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A Hybrid Model Reference Controller Integrated with an Optimization Technique for Generator Speed Control of a Hydropower Plant

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Abstract: ***Designing an effective speed control strategy to stabilize the rotational speed of a synchronous generator is highly important for the operation and stability of a hydropower plant. Traditionally, PID regulators are employed to eliminate the speed deviations due to load changes in such a power system. With the fast development of modern control techniques together with poor control performances of the PID regulators, intelligent speed controllers i.e. fuzzy logic and artificial neural network – based controllers should be considered to find a more feasible speed control scheme. This paper proposes a newly hybrid control strategy applying a model reference adaptive control (MRC) integrated with an efficient optimization mechanism to solve the generator speed control problem. The novel controller is completely able to deal with the speed control problem against the random load changes in a hydroelectric power system with better control performances when compared to several counterparts such as the conventional PID regulator. This claim will be demonstrated through a number of numerical simulations implemented in MATLAB/Simulink platform for a typical hydropower plant model which also be established in this study.***

Index Terms: ***Hydropower plant, speed control, PID, FLC, hybrid MRC.***

I. INTRODUCTION

A hydropower plant normally includes plenty of elements, and such a facility always consists of three major units: a speed governor, a hydro turbine and a synchronous generator. Due to the random and continuous load changes in the hydropower plant, the system frequency, which is proportional to output speed of the synchronous generator, may be usually deviated from the nominal value. Whenever the system frequency deviation occurs, it absolutely affects the stable operation of electric power equipment, causing the instability of the network. As a result, speed control for the synchronous generator in such a hydropower facility plays a vital role in its control and stability [1-3].

In a hydropower plant, there typically exits a control loop which can be used to stabilize the generator speed as the primary control. However, when the load changes are large enough, such a primary control may not good to bring the system back to the stability under a condition of acceptable performances.

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At the same time, it always requires a secondary control loop which usually embeds a regulator as an auxiliary or compensatory control. With the co-operation of these two control loops, it is possible to ensure stability of the generator speed.

To design a regulator for such a second control loop, the conventional PID architecture can be applied at first to damp the frequency fluctuations [4-5]. This regulator, however, might not guarantee the increasingly high requirements regarding the control performances of a modern hydropower plant. In this perspective, the available evidence seems to suggest that the conventional PID regulator should be replaced with a better controller. In the current research, a hybrid integration between a model reference adaptive controller (MRC) and a proportional factor which is determined by an optimization method will be presented. The implementation of the hybrid control architecture is based on two phases. First, the MRC is designed depending upon two artificial neural network models. Second, the optimization mechanism will be executed to determine the best gain factor in cooperation with the MRC to deal with the speed control. With this integration, the control performance of the control system will be successfully obtained.

This paper is organized into five sections. After the Introduction section, the next section will present the modelling of a hydropower plant which should be suitable for the design of speed controllers. Section III then introduces a procedure to build the hybrid MRC architecture for the speed control problem of a synchronous generator. Thereafter, Section IV is presented to implement and analyze several simulations obtained in MATLAB/Simulink platform to demonstrate the applicability of the proposed controller. It is found that the discussions and conclusions with regard to this research will be provided in the last section of the paper.

II. MODELLING OF THE HYDROPOWER PLANT

Each hydropower facility typically consists of several main units as penstock, water turbine, speed governor, synchronous generator and loads. The speed governor normally comprises of two major units: a pilot actuator and a servo motor to control the turbine valve (see Fig. 1(a)). These two units can be mathematically modelled as follows [2]:

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

$$W_g(s) = \frac{\Delta G(s)}{\Delta X_e(s)} = \frac{1}{T_g.s+1} \quad (2)$$

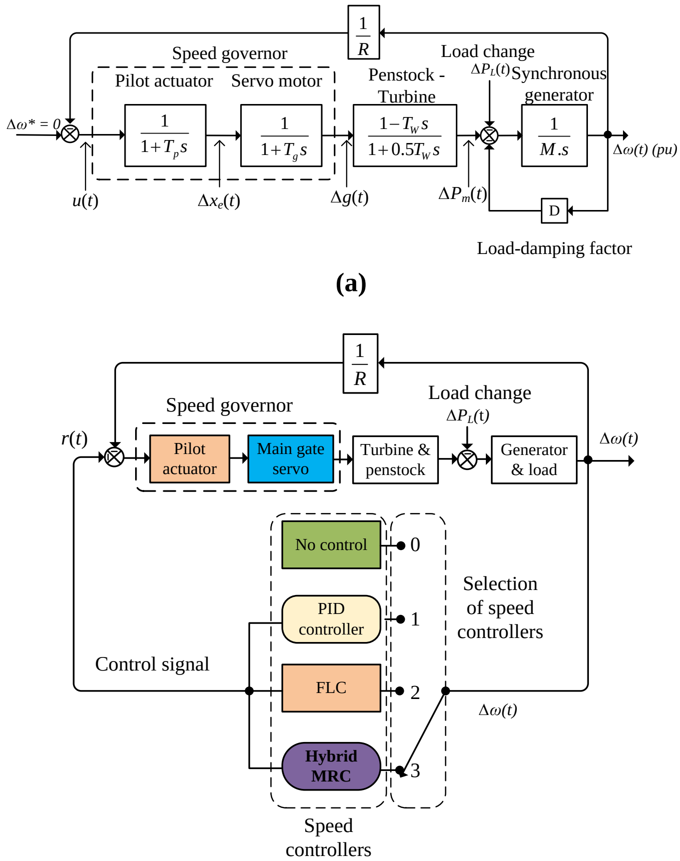
The penstock, which must be technically installed in a hydroelectric facility, is an indispensable component integrated with the turbine valve or main inlet gate to allow the high pressure water flow to rotate the hydro turbine. When cooperated with such a hydro turbine, a mathematical model can be established as:

$$W_T(s) = \frac{\Delta P_m(s)}{\Delta G(s)} = \frac{1-T_w s}{1+0.5T_W s} \quad (3)$$

where $\Delta P_m(t)$ is the mechanical power change as the output of the turbine and T_W is defined as the water start-up time constant. Finally, the synchronous generator, which is only considered in a relationship between the changes of mechanical power input resulting from the hydraulic turbine and the electrical power output, can be modelled as:

$$W_{Gen}(s) = \frac{\Delta P_e(s)}{\Delta P_m(s)} = \frac{1}{2H.s} = \frac{1}{Ms} \quad (4)$$

where H is the inertial constant of the synchronous generator.



(a)

(b)

Fig.1: A block model of hydropower plants
(a) The mathematical model
(b) The block model with different speed controllers

When integrated with load changes describing a load-damping factor as shown in Fig. 1(a), the final transfer function for the generator and load is given as:

$$W_{Gen\_load}(s) = \frac{\Delta\Omega(s)}{\Delta P_m(s) - \Delta P_L(s)} = \frac{1}{M.s+D} \quad (5)$$

where $\Delta P_L(t)$ is the load change, which should always depend on users, resulting rotational speed deviation fluctuations of the synchronous generator. From the foregoing equations (1)-(5), it is evident the following state-space equation describing the model of a hydroelectric power plant can be deduced as:

$$\dot{\underline{x}}(t) = A.\underline{x}(t) + B.u(t) + F.\Delta p_L(t) \quad (6)$$

where $\underline{x}(t)$ is a state vector defined as:

$$\underline{x}(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \end{bmatrix} = \begin{bmatrix} \int_0^t \Delta\omega dt \\ \Delta x_e(t) \\ \Delta g(t) \\ \Delta p_m(t) \\ \Delta\omega(t) \end{bmatrix} \quad (7)$$

Besides, ***A***, ***B***, and ***F*** are a matrix and two vectors which can be indicated below:

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

$$B = \begin{bmatrix} 0 \\ -\frac{1}{T_p} \\ 0 \\ 0 \\ 0 \end{bmatrix} \text{ and } F = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\frac{1}{M} \end{bmatrix}. \quad (8)$$

The state-space model presented in the form (6) with matrices and vectors (7) and (8) can be applied to an investigation of control strategies for maintaining the speed stabilization of the hydropower plant. This aim will be clarified in the following sections.

