ROBUST AND OPTIMAL FUZZY LOGIC PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLERS DESIGN BY BEE ALGORITHM FOR HYDRO-THERMAL SYSTEM

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This paper proposes a robustness and an optimum of the fuzzy logic-proportional integral derivative (FLPID) controllers for automatic generation control (AGC) of a two area interconnected hydro-thermal system and an application of bee algorithm (BA) in order to design FLPID controllers. Traditionally, membership functions (MF) and control rules (CR) of the fuzzy logic controller (FLC) were achieved by trial and error methods of designers. To solve this problem, BA was proposed to concurrently tune PID gains, MF and CR of the FLPID controllers to minimize frequency deviations and tie-line power deviations of power system. Simulation results clearly showed that the performance and the robustness of the optimal FLPID controllers were superior to the conventional PID and the FLPID controllers in terms of settling time and overshoot.

1. INTRODUCTION

Normally, a large scale electrical power systems consists of interconnected control areas or regions, which represent coherent groups of generators, and AGC is very important for power system operation and control in order to supply sufficient and reliable electric power with good quality. The power system has many dynamic characteristics. This means dynamic characteristics can be affected by area load changes and abnormal conditions, such as outages of generation and various system parameters. These lead to have unpredictable variations in frequency and scheduled tie-line power flows between areas. These problems are corrected by controlling the frequency, which is defined as a regulation of the power output of generators within a prescribed area [1].

In a literature review, it was found that there were many works in the area of AGC which concerned about interconnected thermal systems but there were just a

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few works about AGC of interconnected hydro-thermal system involving thermal and hydro subsystem of widely different characteristics [2−4]. The modern hydro-thermal, reheat type turbines and electric governors [5] have been used. A few investigations have been reported for AGC of interconnected hydro-thermal system in the continuous-discrete mode strategy with reheat type turbines and electric governors [6].

The FLC has a number of distinguish advantages over conventional controllers. Since, it is not so sensitive to the variation of system structure, parameters and operation points can be easily implemented in a large scale nonlinear system. Furthermore, FLC is expected as one of a sophisticated technique that is easy to design and to implement. Nevertheless, a determination of MF and CR is an inevitable problem in a design. To achieve satisfied MF and CR, designers' experiences are necessary. The most straightforward approach is to define MF and CR by studying an operating system or an existing controller. Therefore, effective methods for tuning MF and CR in order to minimize the output error or maximize the performance index without trial and error methods are significantly required.

In last few years, an application of BA to solve combinatorial optimization problems has been proposed [7, 8]. In addition, there are a few papers for designing FLPID [9,10]. Therefore, main objectives of this paper are the following:

1) To evaluate the dynamic response considering the PID controllers in the hydro-thermal system. The PID gains are optimized using integral absolute error (IAE).

2) To propose BA to optimize PID gains, MF and CR of the FLPID controllers.

3) To compare the optimal FLPID controllers, the FLPID controllers and the conventional PID controllers by using settling time and overshoot.

4) To consider the robustness of the control system under system parameter variations and load changes.

2. PROBLEM FORMULATION

The interconnected power system is divided into two control areas which are connected by tie-line. In each control area, all generators are supposed to constitute a coherent group. A two area interconnected hydro-thermal system shown in Fig. 1 is used for an investigation in this study. It is assumed that both areas in the power system have the same magnitudes of load disturbances.

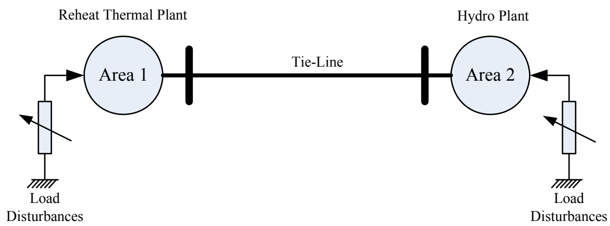


Fig. 1 – Schematic diagram of the two-area interconnected hydro-thermal system.

