Fractional Order Fuzzy PID Controller for Automatic Generation Control of Power Systems

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ABSTRACT

In the continuously growing size and structure of the contemporary power system, when dealing with load demand uncertainties, the use of intelligent Automatic Generation Control (AGC) strategy is very much necessary for satisfactory operation of the power system. In this work, a Hybrid Adaptive Differential Evolution and Pattern Search (hADE-PS) optimized Fractional Order Fuzzy PID (FOFPID) controller is suggested for AGC of power systems. At first, a non-reheat type two-area system is considered, and the improvement of the proposed approach over Bacteria Foraging Optimization Algorithm (BFOA), Teaching Learning Based Optimization (TLBO), Jaya Algorithm (JA), Genetic Algorithm (GA), and Hybrid BFOA and Particle Swarm Optimization Algorithm (hBFOA-PSO) for the identical power systems has been demonstrated. The AGC scheme was then extended to an interconnected reheat type power system and a two-area six-unit system. The results are compared with Firefly Algorithm (FA), Symbiotic Organism Search Algorithm (SOSA), and Artificial Bee Colony (ABC) for the second test system; and TLBO, Hybrid Stochastic Fractal Search and Local Unimodal Sampling (hSFS-LUS), ADE, and hADE-PS tuned PID for the third test system. Finally, the robustness of the suggested controller is examined under varied conditions. Examination of results confirms the improved performance of hADE-PS tuned FOFPID over other controllers with fewer error measures and better undershoot/overshoot/settling times of frequency/tie-line power deviations resulting from disturbances. To authenticate the viability of the recommended scheme, experimental validation using OPAL-RT based real-time simulation has been done.

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1. INTRODUCTION

Automatic Generation Control (AGC) preserves the equilibrium among load and generation to reduce frequency fluctuations during load changes [1]. An suitable AGC scheme is necessary to reduce frequency variations in power systems. In past, investigators have examined various approaches for AGC.

In [2], AGC of the power system has been performed by Grey Wolf Optimization (GWO) optimized classical PI/PID controllers and a comparison has been made with other comparable meta-heuristic optimization methods. In [3], the Artificial Bee Colony (ABC) technique has been used to tune the parameters of PI and PID controllers for AGC of an reheat thermal system. A Teaching Learning Based Optimization (TLBO) method is proposed in [4] for AGC of two test systems. A Symbiotic Organism Search (SOS) tuned PID regulator has been proposed in [5] for AGC of three test systems. A relative performance examination of conventional controllers in Load Frequency Control (LFC) using the Firefly Algorithm (FA) method has been discussed in [6]. A hybrid FA and Pattern Search (hFA-PS) method is employed in [7] for AGC of multi-area power systems with the inclusion of Generation Rate Constraint (GRC). A PID controller with a filter optimized by the Jaya Algorithm (JA) has been suggested for AGC of a power system [8]. For a standard two area non-reheat thermal system, Genetic Algorithm (GA) [9] and Bacteria Foraging Optimization Algorithm (BFOA) [10] techniques have been applied for tuning the PI controllers. A modified Differential Evolution (DE) based fuzzy PID controller has been recommended in [11] for AGC of the power system installed with Flexible AC Transmission System (FACTS) controller. A Hybrid Particle Swarm Optimization and Pattern Search (hPSO-PS) based fuzzy PI controller was employed in [12] for AGC of multi-area power systems. A fuzzy assisted PID with filter-fractional order integral (FPIDN-FOI) structure based on the Imperialist Competitive Algorithm (ICA) was proposed in [13] for various test power systems. A GA optimized fractional order PID (FOPID) controller for frequency regulation of a two-area system has been proposed in [14], where the outcome of FOPID has been equated with Integral, PI, and fuzzy logic based controllers using various time-domain performance indices. LFC of multi-source power systems with AC/DC links employing TLBO optimized PID has been proposed in [15]. An Adaptive DE based PID controller for AGC of power systems has been suggested in [16]. A hybrid stochastic fractal search and local unimodal sampling-tuned cascade structure for AGC of single and multi-area multi-source power systems have been proposed in [17]. A hybrid BFOA-PSO method for AGC of linear/nonlinear power systems has been performed in [18]. Recently, a hybrid technique has been proposed for controller design. A hybrid Firefly-Swarm optimized power system stabilizer has been suggested in [19] for stability improvement of the power system. A hybrid DE-PS method was proposed in [20] to find the Modified Integral Derivative (MID) controller for AGC of the power system in a deregulated condition. The fuzzy PID parameters have been optimized by a hybrid many optimizing liaisons gravitational search algorithm for three test systems in [21]. A hybrid shuffled frog-leaping and PS based PID for frequency control of a two-area system containing PV and the thermal generator has been proposed in [22].

In recent times, researchers are using heuristic optimization methods because of their effectiveness for determining controller values. It has been seen that all search methods offer acceptable outcomes. However, in solving the optimizing tasks, one specific method may not yield better results than others for all problems. Therefore, new techniques are suggested to be tried for real-world problems. For global optimization, DE performance depends on the selection of its parameter such as Crossover Constant (CR) & Scaling Factor (F) [23]. In the whole search process, suitable F and CR values must be used in the search method instead of using constant values throughout the progression. In view of the above, an Adaptive Differential Evolution (ADE) scheme is recommended in this present work where an adaptive method is employed for the choice of appropriate values of F and CR in the optimization process.