III. DESIGN OF A HYBRID MODEL REFERENCE ADAPTIVE SPEED CONTROLLER

The hybrid model reference adaptive controller proposed in this paper and shown in Fig. 2 is consisted of the following two parts corresponding to two operation phases:

(i) A model reference adaptive controller (MRC) based on two artificial neural networks. One ANN is used to identify the plant model at first; then the remaining one is applied to design the controller for the electric power facility.

The details regarding the operating principle of this controller can be found in [5].

(ii) An efficient optimization mechanism should be employed to determine a gain factor *Kp* which is additionally embedded into the MRC controller. The fact that is such a gain factor can be used in an effective correction to enhance the control quality of the system by damping deviation fluctuations of the generator speed.

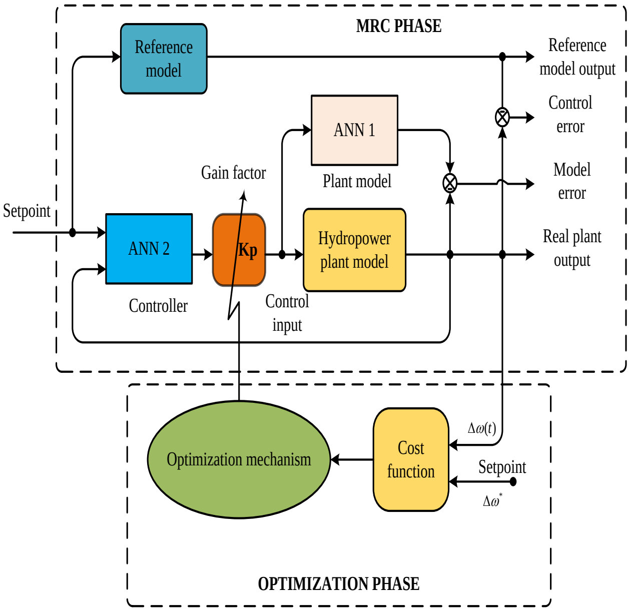


Fig. 2: The block diagram of the hybrid MRC applied for the generator speed control strategy

The hybrid speed controller is executed following two phases. In the first phase, the MRC architecture is trained to design a draft controller for the speed maintaining of the power system. Thereafter, the optimization phase is implemented in a reasonable integration to further improve the control quality, being able to meet the increasingly high requirement of a modern hydropower system in reality. The next section will present the implementation of numerical simulations in MATLAB/Simulink platform to evaluate the applicability of the proposed speed control strategy in comparison with several existed regulators such as PID and fuzzy logic architecture.

IV. AN ANALYSIS OF NUMERICAL SIMULATION RESULTS

Selection of a practically effective speed controller should be dependent on several steps. One of the most important steps is to evaluate its feasibility and effectiveness through numerical simulation results implemented in a believable software such as MATLAB/Simulink package. This section is to present a comprehensive comparison of three speed controllers applied for the generator speed stabilization of a hydropower model. The proposed control strategy is depicted in Fig. 1(b) which has been inspired by the mathematical model of the hydroelectric facility model built in Fig. 1(a). As shown in Fig. 1(b), three speed controllers, namely PID and fuzzy logic control (FLC) which was studied in [5, 8] and the newly hybrid MRC proposed in Section III, are taken into account in the simulation platform together with an uncontrolled scenario. The simulation parameters for a typical hydropower plant model were provided in [2]. The FLC architecture with simulation parameters is also found clearly in [5].