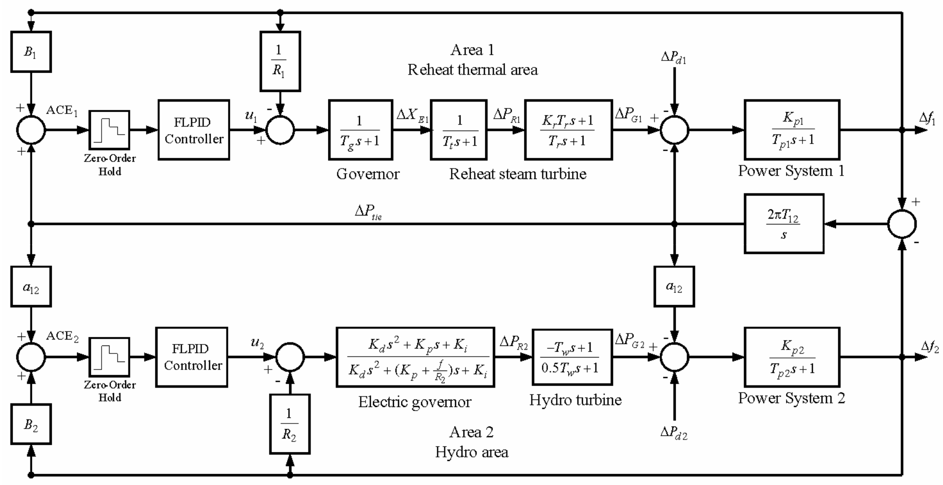


Fig. 2 – Two-area interconnected hydro-thermal system with digital controllers.

Nomenclature:
f = Nominal system frequency, i = Subscript referred to area i (1, 2)
P_{ri} = Area rated power, H_i = Inertia constant, ΔP_{di} = Incremental load change,
ΔP_{Gi} = Incremental generation change, ΔP_{Ri} = Incremental governor change,
ΔP_{tie} = Tie-line power, ΔX_{Ei} = Incremental change in governor value position,
u_i = Control signal, T_{12} = Synchronizing coefficient, K_r = Reheat constant,
T_g = Steam governor time constant, T_t = Steam turbine time constant,
T_r = Reheat time constant, B_i = Frequency bias constant, T_w = Water starting time,
R_i = Governor speed regulation parameter, ACE_i = Area control error,
K_d, K_p, K_i = Electric governor derivative, proportional and integral gains, respectively, J = Cost Index,

$$D_i = \Delta P_{di} / \Delta f_i \qquad T_{pi} = 2H_i / (f \times D_i) \qquad K_{pi} = 1/D_i \qquad a_{12} = -P_{r1}/P_{r2}.$$

The detailed block diagram of an interconnected hydro-thermal system in a continuous-discrete mode strategy with reheat and electric governor is given in Fig. 2 and system parameters are given in a nomenclature. The state space equations of this power system are written in continuous time domain as following:

$$x = Ax(t) + Bu(t) + Ld(t), \tag{1}$$

where A is a system matrix, B is an input and L is disturbance distribution matrices and $x(t)$, $u(t)$ and $d(t)$ are state, control and load changes disturbance vectors, respectively as following:

$$x(t) = [\Delta f_1 \quad \Delta P_{G1} \quad \Delta P_{R1} \quad \Delta X_{E1} \quad \Delta P_{tie} \quad \Delta f_2 \quad \Delta P_{G2} \quad \Delta P_{R2}]^{\mathrm{T}}, \tag{2}$$

$$u(t) = [u_1 \quad u_2]^{\mathrm{T}}, \tag{3}$$

$$d(t) = [\Delta P_{d1} \quad \Delta P_{d2}]^{\mathrm{T}}, \tag{4}$$

where Δ denotes a deviation from nominal values, suffix 1 is used for the thermal area and suffix 2 is used for the hydro area.

