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An Effective Speed Control Strategy for Synchronous Generators of an Interconnected Hydropower System

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ABSTRACT

Load-frequency control problem of an interconnected hydropower system directly relates to the speed control of all synchronous generators in the network. The major goal of the speed control for such a case of complex power grids is to stabilize the rotational speed of the hydraulic turbines, thereby eliminating the fluctuations of both the system frequency and tie-line power flow resulting from random and continuous load changes. The final aim is to bring the network back to a stable state after load change appearances. This paper introduces an effective control scheme as an integration of the conventional PID regulators and the particle swarm optimization technique in dealing with this speed stabilization. Various simulation scenarios with different cases of load changes and fitness functions will be presented using MATLAB/Simulink package to demonstrate the applicability of the proposed control methodology over the traditional PID and fuzzy logic – based control counterparts.

Key words: interconnected hydropower system, speed control, PID, fuzzy logic controller, PSO-based PID.

1. INTRODUCTION

It is obvious that hydropower still plays a vital role in electricity market in a lot of countries at present. New modern hydropower utilities have been recently set up to enhance quality related to control, stability and distribution of the electricity. Advanced techniques such as modern control strategies and optimization methods have also been applied for designing numerous complex hydropower systems.

In power systems, including interconnected hydropower grids, loads depending upon customers usually vary over time. Load changes may appear randomly and continuously at anywhere, causing the net frequency fluctuation. It is obvious the system frequency is proportional to the speed of synchronous generators and tie-line power in an interconnected power system. Therefore, from this point of view, control of generator speed should be strictly considered in order to stabilize the system frequency and the tie-line power flow at scheduled values, thereby bringing the system back to the stability with acceptable technical performances [1-5].

To cope with the speed regulation problem, the supplementary control strategies have been taken into account to tackle the mismatch between load in each area and generation. Due to the interconnection between a number of generation substations, a tie-line bias control scheme has been widely used for the speed regulation or load-frequency control. Traditionally, the integral regulators with ability to eliminate the steady-state of the control system were used at first. However, with the increasing complexity and stringent demands of power systems in practice, the conventional regulators should be replaced with better speed controllers. Even the PID (proportional-integral-derivative) regulators might have been considered to be traditional controllers, they are completely able to deal with the speed stability of an interconnected power system. They are highly suitable for the hydropower systems which comprise of hydraulic turbines characterized by a specific parameter namely starting-up time of water. This time constant refers to the time calculated for a hydraulic turbine from the zero level of fluid column accelerated to rated discharge [1-2]. Since the conveyance system of a hydropower utility normally composes of major elements such as reservoir, control gate, intake, penstock, wheel case and draft tube, it is highly difficult to cope with the starting-up time of water when modelling and controlling the power system in designing the speed control strategy. The PID controller with the optimization of parameters is completely able to tackle the speed control problem of the interconnected hydropower system. This work is to propose a speed control strategy applying the modified PID controllers, in which the particle swarm optimization (PSO) algorithm considered to be one of the most successful optimization mechanisms is utilized to effectively determine three coefficients of the PID controller [6-15]. The applicability of the proposed control methodology will be testified and compared with the traditional PID regulator tuned by auto-tuning method existed in MATLAB/Simulink and the fuzzy logic controller studied in [5].

This paper will be organized as follows. Section 2 presents research background related to this work including the mathematical model of a typical two-area interconnected hydropower system, the traditional speed regulators and the PSO algorithm. Next, Section 3 introduces the proposed control strategy in association with the PSO algorithm. Section 4 then provides numerical simulation results implemented in MATLAB/Simulink environment to demonstrate the effectiveness of the proposed control scheme. Finally, conclusions and discussions regarding this study will be presented in Section 5.

2. RESEARCH BACKGROUND

2.1 Two-area interconnected hydropower system model

A complex hydropower system typically comprises of several subsystems which are defined as generated stations or areas. Each area as shown in Figure 1 is formed by major components, namely a governor, a turbine and a generator.