To achieve a satisfactory outcome in the searching method, suitable equilibrium among exploitation with exploration is being preserved in the optimization method. As DE is a global search technique, it is designed for exploring the search space, whereas the PS is meant to exploit a local area. This paper introduces a new adaptive approach using a hybrid Adaptive Differential Evolution technique and Pattern Search (hADE-PS) optimization technique for tuning of Fractional Order Fuzzy PID (FOFPID) for AGC of power systems.

Our literature study shows that diverse structured fuzzy based controllers tuned via a variety of optimization methods have been proposed for AGC of various systems. However, the effectiveness of fractional order fuzzy PID controllers optimized by hybrid Adaptive Differential Evolution and Pattern Search (hADE-PS) has not assessed so far in standard test systems. Inspired by this, this paper introduces a novel adaptive scheme by using the hADE-PS optimization technique for tuning of fractional order fuzzy PID for AGC of power systems.

The novel offerings of the present work are:

i) FOFPID is proposed in the AGC problem.
ii) hADE-PS technique has been used to vary CR and F values during the search progression.
iii) The superiority of hADE-PS based FOFPID is verified as being superior to some newly proposed approaches in the literature for identical systems.
iv) The sensitive study is done by changing the loading condition and system time constants from their normal values.
v) To authenticate experimentally the appropriateness of the projected scheme, the MATLAB outcomes are compared to OPAL-RT results.

2. SYSTEM UNDERSTUDY

In this paper, three test systems are considered to evaluate the efficacy of the suggested AGC approach. Initially, a widely used non-reheat type interconnected two-area thermal system specified in Fig. 1 [4, 8, 12, 13] is considered. In the next stage, an extensively employed reheat type two-area thermal system displayed in Fig. 2 [3, 5, 6, 13] is selected. Finally, a two-area six-unit, thermal-hydro-gas power system shown in Fig. 3 [15–17] is employed. The data for the above systems is taken from the previously cited references.

2.1 Structure of FOFPID

The design of a Fuzzy Logic Controller (FLC) is subject to the choice of input/output Scaling Factors (SFs) and/or controller parameters. Optimization of SFs is of utmost significance as they affect the control action and hence are employed in the present study. For easy implementation, input and output have the same Membership Functions (MFs) and are retained within the range $(-1, 1)$. Triangular MFs with a Mamdani fuzzy interface are selected because of their easy application. To provide extra flexibility, the power of derivative/integral is taken with Fractional Order (FO).The FOFPID structure employed here consists of fractional fuzzy PI and PD controllers. The SFs of the input are represented by K_1 and K_2, as given in Fig. 4. For obtaining the output of controller (U), the sum of the controller outputs (U) is equal to the FLC output multiplied with K_p plus the fractional integral FLC output multiplied with K_I plus the fractional derivative FLC output multiplied