The system output, which depends on an area control error (ACE) shown in Fig. 2, is given as:

$$y(t) = \begin{bmatrix} y_{1(t)} \\ y_{2(t)} \end{bmatrix} = \begin{bmatrix} ACE_1 \\ ACE_2 \end{bmatrix} = Cx(t), \tag{5}$$

$$ACE_i = \Delta P_{tie,j} + B_i \Delta f_i, \quad i = 1,2 \tag{6}$$

where C is an output matrix.

In this paper, the considered system is controlled by using the conventional PID controllers, the FLPID controllers and the optimal FLPID controllers.

3. FUZZY LOGIC-PROPORTIONAL INTEGRAL DERIVATIVE (FLPID) CONTROLLERS

The FLPID controllers to solve this problem, as presented in Fig. 3, consist of the FLC and the conventional PID controllers, connecting in series.

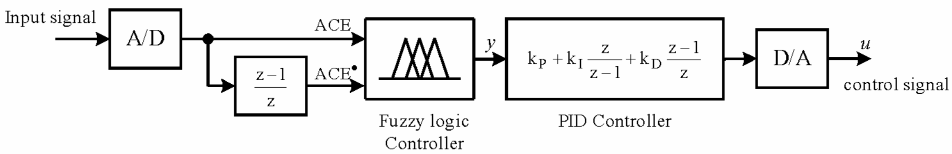


Fig. 3 – Structure of FLPID controllers in discrete mode.

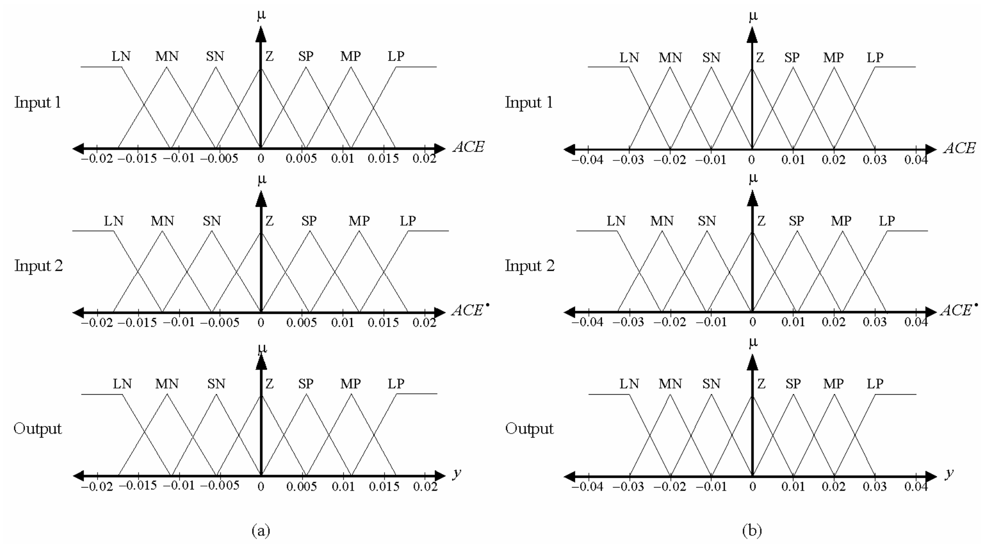
The FLC has two input signals, namely, ACE and ACE• and then the output signal (y) of FLC is the input signal of the conventional PID controllers. Finally, the output signal from the conventional PID controllers called the control signal (u) is used for controlling AGC in the interconnected hydro-thermal system. By taking the system output, the control signal for the FLPID controllers is given by:

$$u(z) = -\left(k_P y + k_I \frac{z}{z-1} y + k_D \frac{z-1}{z} y \right). \tag{7}$$

The MF of FLC, shown in Fig. 4, consists of three MF. Each MF has seven memberships, comprising two trapezoidal and five triangular memberships. In case of two-inputs and one-output, CR can be shown graphically in a table where every cell shows the output MF of CR as a relationship between input 1 and 2. The CR are built from ***if-then*** statement (if input 1 and input 2, then output 1). Figure 5 shows the appropriate CR in this study. Let us consider the third row and the forth column in Fig. 5, that means, if ACE is SN and $\mathrm{ACE}^{\bullet}$ is Z then y is SN.