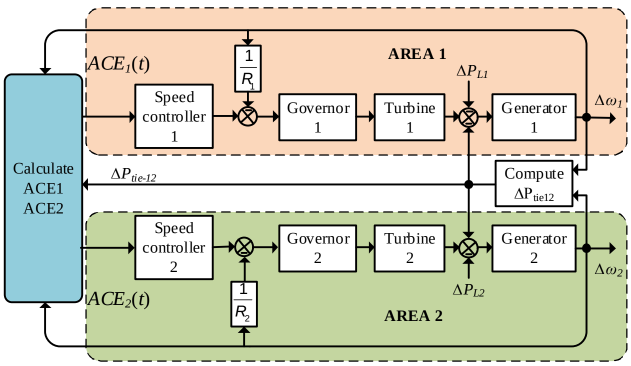

Figure 1: Traditional speed control strategy for a two-area interconnected hydropower system

According to [1], the transfer functions for these three units are as follows:

- The governor:

$$W_g(s)=\frac{\Delta g(s)}{\Delta x_e(s)}=\frac{1}{1+s.T_g} \tag{1}$$

- The hydraulic turbine:

$$W_t(s)=\frac{\Delta P_m(s)}{\Delta g(s)}=\frac{1-T_w s}{1+0.5T_w s} \tag{2}$$

- The generator together with load:

$$W_{Gen}(s)=\frac{\Delta\omega(s)}{\Delta P_m(s)-\Delta P_e(s)}=\frac{1}{Ms+D} \tag{3}$$

Each area with the above three components is connected with each other through transmission lines which are defined as tie-lines to exchange power. Whenever the load changes occur in areas, the generator speeds are deviated from the rated values, thus the tie-line power flow variations will also be resulted in the following relationship:

$$\Delta P_{12}(t)=T_{12}\left(\Delta\omega_1(t)-\Delta\omega_2(t)\right) \tag{4}$$

Where T_{12} is a synchronizing torque coefficient which is specified for each tie-line.

Technically, there always exists a primary control loop for each area implemented by a speed governor. This is a feedback control loop using a gain of *1/R* with *R* is the speed regulation factor characterized for each governor in dealing with the speed control of the synchronous generator. Since this control loop is not good enough to bring the power system back to the stable state, it needs one more compensated control loop named secondary counterpart. In such a control loop, a speed controller will be used to further improve control performances of the system. This type of speed controller will be presented in the next sections.

2.2. Traditional speed regulators

Speed control of the synchronous generators to stabilize the net frequency of an interconnected hydropower system is one of the most vital control problems. Traditionally, the integral regulators were used at first to force the steady state error of the system to be zero. In [1], the steady state errors relating to the speed deviations in Figure 1 are calculated as follows:

$$\Delta\omega_i(t)=\frac{-\Delta P_{L,i}}{\left(\frac{1}{R_1}+\frac{1}{R_2}\right)+\left(D_1+D_2\right)}\quad i=1,2 \tag{5}$$

According to the tie-line bias control strategy, the ACE signal is used as the control signal of the speed controller. This control signal is defined as:

$$ACE_i(t)=\Delta P_{12}^i(t)+B_i\Delta\omega_i(t) \tag{6}$$

Where $\Delta P_{12}^i(t)$ and $\Delta\omega_i$ are tie-line power flow deviation and speed change, respectively. The factor B_i is denoted as:

$$B_i=\frac{1}{R_i}+D_i \tag{7}$$

The combination of tie-line power and speed deviations forms the control signal to be the input of the integral regulator as presented below:

$$u_i(t)=K_{I,i}\int ACE_i(t)dt \tag{8}$$

The output signal $u_i(t)$ is then taken to the governor to execute compensated control. This is defined as the secondary control loop for each area in dealing with the speed regulation of the interconnected power system.