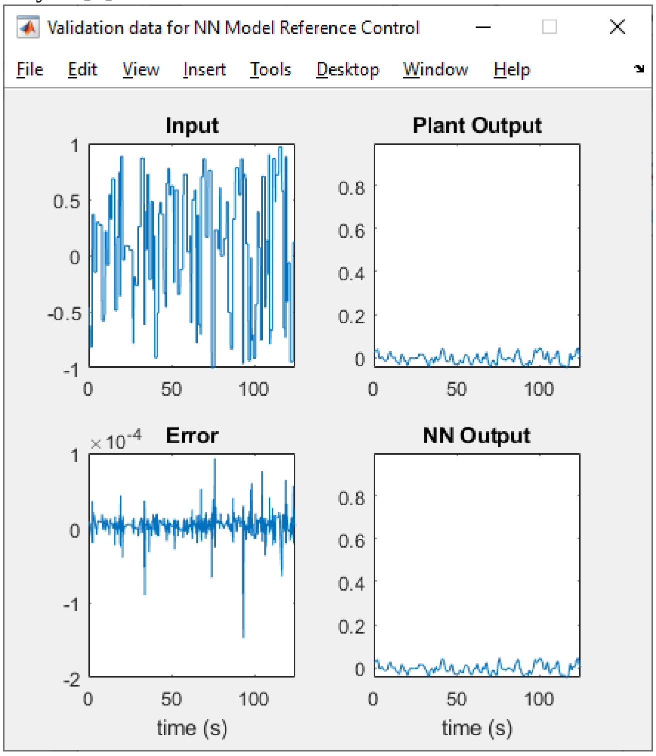


Fig. 4: Validation data for the ANN 1 when training it to identify the control plant

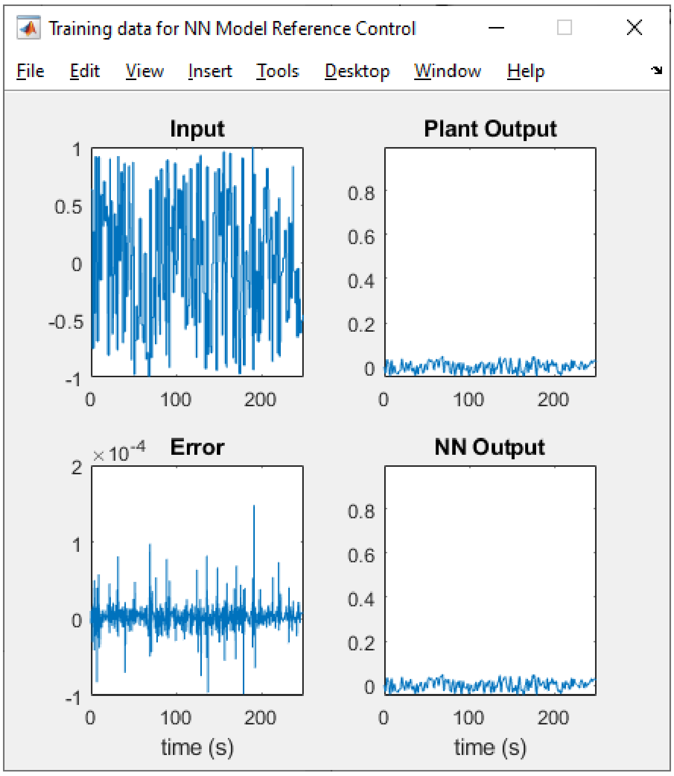


Fig. 5: Training data for the ANN 1

It is noted that a multi-level load change $\Delta P_L(t)$ as shown in Figs. 10-11 will be embedded in the power system model to testify the control performance for all scenarios including three speed controllers and a case without using regulator.