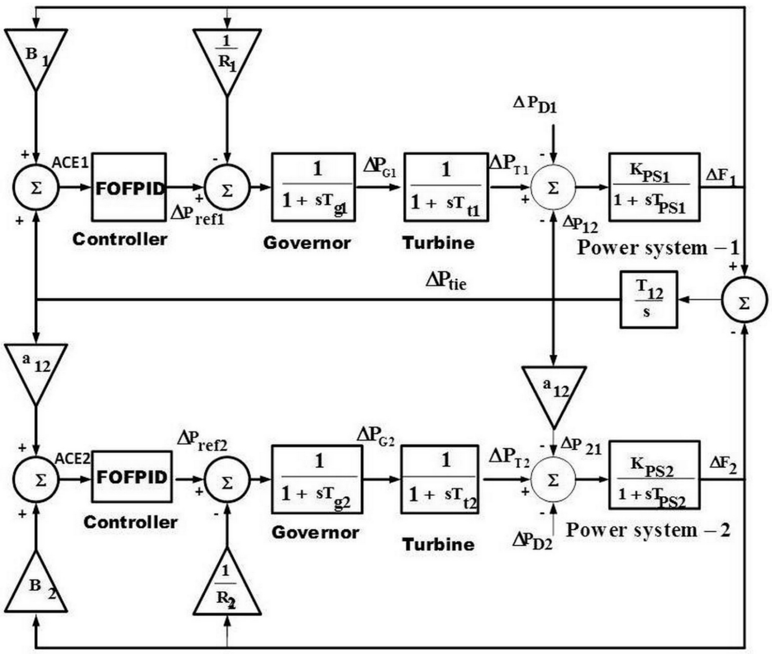

Fig.1: *First test system [4, 8, 12, 13].*

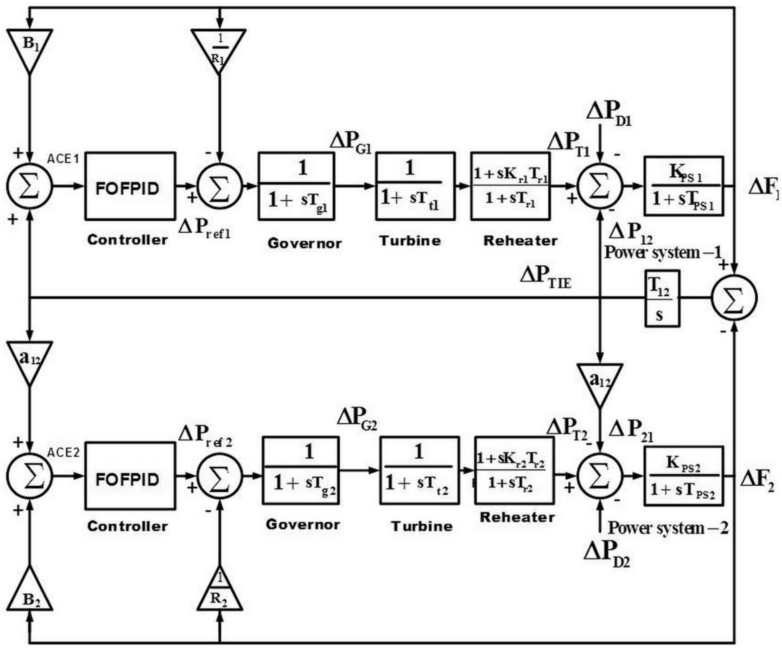

Fig.2: *Second test system [3, 5, 6, 13].*

with K_D. Respective Area Controller Errors (ACE) is given by

$$\mathrm{ACE}_1 = B_1 \Delta F_1 + \Delta P_{tie12} \tag{1}$$

$$\mathrm{ACE}_2 = B_2 \Delta F_2 + \Delta P_{tie21} \tag{2}$$

The fuzzy controller takes an error signal $e(t)$ and the fractional rate of the $e(t)$ as inputs to FLC. The FOFPID controller's outputs are control inputs to the generators of each area. The input scaling factors are represented by K_1 and K_2. The fuzzy controller output is passed through a PID controller with gain parameters denoted by K_P, K_D, and K_I, respectively. The input fractional derivative order and PID fractional integral order and fractional derivative are represented by λ_1, μ, and λ_2, respectively. In this study, the assumptions for the FLC structure are (i) fixed membership functions, and (ii) a fixed rule base. From [12], the membership functions for FLC input, output, and rule base are