Due to poor control performances resulting from the integral regulators, PI and PID candidates have been applied for the speed control problem. It is found that a lot of practical electrohydraulic governors are equipped with the PID regulators which are able to technically allow the system responses fast enough with the changes in load demands or other parameters. The principle of the PID controller utilized in this perspective is:

$$\begin{aligned}u_i(t)&=K_{P,i}.ACE_i(t)+K_{I,i}\int ACE_i(t)dt+K_{D,i}\frac{dACE_i(t)}{dt}\\&=K_{P,i}\left(ACE_i(t)+\frac{1}{T_{I,i}}\int ACE_i(t)dt+T_{D,i}\frac{dACE_i(t)}{dt}\right)\end{aligned} \tag{9}$$

Where $K_{P,i}$, $K_{I,i}$ and $K_{D,i}$ denote the proportional, integral and derivative factors, respectively. They need to be tuned by applying an effective method to make sure that the system can obtain good control quality.

2.3. An overview of particle swarm optimization technique

Particle swarm optimization (PSO) technique has been considered to be one of the most effective bio-inspired optimization methods [7-15]. This optimization mechanism is inspired from social behavior of animal groups such as birds and fish. Naturally, a swarm of birds tends to fly over space to search for food. They are assumed to fly randomly with arbitrary velocities from any locations in the space. The final goal is to find exactly the destination of food.
Inspired from this natural behavior, an optimization mechanism is launched following several steps below:

Step 1: Initialization.
Consider a swarm with n particles corresponding to n variables which need to be optimized. Also, it is supposed that there are m swarms which are randomly initialized for this optimization mechanism. Here, the ith swarm is characterized by a position vector and a velocity vector with n elements as indicated below:

$$\bar{x}_i = \begin{bmatrix} x_{i,1} \\ x_{i,2} \\ \cdots \\ x_{i,n} \end{bmatrix}; \quad \bar{v}_i = \begin{bmatrix} v_{i,1} \\ v_{i,2} \\ \cdots \\ v_{i,n} \end{bmatrix} \tag{10}$$

Step 2: Execution of optimization iterations.
In this step, it is necessary to execute N optimization iterations with two main phases:
(i) *Evaluate the fitness or objective function*.
A fitness function can be defined in various perspectives. One of these cases is:

$$f_{obj} = \int_0^{\tau} |e(t)| dt \tag{11}$$

Where e(t) is the error signal of the desired and the real outputs of the considering control system. This function may refer to the IAE (integral absolute error). The initial values defined in two vectors (10) should be evaluated depending upon the fitness function as indicated in the PSO mechanism.
(ii) *Update the two vectors* (10)
Assuming that both position and velocity vectors at the jth iteration presented in (10) are able to be updated following two equations given below:

$$\bar{v}_{i,j+1} = w.\bar{v}_{i,j} + c_1\left(p_{best,ij} - \bar{x}_{i,j}\right) + c_2\left(g_{best,ij} - \bar{x}_{i,j}\right) \tag{12}$$

$$\bar{x}_{i,j+1} = \bar{x}_{i,j} + \bar{v}_{i,j+1}; i = 1, 2, \ldots., m; j = 1, 2, \ldots., N \tag{13}$$

Where c_1, c_2 and w denote weighting factors.
After updating the two vectors as shown in (12) and (13), the evaluation of the fitness function is again executed. Then, the local best vectors and global best vectors are found. They are recorded in each iteration.

Step 3: Testify the termination criteria
In the PSO mechanism, beside the maximum number of iterations N, it is necessary to define a stopping or termination criterion. It is normally defined as an optimization error. If one of the termination criteria is met, the optimization mechanism is terminated immediately.

3. PROPOSED SPEED CONTROL STRATEGY

Based on the traditional control diagram as shown in the previous section, an improved control strategy is presented in Figure 2. In this control diagram, an effective optimization technique, such as PSO, is used to optimize parameters of the speed controllers applied for the two-area hydropower system. With a PID controller, three factors need to be optimized based on the PSO algorithm, including *Kp*, *Ki* and *Kd*. By applying the PSO algorithm, the PID regulators having three factors will be successfully tuned without considering parameters of all components in the system. This means that the interconnected power system may not require whole known parameters because the PSO mechanism may only execute depending upon a suitable fitness function. Instead, there are able to have a number of unknown parameters, and this phenomenon is highly meaningful for the system having the practical loads characterized by random and continuous changes. They will be verified in the next section of the paper.

