\Phi + z_p \tanh(t_{ep}.s)\right] \approx -T_w.s \qquad (1)$$

Where $T_W(s)$ is the water starting time constant at the rated load. The other parameters can be clearly found in [1-3].

Besides, hydro turbines that convert potential energy of moving water into mechanical energy to rotate the generator's shaft are considered to be primary movers in a hydroelectric generation plant. In [3], the hydro turbine can be approximately modelled as:

$$W_T(s) = \frac{\Delta P_m(s)}{\Delta G(s)} = \frac{1 - T_w s}{1 + \frac{1}{2} T_W s} \qquad (2)$$

The speed governor, one of the most important components of a hydroelectric power plant, is used for adjusting the speed of the synchronous generator by varying the water flow through a turbine valve which is normally called the main inlet valve. In order to establish the transfer function of such a speed governor, it is necessary to consider the following two relationships:

$$W_P(s) = \frac{\Delta X_e(s)}{U(s)} = \frac{1}{T_P.s + 1} \qquad (3)$$

$$W_g(s) = \frac{\Delta G(s)}{\Delta X_e(s)} = \frac{1}{T_g.s + 1} \qquad (4)$$

In the above two transfer functions, $W_P(s)$ and $W_g(s)$ represent the relationships between the control signal u(t) and the change in the pilot actuator $\Delta x_e(t)$ and the change of the main inlet valve angle $\Delta g(t)$.

The generator of a hydropower plant, which is normally called synchronous generator, converts mechanical energy of the water turbine into the electric energy to distribute to the grid. It is modelled to form the following transfer function:

$$W_{G-L}(s) = \frac{\Delta \Omega(s)}{\Delta P_m(s) - \Delta P_L(s)} = \frac{1}{M.s + D} \qquad (5)$$

In (5), $\Delta P_m(s)$ and $\Delta P_L(s)$ are the deviations of the mechanical power output of the hydro turbine and load, respectively.

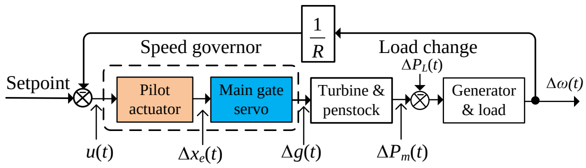

Figure 1. A typical block diagram for isolated hydro-power plants

It is straightforward to deduce the state-space model which should be important for designing speed control strategies of a hydropower plant. First, a state vector should be defined as:

$$x(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \end{bmatrix} = \begin{bmatrix} \int_0^t \Delta\omega dt \\ \Delta x_e(t) \\ \Delta g(t) \\ \Delta p_m(t) \\ \Delta\omega(t) \end{bmatrix} \qquad (6)$$

Second, the state-space model can be represented as follows:

$$\dot{x}(t) = A.x(t) + B.u(t) + F.\Delta p_L(t) \tag{7}$$

Where:

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & -\frac{1}{T_p} & 0 & 0 & -\frac{1}{T_p R_p} \\ 0 & \frac{1}{T_p} & -\frac{1}{T_p} & 0 & 0 \\ 0 & -\frac{2}{T_g} & (\frac{2}{T_w}+\frac{2}{T_g}) & -\frac{2}{T_w} & 0 \\ 0 & 0 & 0 & \frac{1}{M} & -\frac{D}{M} \end{bmatrix};$$

$$B = \begin{bmatrix} 0 \\ -\frac{1}{T_p} \\ 0 \\ 0 \\ 0 \end{bmatrix} \text{ and } F = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\frac{1}{M} \end{bmatrix} \tag{8}$$

III.DESIGN OF SPEED CONTROLLERS FOR SYNCHRONOUS GENERATORS

General speaking, to stabilize the rotational speed of a synchronous generator in an isolated hydroelectric facility, two types of controllers can be typically applied as follows:

(1) Conventional speed regulators: integral, proportional – integral (PI) and proportional – integral – derivative (PID)
(2) Intelligent speed controllers: fuzzy logic and neural network-based controllers

Such two speed controllers use the derivation of speed as the control input; and the output signal is to deliver to the speed governor. It is based on the compensatory control theory with a two close control loops (see Figure 2). When appearing any load change in the power plant, the first control loop, normally called primary control, will be initially launched with a feedback gain regarding the droop factor of the speed governor. Then, the second control loop, normally called secondary control, will be activated to compensate the load change in a more effective method. The foresaid speed controllers are applied in the secondary control to stabilize the generator's rotational speed. In this paper, to bring the hydropower plant back to the stable steady – state after the load changes, a fuzzy logic architecture will be proposed as shown in Figure 2 and Figure 3. The applicability of such fuzzy logic controller will be testified in the next section.