These load changes are highly suitable for the operation of a practical power system. The novel hybrid MRC will be implemented following two phases as presented in the previous section.

For more details, it is trained by the ANN 1 to identify the power system model at first. The simulation parameters are indicated in Appendices of this paper. The training process is depicted in detail as shown in Figs. 4-6. As the second period of the training process, the ANN 2 will be activated to design the controller according to the working principle of the MRC architecture. Some of the training results are represented in Figs. 7-8. The simulation parameters must be initially provided as in the Appendices.

In the optimization phase of the proposed hybrid MRC execution, the PSO mechanism which stands for particle swarm optimization method will be implemented to determine a gain factor K_P. There is an overwhelming evidence for the notion that the PSO technique is one of the most effective optimization methods in dealing with the determination of several parameters [7, 8]. With the initial parameters given in the Appendices, the PSO has been executed, obtaining the convergence plotted in Fig. 9. The cost function formed in a simulation time T of 200s is selected in this paper as:

$$f_{\text{cost}} = \int_0^T |\Delta\omega(t)| t dt. \qquad (9)$$

The gain factor as well as the cost function is converged, successfully determining the factor K_P for the hybrid MRC. The optimal value of K_P is 2% according to the result predicted in Fig. 9. The next three Figs. 10-12 show simulation results for three speed controllers.

Fig. 10 and Fig. 11 plot dynamic responses with regard to five parameters of the state vector presented in (7) together with the load change $\Delta P_L(t)$.

Because the main goal of the speed control strategies is to stabilize the rotational speed of the synchronous generator, it is necessary to show up the speed deviation dynamics $\Delta\omega(t)$ as plotted in Fig. 12.

It is clear this deviation cannot be eliminated in case of without a speed controller.

The three speed controllers are completely able to damp the fluctuations of the speed deviations with different performances. Obviously, the two intelligent speed controllers applying the fuzzy logic (studied in [5]) and the hybrid MRC proposed in this work achieve much better control performances in comparison with that of the traditional PID regulator.

All control indexes i.e. rise time, overshoot, undershoot, settling time and steady-state error resulting from the two intelligent controllers are good enough to quickly bring the stable state to the system after the load change appearance. Also, the hybrid MRC, when compared to the FLC speed regulator as shown in Fig. 12, obtained a little better control characteristic. This obviously confirms the novelty of the current work.