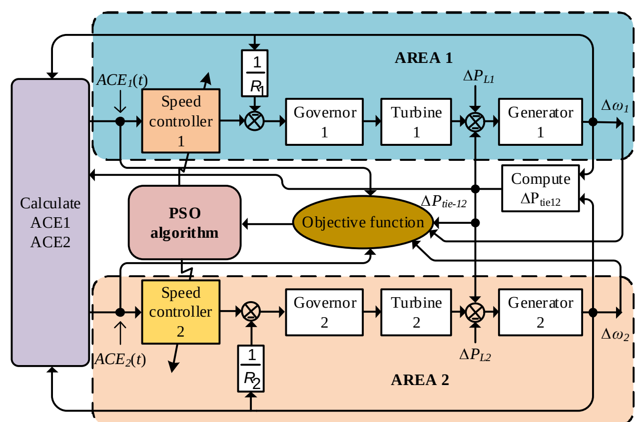

Figure 2: Proposed speed control strategy for a two-area interconnected hydropower system

4. SIMULATION RESULTS AND DISCUSSIONS

To verify the feasibility of the proposed control strategy, this section presents three simulation scenarios corresponding to the two-area interconnected hydropower system shown in Figure 2. The typical simulation parameters used for the proposed model are found in [1].

(1) **Scenario 1**: The load changes are assumed to be occurred in two areas as step variations (see Figure 3) and the fitness function for the PSO is:

$$f_{obj\_1} = \int_0^{\tau} \left(\begin{array}{l} |\Delta\omega_1(t)| + |\Delta\omega_2(t)| + |\Delta P_{12}(t)| \\ + |ACE_1(t)| + |ACE_2(t)| \end{array} \right) dt \rightarrow \min \qquad (14)$$

Where τ denotes the time simulation. The above objective function is defined in association with the IAE (integral of absolute error) criterion. Using such an objective function it is clear the deviations of both the net frequency and tie-line power flow can be eliminated successfully.

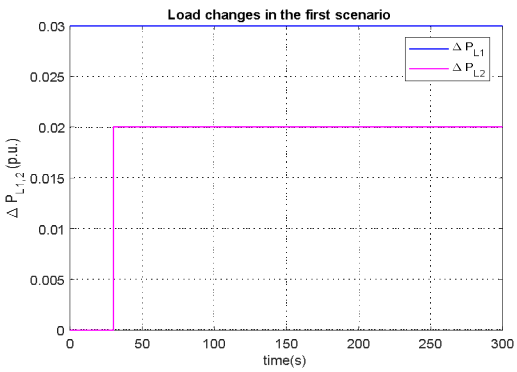

Figure 3: Load changes in the first and second scenarios

(2) **Scenario 2**: The load changes are also similar to the first scenario, however, the fitness or objective function is related to the ITSE (integral time square error) as shown below:

$$f_{obj\_2} = \int_0^{\tau} \left[\begin{array}{l} (\Delta\omega_1(t))^2 + (\Delta\omega_2(t))^2 + (\Delta P_{12}(t))^2 \\ + (ACE_1(t))^2 + (ACE_2(t))^2 \end{array} \right] tdt \rightarrow \min \ (15)$$

(3) **Scenario 3**: The load changes are randomly and continuously variated as shown in Figure 10 and Figure 11. The fitness function defined in (15) is also utilized in this scenario.