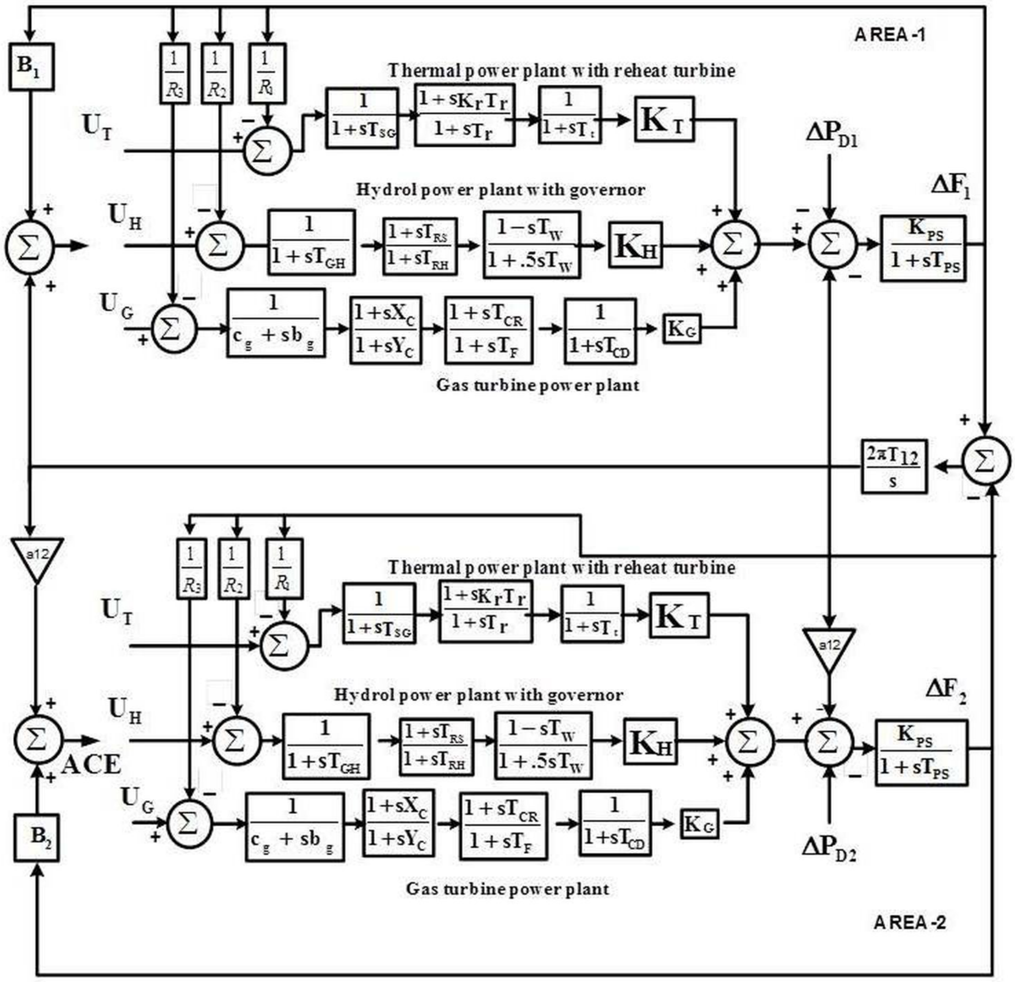

Fig.3: *Third test system [15–18].*

$$F^{G+1} = \begin{cases} F^{\min} + \sqrt{randU * (F^{\max} - F^{\min})\,(F^{med} - F^{\min})} & \text{if } randU < \left(F^{\max} - F^{\min}\right)\left(F^{med} - F^{\min}\right) \\ F^{\max} - \sqrt{(1 - randU) * (F^{\max} - F^{\min})\,(F^{\max} - F^{med})} & \text{otherwise} \end{cases} \tag{3}$$

$$CR^{G+1} = \begin{cases} CR^{\min} + \sqrt{randU * (CR^{\max} - CR^{\min})\,(CR^{med} - CR^{\min})} & \text{if } randU < \left(CR^{\max} - CR^{\min}\right)\left(CR^{med} - CR^{\min}\right) \\ CR^{\max} - \sqrt{(1 - randU) * (CR^{\max} - CR^{\min})\,(CR^{\max} - CR^{med})} & \text{otherwise} \end{cases} \tag{4}$$

taken. The input scaling factors, the PID parameters, and fractional order parameters (λ_1, μ, and λ_2) are optimized using the hADE-PS technique to reduce the Integral of Time Absolute Error (ITAE) objective function.

2.2 Optimization Technique: Hybrid ADE-PS

The efficacy of the DE depends on the choice of its F and CR parameters. In this study, an adaptive approach is used to choose the F and CR values throughout the search process. Triangular Distributions of F ($\wedge F$) and CR ($\wedge CR$) in the range $\wedge F = [0.1, 1, 2]$ and $\wedge CR = [0.1, 0.4, 1]$ are used. To determine F_K and CR_K in generation K, the min, max, and medium values are used which F_K and CR_K are given by Eqs. (3) and (4).

The ADE process is clarified in more detail in [24]. The Pattern Search (PS) method has proved to be worthy in many hybrid methods [12, 20]. The details about the PS algorithm can be found in references [12, 20]. Initially, the ADE technique is run and PS is then applied to take the initial values from the final results of ADE.

2.3 Objective Function

To optimize the controller values, ITAE is selected in this study and is computed for two areas as

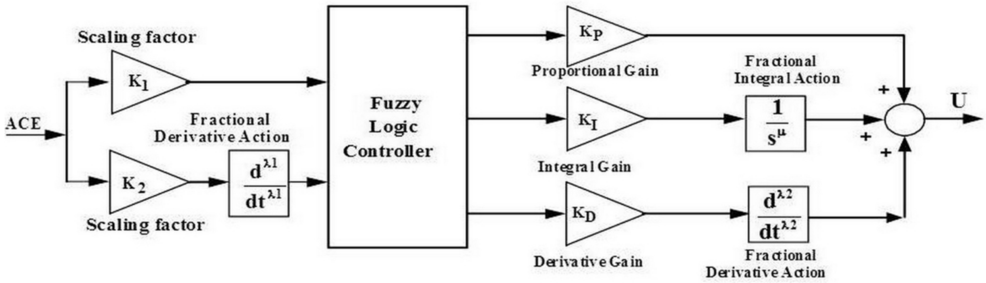

Fig.4: *Structure of Suggested Fractional Order Fuzzy PID Controller.*

Table 1: *Tuned control parameters of FOFPID controller for the first system (two area non-reheat).*

Technique		Controller parameters							
		K_1	K_2	K_P	K_I	K_D	λ_1	μ	λ_2
hADE-PS	Area-1	1.9004	0.2474	1.6646	1.7060	0.3734	0.9623	0.9866	0.5813
	Area-2	0.9061	0.9772	0.8898	0.5248	1.2583	0.7666	0.4519	0.4543
hFA-PSO	Area-1	1.6047	0.2187	1.6183	1.8671	0.3208	0.9755	0.9791	0.5357
	Area-2	0.8764	0.9595	0.8056	0.5276	1.1749	0.7427	0.4212	0.4206
hDE-PS	Area-1	1.9994	0.2117	1.4163	1.6739	0.3102	0.9778	0.9683	0.5202
	Area-2	0.7639	0.9351	0.7923	0.5488	1.0881	0.7380	0.3899	0.3903
hMOL-GSA	Area-1	1.9202	0.2979	1.5600	1.7426	0.2884	0.9151	0.9317	0.5190
	Area-2	0.8874	0.9315	0.8147	0.4504	1.1783	0.7139	0.4092	0.4450
hSFLA-PS	Area-1	1.9344	0.2834	1.5782	1.6970	0.3386	0.9239	0.8943	0.5094
	Area-2	0.8795	0.9450	0.8194	0.5332	1.2055	0.7379	0.4058	0.4252