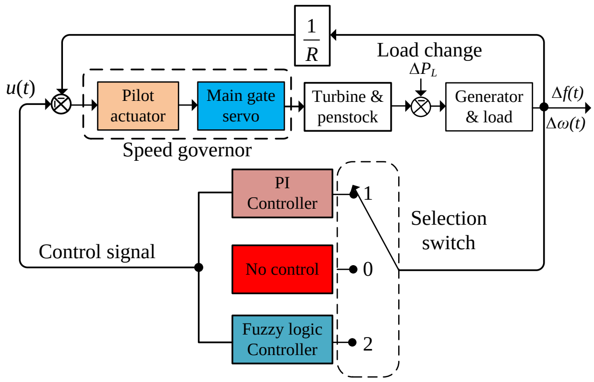

Figure 2 : Speed control strategies for the synchronous generator of a hydropower plant

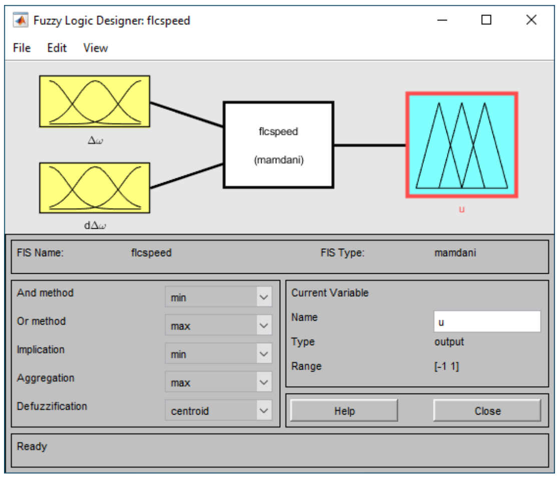

Figure 3 (a)

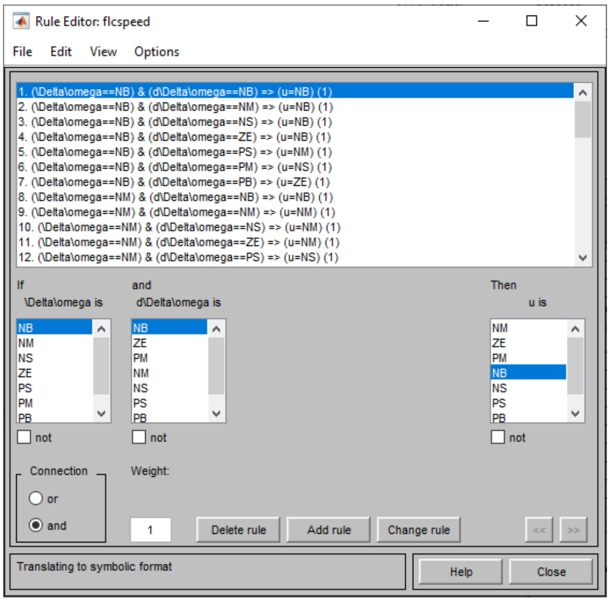

Figure 3 (b)

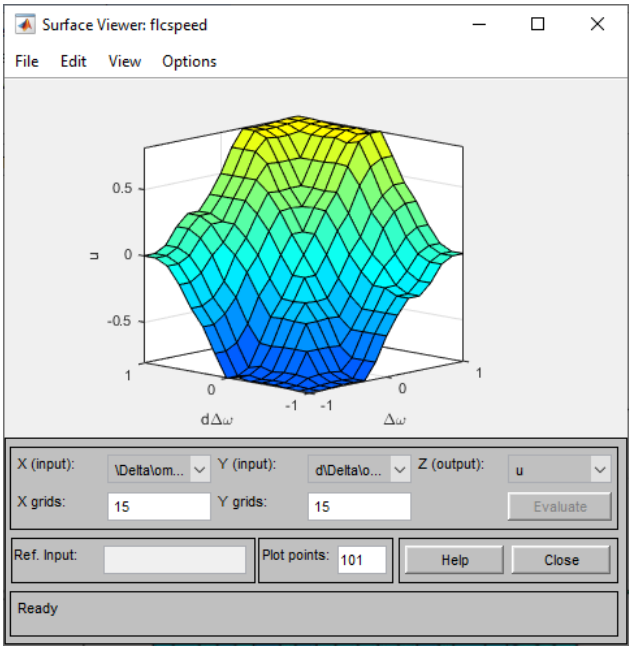

Figure 3 (c)

Figure 3: Fuzzy logic architecture proposed for designing the speed controller

(a) Fuzzy logic model

(b) Fuzzy rules

(c) Fuzzy surface

IV. EVALUATION OF SIMULATION RESULTS

This section presents simulation results implemented in MATLAB/Simulink platform. The simulation procedure is as follows:

(i) First, the dynamic responses of the hydropower plant model established in Section II will be created without using the speed controllers (see Figure 4).