The process of simulation implementation is based on the above three cases and considered for the three speed controllers, i.e. traditional PID, PSO-based PID and fuzzy logic controller (FLC) reported in [5]. Simulations results are depicted in Figures 4-13. The convergences of the PSO algorithm applied for optimizing coefficients of the two PID controllers corresponding to two areas are presented in Figures 3-5. It is noted that there are 6 parameters need to be optimized according to the PSO algorithm. Also, the maximum iterations are 100 for such optimization mechanism. The Figures 3-5 are showing the good convergence of the PSO after about twenty iterations. Figures 7-9 illustrate the dynamic responses of the PSO-based PID controllers in comparison with the traditional PID regulators when solving the speed stabilization. It is noted that the traditional PID regulators have been tuned depending upon the automatic tool in Simulink. From Figures 7-9, it is obvious the control performances obtained from the proposed PID regulators are much better than the traditional counterparts. For instance, in Figure 9, the dynamic responses of output speed fluctuations resulting from the proposed PSO-based PID controllers show that these oscillations are successfully eliminated with good control indices, such as small overshoots, low undershoot, short transient time and no steady-state errors. Meanwhile, the conventional PID regulators, even determined by an automatic tuning tool in MATLAB/Simulink, they are not able to achieve good control performances. The simulation results also reveal that the fitness function provided in (15) obtained significantly better control performances compared to the first one indicated in (14).

To confirm the superiority of the proposed PSO-based PID controllers in dealing with the speed control problem, this paper also presents a comparison with the fuzzy logic controllers studied in [5]. Even these modern controllers are able to get better control performances for a single control area, however, a comprehensive evaluation for the two-area interconnected hydropower system may confirm that these cannot obtain the similar quality compared to the PID regulators, especially for the proposed PSO-PID counterparts. Figures 10-13 for the third simulation scenario with two random and continuous load changes in two areas verify the better control performances of the proposed speed controllers. Figure 13 shows the objective function calculated according to (15), completely being able to verify the superiority of the PSO-based PID regulator in comparison with the fuzzy logic controller. It is a confirmation of the feasibility when applying the PSO-based PID regulator for solving the speed problem of an interconnected power system.