$$\text{ITAE} = \int_0^T t\,\{|\Delta F_1| + |\Delta F_2| + |\Delta P_{tie12}|\} \qquad (5)$$

where ΔF_1 and ΔF_2 are the variation in frequency. ΔP_{tie12} is the tie-line power error. T is the time in second. The expression given in Eq. (5) is minimized with the restrictions given by $K_{1\min} < K_1 < K_{1\max}$, $K_{2\min} < K_2 < K_{2\max}$, $K_{P\min} \leq K_P \leq K_{P\max}$, $K_{I\min} \leq K_I \leq K_{I\max}$, $K_{D\min} \leq K_D \leq K_{D\max}$, $\lambda_{1\min} \leq \lambda_1 \leq \lambda_{1\max}$, $\mu_{\min} \leq \mu \leq \mu_{\max}$, and $\lambda_{2\min} \leq \lambda_2 \leq \lambda_{2\max}$. As noticed in various studies, the limiting values of K_1, K_2, λ_1, μ, and λ_2 are (0,1) and the limiting values of K_P, K_I, and K_D are (−2,10) as suggested in [9–13].

3. RESULTS AND DISCUSSION

3.1 First Test System

Initially, a two-area thermal system (non-reheat) given in Fig. 1 [4, 8, 12, 13] is taken. A 5 % SLP is assumed in area-1 at $t = 0$ s. The values of our proposed FOFPID are searched by the hADE-PS method and are gathered in Table 1. For the application of hADE-PS, a population of 30 and 50 generations are employed as suggested in the literature. The proposed hADE-PS technique is executed 10 times, and the best parameters (as per smallest ITAE value) obtained in 10 runs are used as the controller parameters. The performance of our suggested controller, hADE-PS based FOFPID, is compared with various recently projected optimization-based control schemes like PSO based FPI [12], TLBO based PID [4], JA based PIDN [8], hPSO-PS based FPI [12], BFOA [10], GA [9], and hBFOA-PSO [18] based PI as shown in Table 2. Table 2 shows that settling time (T_s) and peak undershoots (U_s) of the ΔF_1, ΔF_2, and ΔP_{tie}; and the ISE, ITSE, IAE, and ITAE attained with our hADE-PS based FOFPID controller are less than that of the other schemes for the system. Hence, it is clear that the recommended hADE-PS optimized FOFPID provides better results compared to the other approaches tested.

The system response with hADE-PS optimized FOFPID for the above SLP is revealed in Figs. 5–7. The same with TLBO based PID [7], JA based PIDN [11], BFOA [13], GA [9], and hBFOA-PSO [18] based PI are also shown in Figs. 5–7 for the same system. Figs. 5–7 show that hADE-PS based FOFPID gives superior responses with a lower amount of T_s, and minimum U_s, compared to the other approaches tested.

To demonstrate the benefit of the ADE-PS method, other techniques such as hFA-PSO [19], hDE-PS [20], hMOL-GSA [21], and hSFLA-PS [22] for the same FOFPID controller structure are analysed. The optimized values are gathered in the Table 1. Table 2 shows that for an identical system and control structure, our proposed ADE-PS offers better results than the hFA-PSO,

Table 2: *Performance index for the first system at $\Delta P_{D1} = 0.05\,puMW$.*

Controller/Technique	Settling Time T_s (s)			Undershoots U_s (−ve)			Objective Function J_s			
	ΔF_1 $\times 10^{-1}$	ΔF_2 $\times 10^{-1}$	ΔP_{tie} $\times 10^{-1}$	ΔF_1 $\times 10^{-1}$	ΔF_2 $\times 10^{-1}$	ΔP_{tie} $\times 10^{-1}$	ISE	ITSE	IAE $\times 10^{-2}$	ITAE $\times 10^{-2}$
FPI/PSO [12]	60.7	71.5	56.9	3.89	1.56	0.64	1.15×10^{-3}	1.05×10^{-3}	9.78	18.27
PID/TLBO [4]	53.3	59.0	33.2	3.07	1.78	0.70	1.26×10^{-3}	1.12×10^{-3}	9.07	13.47
PIDN/JA [8]	29.7	27.5	25.6	6.00	3.61	1.23	2.44×10^{-3}	1.41×10^{-3}	8.26	6.86
FPI/(hPSO-PS) [12]	40.7	52.5	40.1	3.55	1.22	0.59	6.06×10^{-4}	3.64×10^{-4}	5.69	7.99
PI/BFOA [10]	55.2	70.9	63.5	13.12	11.43	4.14	3.52×10^{-2}	4.67×10^{-2}	51.43	91.56
PI/GA [9]	100.3	100.3	93.7	12.03	10.03	3.57	2.69×10^{-2}	3.82×10^{-2}	52.80	127.70
PI/(hBFOA-PSO) [18]	73.9	76.5	57.3	12.36	10.42	3.69	2.36×10^{-2}	2.60×10^{-2}	36.38	58.28
FOFPID/ hADE-PS	9.3	0	0	0.20	0.03	0.01	11.17×10^{-6}	2.58×10^{-7}	0.16	0.83
FOFPID/ hFA-PSO	10.0	1.5	0	0.23	0.04	0.02	11.79×10^{-6}	21.42×10^{-7}	1.23	0.94
FOFPID/ hDE-PS	21.2	1.5	0	0.24	0.05	0.02	11.84×10^{-6}	24.53×10^{-7}	1.33	1.00
FOFPID/ hMOL-GSA	20.0	1.6	0	0.23	0.04	0.01	11.89×10^{-6}	22.01×10^{-7}	1.35	1.39
FOFPID/hSFLA-PS	19.4	1.5	0	0.23	0.04	0.01	11.97×10^{-6}	21.47×10^{-7}	1.37	1.77