For designing of the FLPID controllers, PID gains have only three parameters to tune including a proportional gain, an integral gain and a derivative gain. The MF and CR have many parameters to tune. The MF has 2 trapezoidal and 5 triangular memberships. So that, there are 23 parameters to tune. For the FLC with two-inputs and one-output there are 69 parameters to tune.

In the CR list, for two-inputs and one-output FLC, CR must be specified in seven numbers (1–7), 1: LN, 2: MN, 3: SN, 4: Z, 5: SP, 6: MP, and 7: LP. Then, there are 49 parameters to tune. However, the total parameters for two-inputs and one-output the FLPID controller are 121 (3+69+49 = 121) tuning parameters.



LN: large negative; MN: medium negative; SN: small negative;Z: zero;
SP: small positive; MP: medium positive;LP: large positive.
Fig. 4 – Membership function of FLPID controllers; a) reheat thermal area; b) hydro area.

					$\dot{ACE}$			
		LN	MN	SN	Z	SP	MP	LP
	LN	*LN*	*LN*	*LN*	*MN*	*MN*	*SN*	*Z*
	MN	*LN*	*LN*	*LN*	*MN*	*SN*	*Z*	*SP*
	SN	*LN*	*LN*	*LN*	*SN*	*Z*	*SP*	*MP*
ACE	Z	*MN*	*MN*	*SN*	*Z*	*SP*	*MP*	*MP*
	SP	*MN*	*SN*	*Z*	*SP*	*LP*	*LP*	*LP*
	MP	*SN*	*Z*	*SP*	*MP*	*LP*	*LP*	*LP*
	LP	*Z*	*SP*	*MP*	*MP*	*LP*	*LP*	*LP*

Fig. 5 – The CR for non-optimal FLPID controllers.

4. **BEE ALGORITHM**

The BA was proposed by Karaboga [8] for optimizing numerical problems. The algorithm mimics the food foraging behavior of swarms of honey bees. The random optimization algorithm, which is obtained by honey bees' method, is simple, robustness and popularity. The procedure of BA is given as below:

Step 1: Generate randomly initial populations of n scout bees for parameters of k_P, k_I, k_D, MF and CR. These initial populations must be feasible candidate solutions that satisfy constraints. Set $NC = 0$.

Step 2: Evaluate a fitness value of initial populations.

Step 3: Select m best sites for neighborhood search.

Step 4: Separate the m best sites in to two groups, the first group has e best sites and another group has m-e best sites.

Step 5: Set a size of neighborhood search of each best sites (patch size, ngh).

Step 6: Recruit bees for selected sites (more bees for the best e sites).

Step 7: Select the fittest bees from each patch.

Step 8: Check a stopping criterion. If satisfied, terminate the search, else $NC = NC+1$.

Step 9: Assign the n-m remaining bees to random search.

Step 10: New population of scout bees. Go to Step 2.

where NC is number of iteration, ngh is neighborhood size [9].