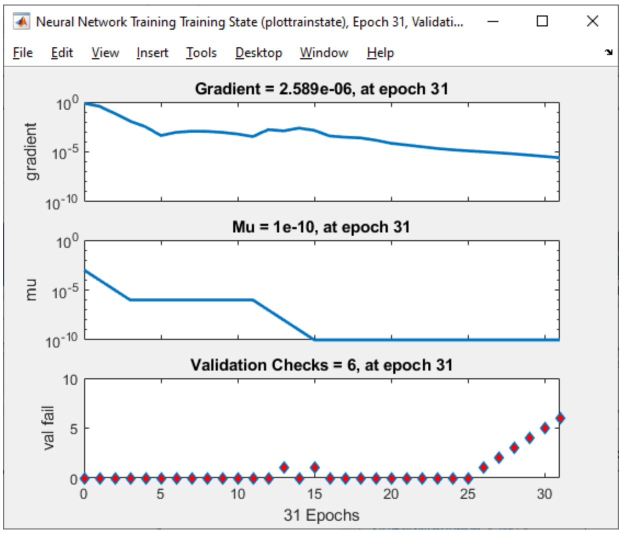


Fig. 6: The training state for training the ANN 1 model

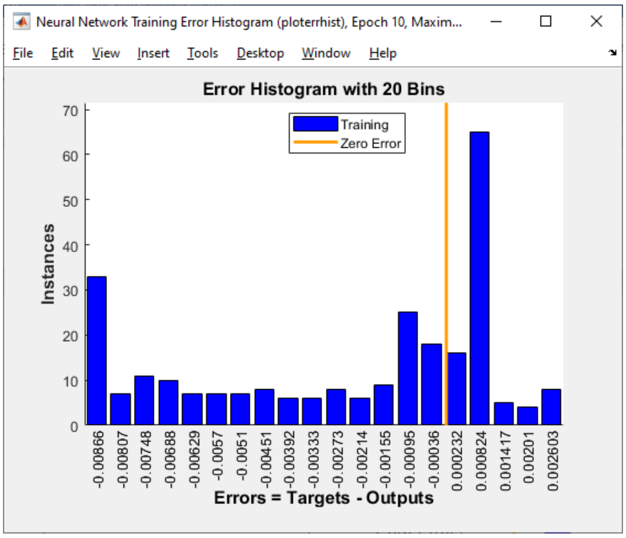


Fig. 7: The histogram for training the ANN 2 model to design the controller of the MRC

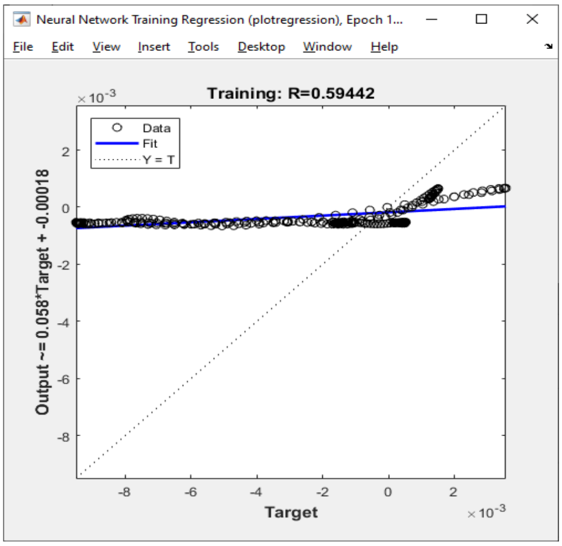


Fig. 8: The training regression for training the ANN 2 model to design the controller of the MRC architecture

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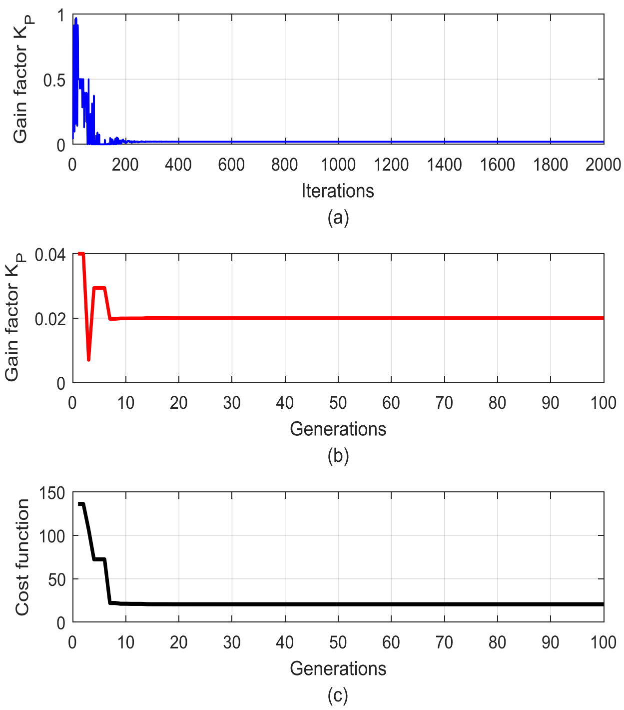