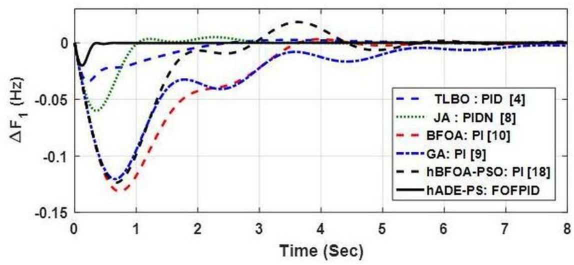

Fig.5: *ΔF_1 for the first system.*

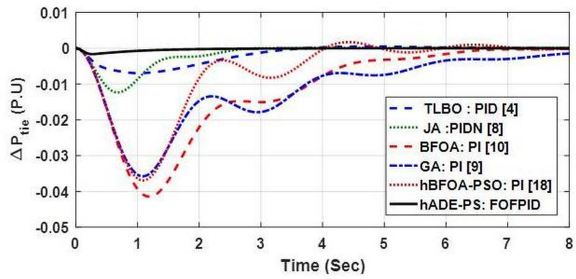

Fig.7: *ΔP_{tie} for the first system.*

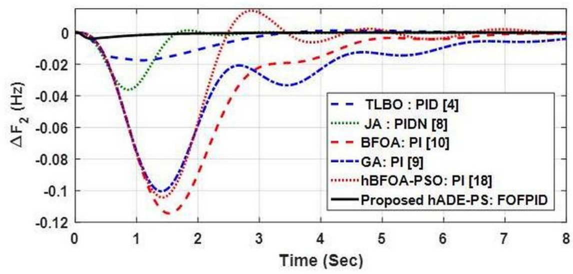

Fig.6: *ΔF_2 for the first system.*

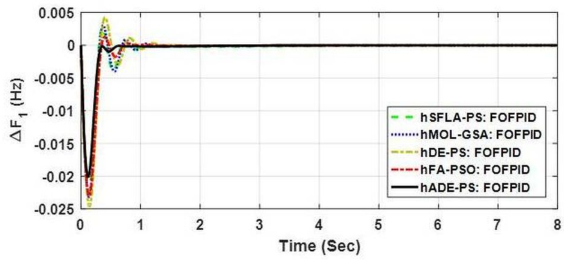

Fig.8: *ΔF_1 for FOFPID controller (first system).*

hDE-PS, hMOL-GSA, and hSFLA-PS optimisation techniques. The proposed ADE-PS attains minimal ISE/ITSE/IAE/ITAE ($11.17 \times 10^{-6}/2.58 \times 10^{-7}/0.16 \times 10^{-2}/0.83 \times 10^{-2}$), T_s (0.93, 0, 0), and U_s (−0.020, −0.003, −0.001) values for the same system and control structure as given in Table 2. It is noticeable that the ITAE value with projected ADE-PS is reduced by 11.70 %, 17 %, 40.28 %, and 51.17 % compared to hFA-PSO, hDE-PS, hMOL-GSA and hSFLA-PS, respectively. Similarly, ISE values are reduced by 5.25 %, 5.65 %, 6.0 %, and 6.68 %. ITSE values are reduced by 87.95 %, 89.48 %, 88.27 %, and 87.9832 %. IAE values are reduced by 86.99 %, 87.96 %, 88.14 %, and 88.32 % compared to hFA-PSO, hDE-PS, hMOL-GSA and hSFLA-PS, respectively. Fig. 8 shows that ADE-PS provides improved dynamic response compared to other methods tested for the same controller structure.