(ii) Second, the dynamic responses of the plant model applying the PI regulator will be presented (see Figure 5).

(iii) Third, the dynamic responses of the plant model applying the fuzzy logic speed controller will be illustrated (see Figure 6).

Assuming that three cases of load changes are also provided for the above procedure: (1) the step load change, (2) the three-level load change and (3) the randomly multi-level load change (see curves $\Delta P_L(t)$ in Figures 4-6). These load changes, especially the last one, are suitable for the practical load variations in a power system. The parameters used for simulation can be seen in [3]. The analysis and evaluation of the numerical simulation results is presented below.

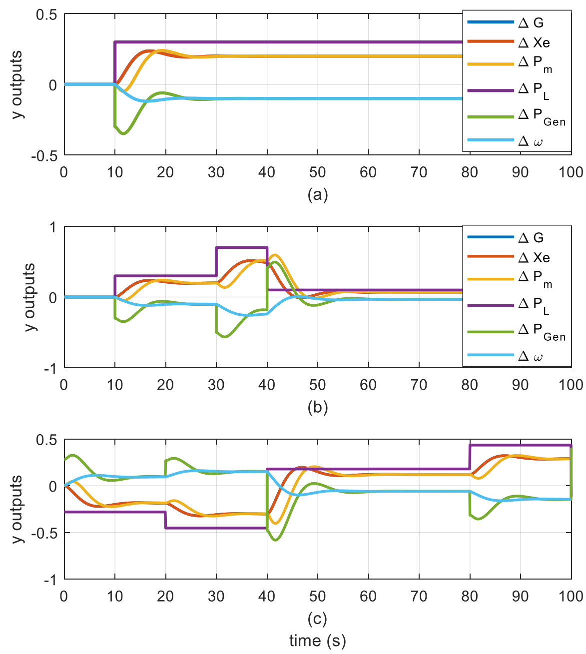

Figure 4. Dynamic responses of the hydropower plant in case of no control

As shown in Figure 4, without speed controllers, there is always a big steady state error of the speed deviation $\Delta\omega(t)$, resulting a undesired frequency variation which needs to be eliminated. In Figure 5 and Figure 6, these deviations are damped successfully. The steady state errors are eliminated with acceptable settling times. This verifies the effectiveness of the proposed PI and fuzzy logic speed controllers. To compare more specifically, Figure 7 illustrates the dynamics of the speed deviation fluctuation for the three foresaid cases of controllers. The simulation results presented in this Figure puts a claim that the fuzzy logic speed controller obtains the best control performances: lower overshoots/undershoots and shorter settling times. Therefore, it is a feasible control strategy to this problem.

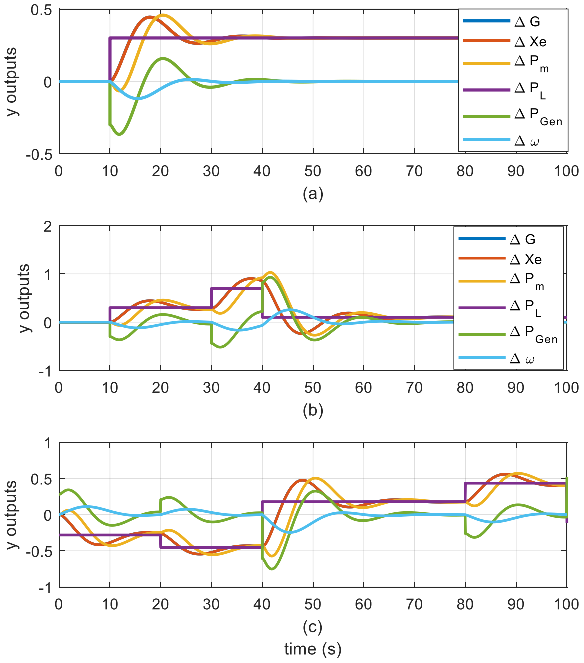

Figure 5. Dynamic responses of the hydropower plant in case of applying a PI regulator