5. IMPLEMENTATION AND RESULTS

Simulations were performed by using the conventional PID, the non-optimal FLPID and the optimal FLPID controllers applied to a two-area interconnected hydro-thermal system as shown in Fig. 2, when applying 0.01 p.u.MW step load disturbance into both areas. The same system parameters are given in Appendix. All models were simulated in Matlab. According to experiments, the following parameters of the BA method are used: n = 10, m = 5, e = 2, ne = 50, ngh = 0.01, and NC = 20,000. In the optimization, the minimisation of the integral absolute error (IAE) of the frequency deviation in both areas and of the power deviation at tie-line is selected as the performance index. Accordingly, the objective function J is set by:

$$\text{Minimize } J = \int_0^{50} \left(\left|\Delta f_1\right| + \left|\Delta f_2\right| + \left|\Delta P_{tie}\right|\right) \mathrm{d}\, t. \tag{8}$$

After tuning, the optimal FLPID controllers have the optimized PID gains shown in table 1. The optimized MF of input 1, 2 and output are depicted in Fig. 6 and the optimized CR are given in Fig. 7.

Table 1

Tuned parameters of PID controllers

Area	k_p	k_I	k_D
Thermal area	1.0602	0.4793	0.6316
Hydro area	0.2929	0.1828	0.0905

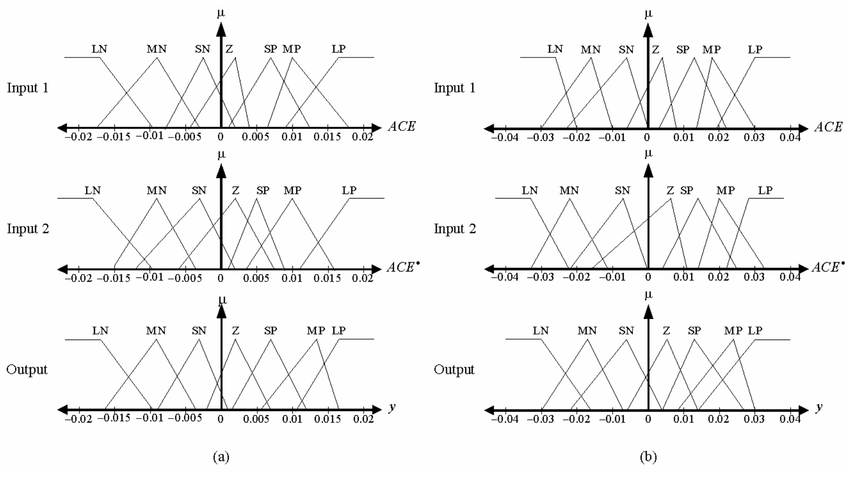


Fig. 6 – Optimized MF for optimal FLPID controllers:
a) reheat thermal area; b) hydro area.

		$ACE^{\bullet}$						
		LN	MN	SN	Z	SP	MP	LP
ACE	LN	*LN*	*LN*	*LN*	*LN*	*MN*	*SN*	*Z*
	MN	*LN*	*LN*	*LN*	*LN*	*MN*	*Z*	*SP*
	SN	*LN*	*LN*	*LP*	*SN*	*MP*	*SP*	*MP*
	Z	*MN*	*MN*	*SP*	*Z*	*LP*	*MP*	*MP*
	SP	*MN*	*SN*	*Z*	*MP*	*LP*	*LP*	*LP*
	MP	*SN*	*Z*	*SP*	*MP*	*LP*	*LP*	*LP*
	LP	*Z*	*SP*	*MP*	*MP*	*LP*	*LP*	*LP*

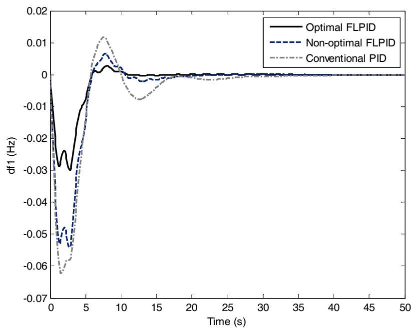
(a)