3.2 Second Test System

An interconnected 2 area reheat thermal system as illustrated in Fig. 2 is assumed [3, 5, 6, 13] for our second test system. At $t = 0\,$s, a 1 % SLP is consider in area-1. The tuned parameter values are delivered in Table 3. Also, the optimized values of hFA-PSO, hDE-PS, hMOL-GSA, and hSFLA-PS are shown in Table 3. The T_s in second, U_s of ΔF_1, ΔF_2, ΔP_{tie}, and error indices are given in Table 4. The outcomes of ABC [3], SOSA [5], and FA [6] tuned PID controller

Table 3: *Tuned control parameters of FOFPID controller for the second system (two area reheat).*

Technique		Controller parameters							
		K_1	K_2	K_P	K_I	K_D	λ_1	μ	λ_2
hADE-PS	Area-1	1.5841	0.4369	0.1369	1.8761	1.1949	0.9892	0.7861	0.2671
	Area-2	0.5173	0.6405	0.8691	0.6005	1.9993	0.2163	0.3640	0.5292
hFA-PSO	Area-1	1.6494	0.5213	0.1801	1.8364	1.1989	0.8517	0.8696	0.2489
	Area-2	0.5882	0.6728	0.9837	0.6883	1.7378	0.3420	0.1991	0.5825
hDE-PS	Area-1	1.5052	0.3209	0.1649	1.5866	1.0424	0.8674	0.8171	0.3417
	Area-2	0.4729	0.6132	0.8131	0.6093	1.7142	0.3462	0.2566	0.4171
hMOL-GSA	Area-1	1.3996	0.2922	0.1347	1.4854	1.0572	0.8167	0.7852	0.3367
	Area-2	0.4358	0.4894	0.6479	0.5452	1.6121	0.2807	0.2003	0.4874
hSFLA-PS	Area-1	1.4594	0.3948	0.0954	1.5682	1.0020	0.7961	0.7386	0.2978
	Area-2	0.3835	0.5163	0.7397	0.6248	1.6087	0.3139	0.3227	0.4722

Table 4: *Performance index for the second system at $\Delta P_{D1} = 0.01\,puMW$.*

Controller/Technique	Settling Time T_s (s)			Undershoots U_s $(-ve)$			Objective Function J_s			
	ΔF_1 $\times 10^{-1}$	ΔF_2 $\times 10^{-1}$	ΔP_{tie} $\times 10^{-1}$	ΔF_1 $\times 10^{-2}$	ΔF_2 $\times 10^{-2}$	ΔP_{tie} $\times 10^{-2}$	ISE	ITSE	IAE $\times 10^{-2}$	ITAE $\times 10^{-2}$
PID/FA [9]	98.2	66.7	17.8	1.54	1.17	0.35	2.60×10^{-4}	2.46×10^{-4}	4.16	10.12
PID/SOSA [8]	66.0	70.8	16.1	1.65	1.28	0.38	2.84×10^{-4}	2.44×10^{-4}	4.03	9.96
PID/ABC [6]	53.9	60.1	14.8	0.51	0.32	0.10	3.62×10^{-5}	5.73×10^{-5}	2.03	5.72
Proposed FOFPID based hADE-PS technique	3.6	7.03	1.04	0.39	0.12	0.04	4.32×10^{-6}	1.71×10^{-6}	0.38	0.42
FOFPID/hFA-PSO	3.6	7.12	0	0.44	0.12	0.04	4.69×10^{-6}	1.75×10^{-6}	0.39	0.50
FOFPID/hDE-PS	4.5	7.20	0	0.52	0.18	0.05	7.85×10^{-6}	2.86×10^{-6}	0.49	0.57
FOFPID/hMOL-GSA	4.8	7.30	0	0.59	0.22	0.07	10.7×10^{-6}	4.28×10^{-6}	0.58	0.67
FOFPID/hSFLA-PS	4.6	7.21	0	0.57	0.20	0.06	9.76×10^{-6}	3.93×10^{-6}	0.57	0.70

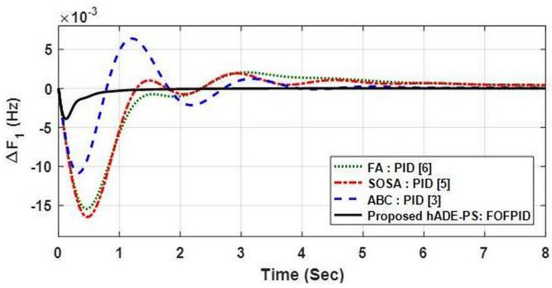

Fig.9: ΔF_1 *for the second system (SLP=1 % in area-1).*

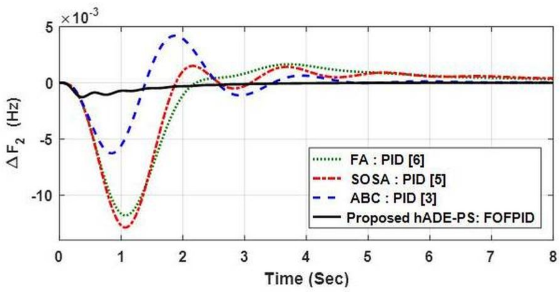

Fig.10: ΔF_2 *for the second system (SLP=1 % in area-1).*

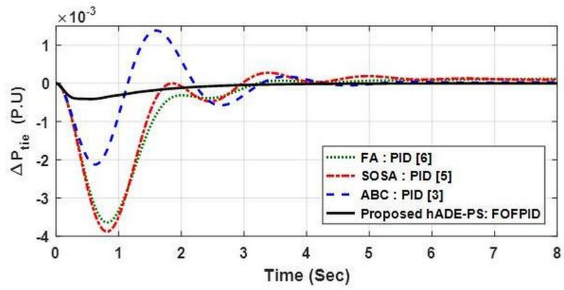

Fig.11: ΔP_{tie} *for the second system (SLP=1 % in area-1).*

for the identical system are also gathered in Table 4. Table 4 shows that, our proposed FOFPID provides lower objective values (ISE $= 4.32 \times 10^{-6}$, ITSE $= 1.71 \times 10^{-6}$, IAE $= 0.38 \times 10^{-2}$, ITAE $= 0.42 \times 10^{-2}$) compared to the recently published AGC approaches tested.