Fig. 9: The convergence of the PSO mechanism to determine the gain factor K_p

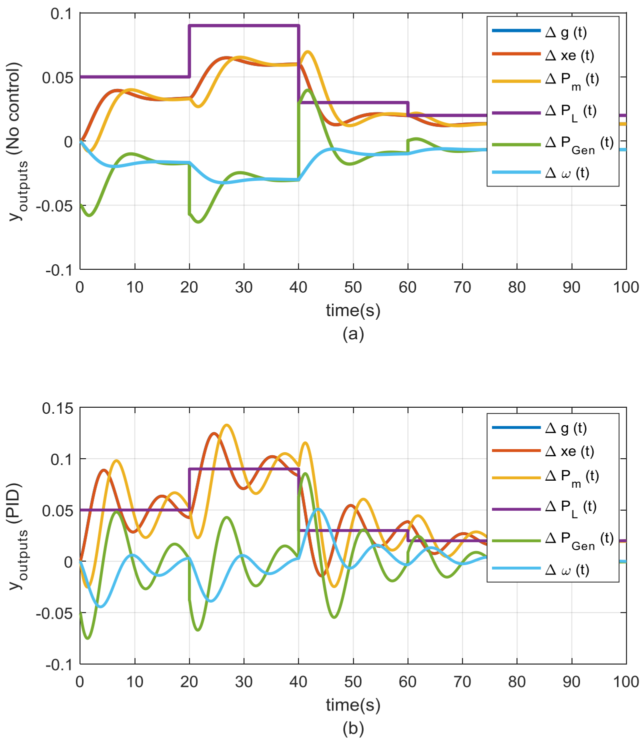

Fig. 10: Simulation results for the uncontrolled perspective and the PID regulator
(a) Uncontrolled case
(b) PID regulator

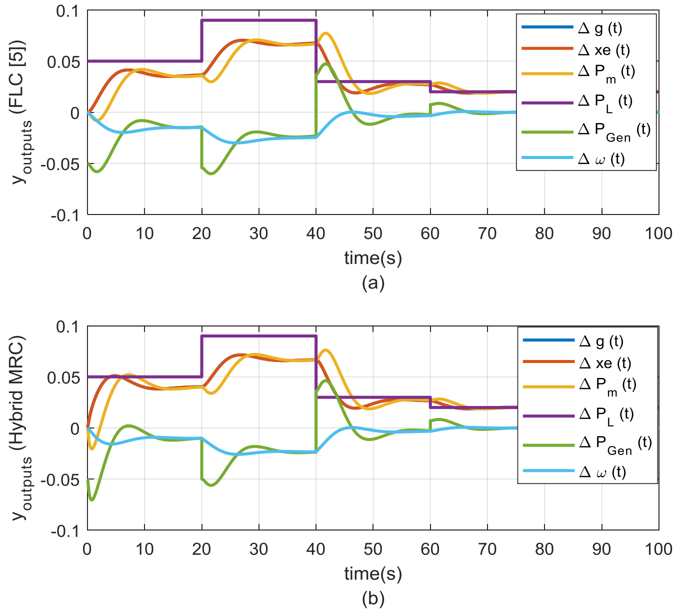

Fig. 11: Simulation results for the FLC and hybrid MRC
(a) Dynamic responses of the FLC [5]
(b) Dynamic responses of the proposed hybrid MRC

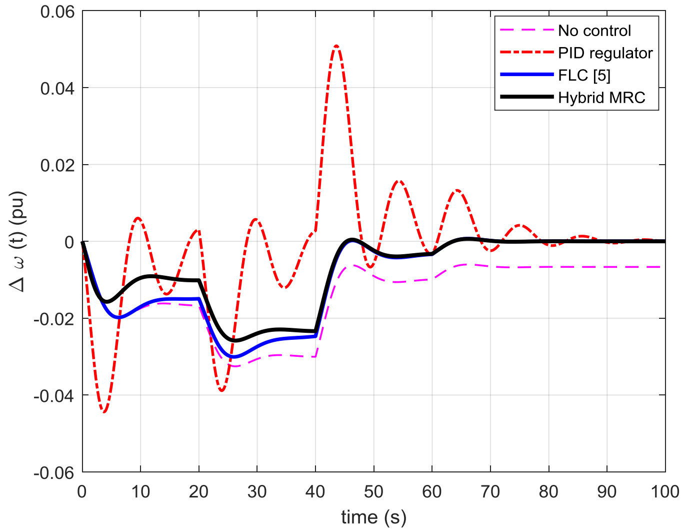

Fig. 12: A comprehensive comparison of the speed deviation dynamics resulting from four scenarios