		$ACE^{\bullet}$						
		LN	MN	SN	Z	SP	MP	LP
ACE	LN	*LN*	*LN*	*LN*	*MN*	*LN*	*SN*	*Z*
	MN	*LN*	*LN*	*LN*	*MN*	*SN*	*Z*	*SP*
	SN	*LN*	*LN*	*MN*	*MN*	*LN*	*SP*	*MP*
	Z	*MN*	*MN*	*MN*	*Z*	*Z*	*MP*	*MP*
	SP	*MN*	*SN*	*Z*	*SP*	*LP*	*LP*	*LP*
	MP	*SN*	*Z*	*SP*	*MP*	*LP*	*LP*	*LP*
	LP	*Z*	*SP*	*MP*	*MP*	*LP*	*LP*	*LP*

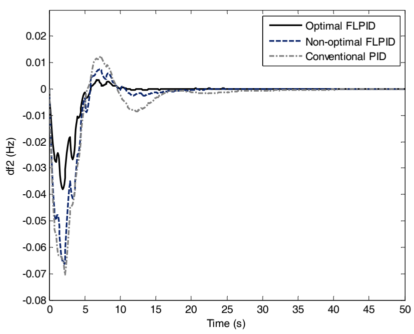
(b)

Fig. 7 – The optimized CR for optimal FLPID controllers:
a) reheat thermal area; b) hydro area.

The frequency deviations of both areas after a sudden load change are shown in Fig. 8 and Fig. 9. The non-optimal FLPID controllers highly improve the system performance compared to with the conventional PID controllers. Moreover, the optimal FLPID controllers are significantly superior to the conventional PID controllers. It gives a better performance than the non-optimal FLPID controllers. The settling time and overshoot are reduced considerably.

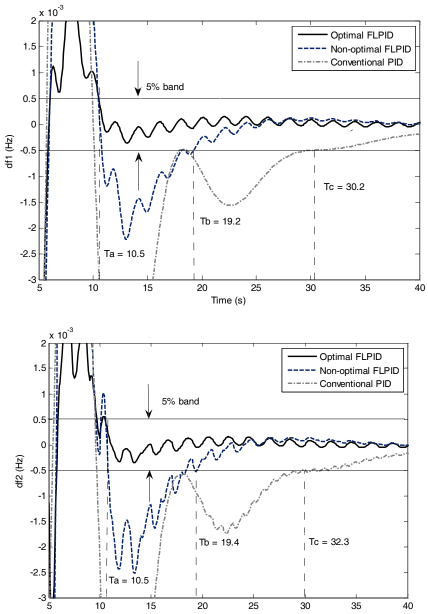


(a)



(b)

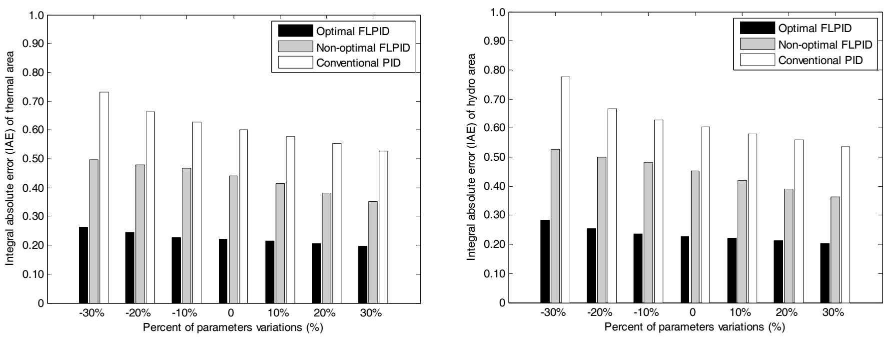
Fig. 8 – The frequency deviation in both areas for different controller types:
a) reheat thermal area; b) hydro area.



(a)

(b)

Fig. 9 – The frequency deviation of both areas in a larger scale and settling time for optimal FLPID (T_a) ,Non-optimal FLPID (T_b), and conventional PID (T_c); a) reheat thermal area; b) hydro area.



(a) (b)

Fig. 10 – Comparison results of IAE of both areas under parameters variations: a) reheat thermal area; b) hydro area.