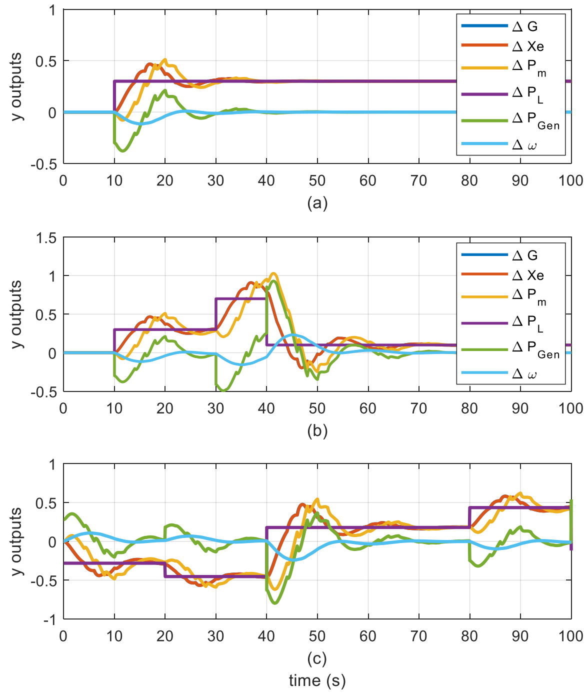

Figure 6. Dynamic responses of the hydropower plant in case of applying a fuzzy logic controller

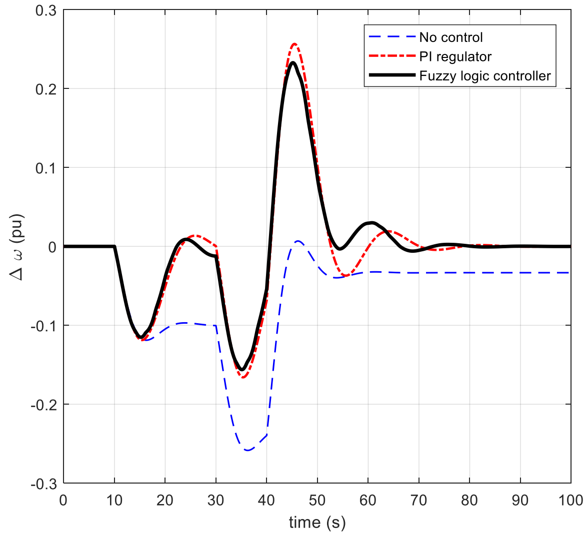

Figure 7. A comparison of the speed deviation responses for three simulated cases for the second load change condition

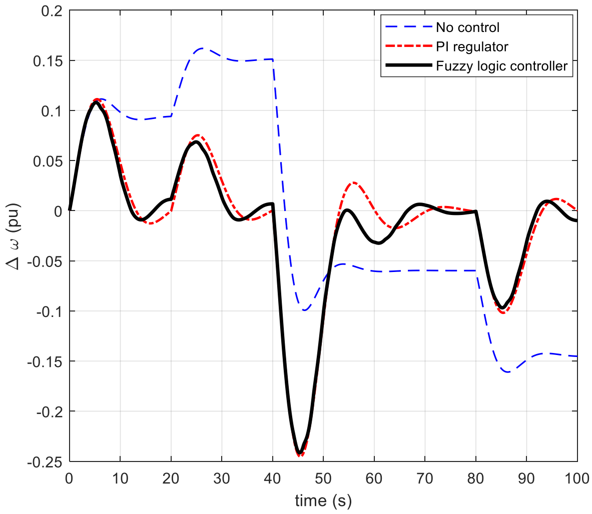

Figure 8. A comparison of the speed deviation responses for three simulated cases for the third load change condition

V. CONCLUSION AND FUTURE WORK

This study has conducted the modelling and speed control of a hydropower plant. The power facility has been mathematically modelled as the first step. Thereafter, speed control strategies have been proposed to stabilize the system dynamics. Simulation results provided confirmatory evidence that the mathematical model and the fuzzy logic speed controllers are feasible and reliable in hydropower plant control and stability. Further research in this area may include the mathematical model and simulation of a multi-area hydropower system for eliminating the fluctuation of synchronous generators' speed deviations, thereby bringing the network back to the stability.

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Author's Profile

Dao Thi Mai Phuong received Msc degree in *Automation and Control* at Hanoi University of Science and Technology, in 2010. She received the PhD degree in *Control Science and Engineering* at Hunan University, in 2017. She is working as a lecturer and researcher at Hanoi University of Industry in Hanoi, Vietnam. Her research interests include smart grids, intelligent control, control theory and applications.

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