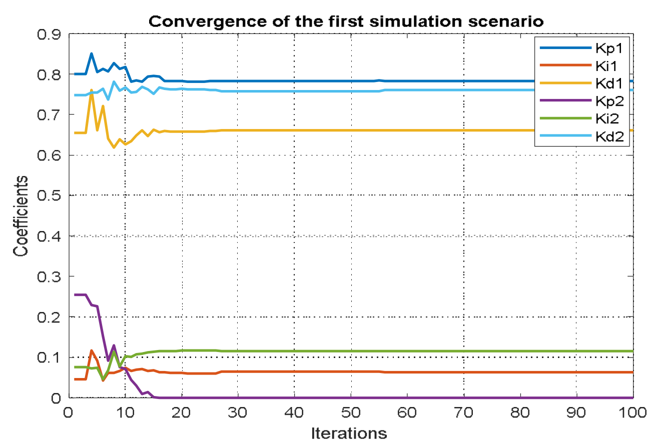

Figure 4: The convergence of the PSO algorithm for the first scenario

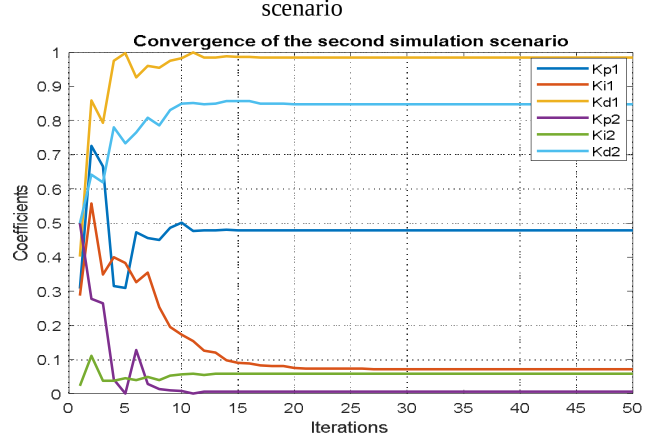

Figure 5: The convergence of the PSO algorithm for the second scenario

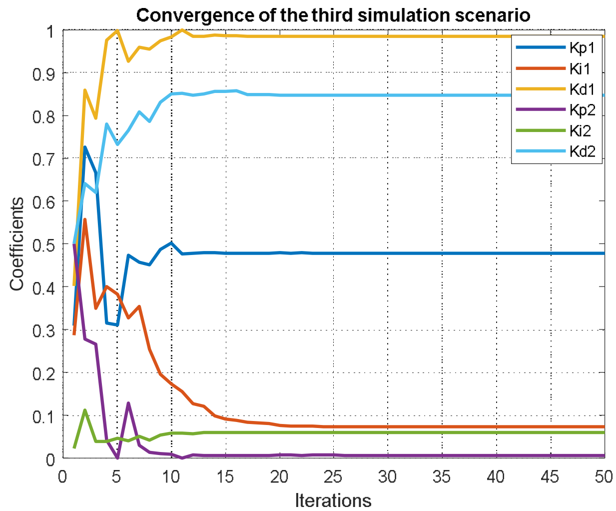

Figure 6: The convergence of the PSO algorithm for the third scenario

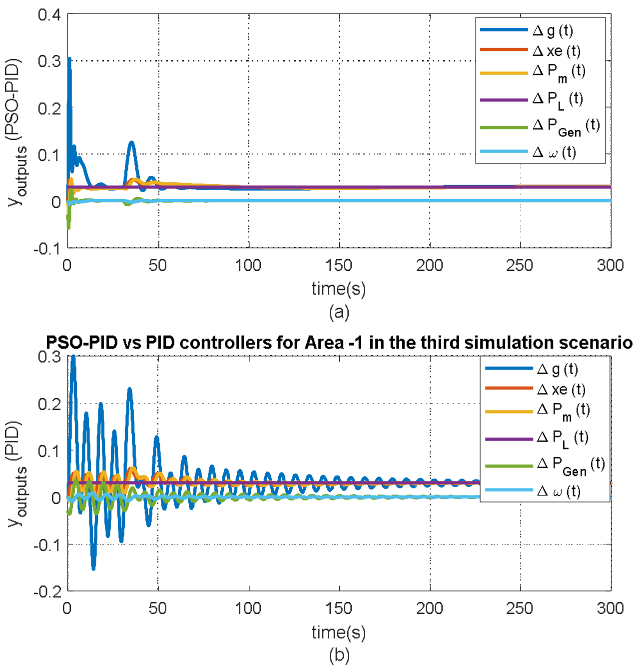

Figure 7: Comparison between PSO-based PID and conventional PID controllers for the first scenario – Area 1
(a) PSO – based PID controllers
(b) Conventional PID regulators

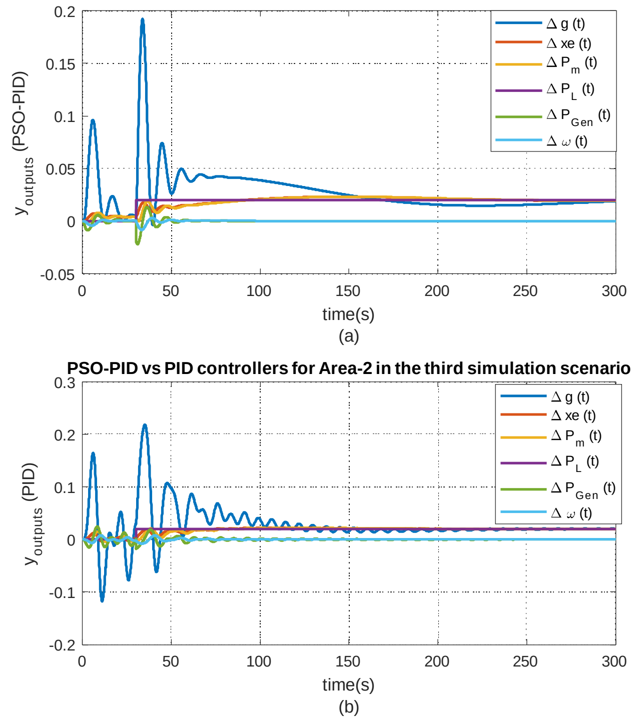

Figure 8: Comparison between PSO-based PID and conventional PID controllers for the first scenario Area - 2
(a) PSO – based PID controllers
(b) Conventional PID regulators