Next, the robustness of each controller against system parameters variations are evaluated by IAE. These values are calculated under an occurrence of load disturbances while all system parameters are varied from -30% to 30% of nominal values. The comparison results shown in Fig. 10 illustrate values of IAE of both areas. It illustrates that values of IAE in case of the optimal FLPID controllers are rarely changes. This clarifies that the robustness of the optimal FLPID controllers against parameters variations is superior to the conventional PID and the non-optimal FLPID controllers.

Finally, frequency control effects of the conventional PID, the non-optimal FLPID and the optimal FLPID controllers are evaluated under different random step load variations which are applied to both areas as shown in Fig. 11. The results of frequency deviations of both areas is shown in Fig. 12. The frequency deviations are improved considerably by the optimal FLPID controllers in comparison with the case of the conventional PID and the non-optimal FLPID controllers.

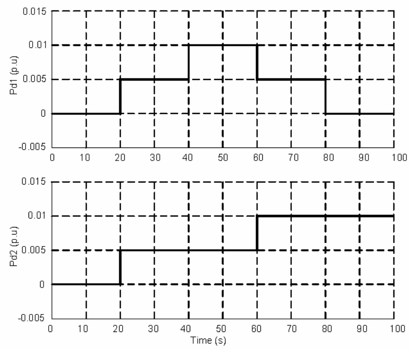
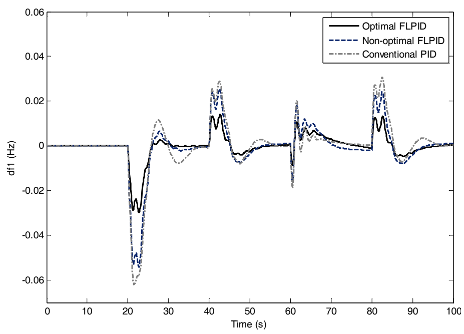
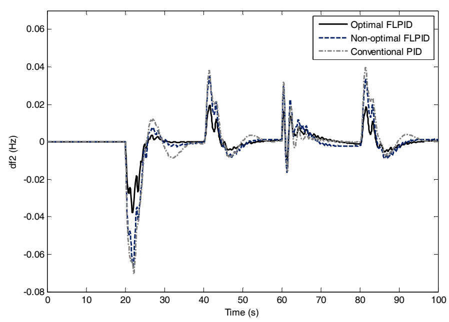


Fig. 11 – Random step load change in thermal and hydro areas.



(a)



(b)

Fig. 12 – Time response of Δf_1 and Δf_2 under random load change: a) reheat thermal area; b) hydro area.

6. CONCLUSIONS

In this paper, an application of BA has been used for developing robust and optimal FLPID controllers for AGC of a two-area interconnected hydro-thermal system. The proposed technique for designing the FLPID controllers helps designers to save time when comparing with conventional trial and error design procedures. Another benefit of this approach is that it does not require experts for a design of FLC. Finally, simulation results show that the optimal FLPID controllers perform significantly better than other controllers in settling time, overshoot and IAE. Consequently, the optimal FLPID controllers are effective, efficient and robust over a wide range of operating conditions.

APPENDIX

In the following, most parameters of the two-area interconnected hydro-thermal system in figure 2 as in [6] and some of parameters have been modified: $f = 60$ Hz, $T_r = 10.0$ s, $T_t = 0.3$ s, $T_w = 1.0$ s, $T_g = 0.08$ s, $K_r = 0.5$, $K_p = 1.0$, $K_d = 4.0$, $K_i = 5.0$, $H_1 = H_2 = 5$, $R_1 = R_2 = 2.4$ Hz/p.u.MW, $P_{tie,\max} = 200$ MW, $P_{r1} = P_{r2} = 2000$ MW, $D_1 = D_2 = 8.33 \times 10^{-3}$ p.u.MW/Hz.

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