V. CONCLUSIONS AND FUTURE WORK

This work has concentrated on designing and testing the applicability of a hybrid MRC speed controller to stabilize a hydropower plant. The simulation results obtained when compared with other speed controllers such as PID and fuzzy logic inference provided the confirmation that the MRC proposed in this study is completely able to tackle the speed stability of such a hydroelectric power plant. Typically, the studied novel controller which has two execution phases, i.e. MRC and optimization phases can effectively eliminate the speed deviations, assuring good control features for a modern hydropower facility.

A further look regarding this work is that the practical power systems should be taken into account to spread the application of the proposed hybrid MRC. This means that the future work needs to be implemented, focusing on increasing the complexity and size of the power system. In this context, a multi-area interconnected hydropower grid with various nonlinearities and uncertainties should be a promising potential control system. The success when applying the proposed hybrid MRC control strategy for such a large-scale electric power grid will absolutely confirm its superiority in dealing with the speed stabilization problem.

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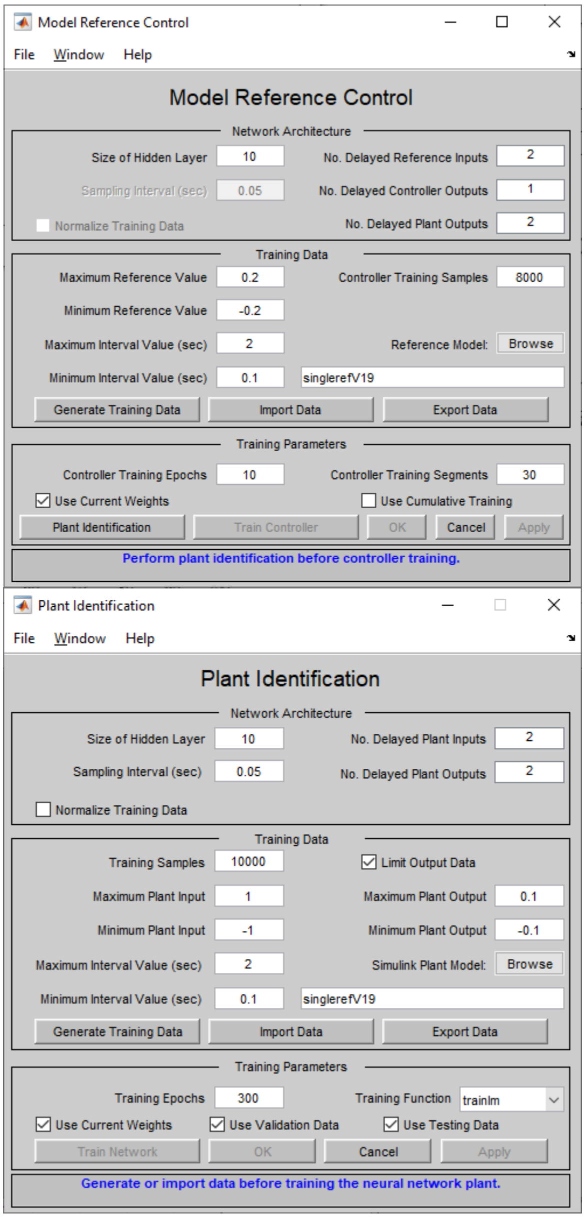
APPENDICES

MRC training parameters



PSO parameters: population size = 20, Maximum generations = 100.

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