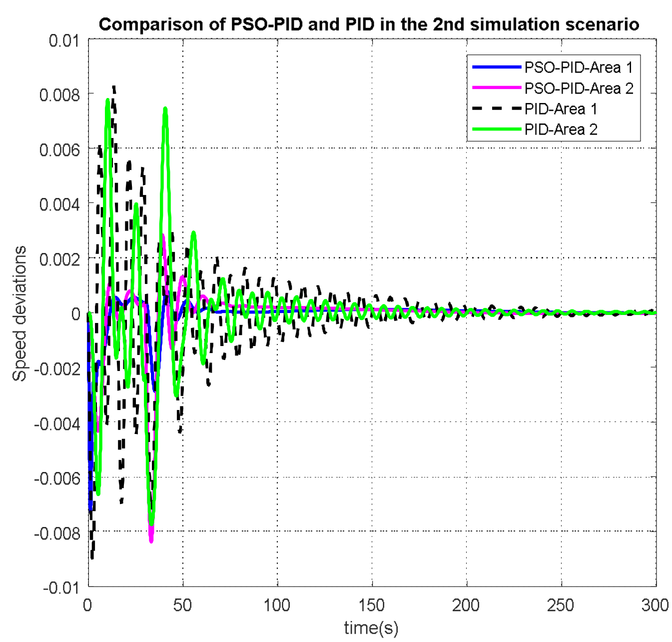

Figure 9: Comparison of dynamic speed deviation responses between PSO-PID and conventional PID controllers for the second scenario

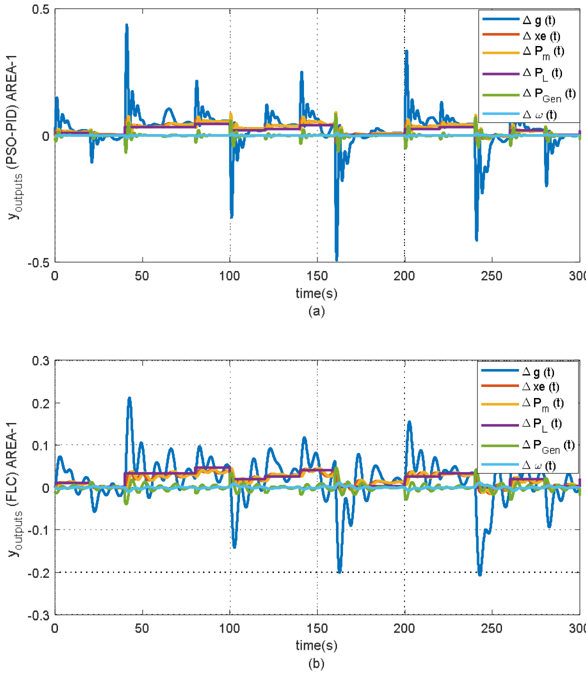

Figure 10: Simulation results Area 1 in the third scenario
(a) PSO – based PID controllers
(b) Fuzzy logic controllers

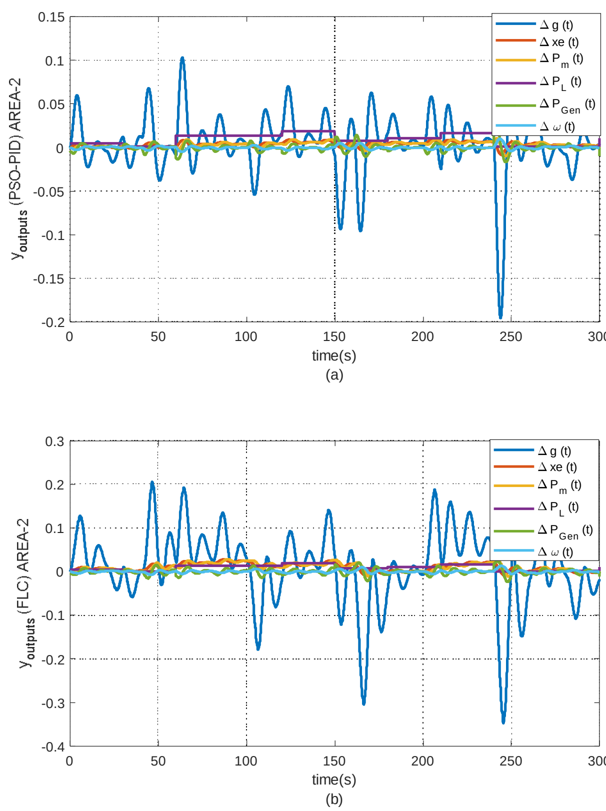

Figure 11: Simulation results area 2 in the third scenario
(a) PSO – based PID controllers
(b) Fuzzy logic controllers

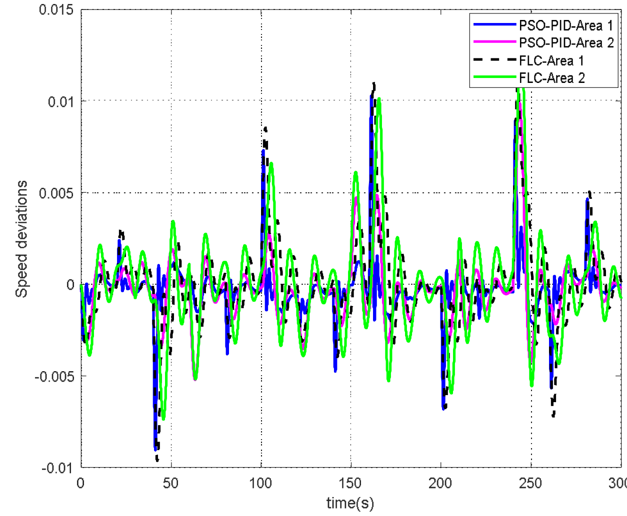

Figure 12: A comparison of the PSO-based PID and FLC controllers regarding the speed deviations in the third scenario

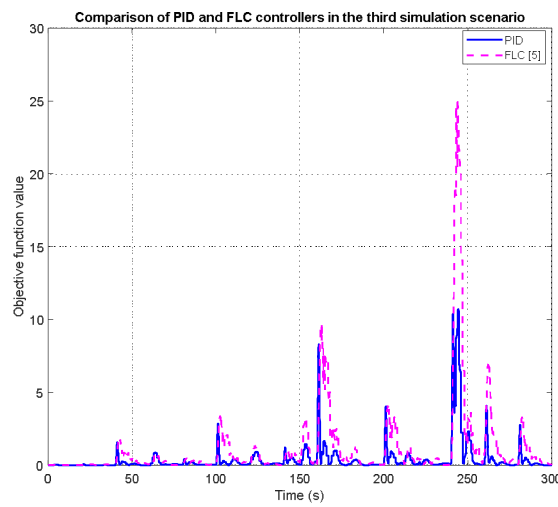

Figure 13: Objective functions for the third scenario

5. CONCLUSIONS AND DISCUSSIONS

This paper has presented an effective speed control strategy in dealing with the load-frequency control or speed stabilization of an interconnected power system. The proposed control method is simply related to an integration between a traditional PID regulator and a good optimization technique, e.g. PSO. However, it is confirmed that this combination has been able to obtain better control performances in comparison with those of the conventional PID regulators as well as the fuzzy logic-based controllers. Therefore, it is highly suitable for solving the speed control as an effective part of power system control, stability and distribution.

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