The comparative system performance results for the previously mentioned above disturbance are presented in Figs. 9–11 from which it is obvious that the system response is considerably enhanced by our proposed hADE-PS based FOFPID controller when compared to published results.

To examine the effect of the type and size of SLP on system response, a sudden load shedding

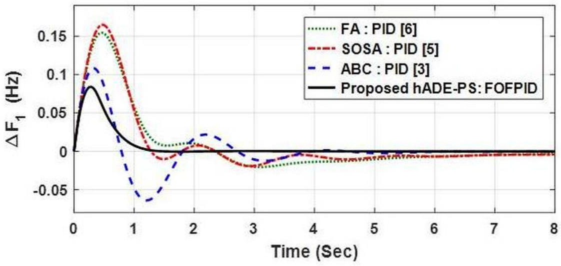

Fig.12: *ΔF_1 for the second system (SLP=−10 % in area-1).*

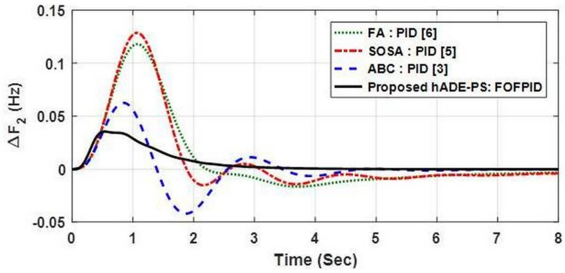

Fig.13: *ΔF_2 for the second system (SLP=−10 % in area-1).*

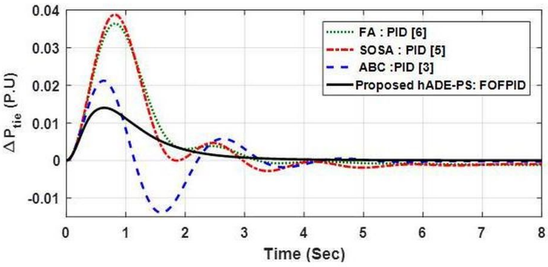

Fig.14: *ΔP_{tie} for the second system (SLP=−10 % in area-1).*

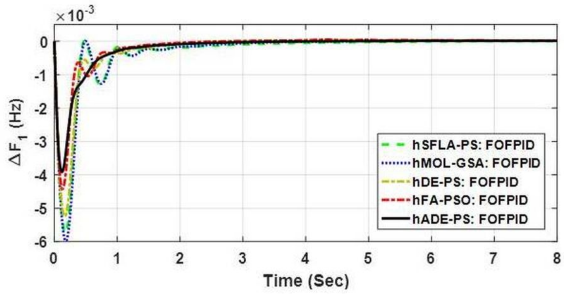

Fig.15: *ΔF_1 for FOFPID controller (second system).*

of 10 % (−10 % step load increase) is assumed at $t = 0$ s in area-1. The system performance response is presented in Figs. 12–14. Figs. 12–14 show that the proposed FOFPID is robust and performers adequately when the type and size of load demand varies. Also, the suggested AGC method provides better system performance than some newly suggested methods like FA/SOSA/ABC based PID controller.

For the similar test system and control configuration, Table 4 shows that ADE-PS offers better results than the hFA-PSO, hDE-PS, hMOL-GSA, and hSFLA-PS optimisation techniques. The proposed ADE-PS shows lower ISE/ITSE/IAE/ITAE ($4.32 \times 10^{-6}/1.71 \times 10^{-6}/0.38 \times 10^{-2}/0.42 \times 10^{-2}$), T_s (0.36, 0.703, 0.104) and U_s (−0.0039, −0.0012, −0.0004) values compared to the other systems for the same system and control structure as gathered in Table 4. Table 4 shows that the ITAE value with ADE-PS is reduced by 16 %, 26.31 %, 37.31 %, and 40 % compared to hFA-PSO, hDE-PS, hMOL-GSA, and hSFLA-PS, respectively. The comparative results are shown in Fig. 15 which proves that the ADE-PS approach offers enhanced performance compared to the other methods.

3.3 Third Test System

The multi-source multi-area 6-unit power system shown in Fig. 3 is taken in this current study because it is extensively used in references to propose AGC schemes [15, 16]. The system data was taken from [15, 16]. The tuned controller values, ITAE value and T_s results are gathered in Table 5, by using 1 % SLP in area-1. To show the supremacy of our hADE-PS based FOFPID method, the outcomes of hADE-PS, ADE [16], hSFS-LUS [20], and TLBO [15] tuned PID, as well as hFA-PSO, hDE-PS, hMOL-GSA, and hSFLA-PS are shown in Table 5.

It can be comprehended from the outcomes that lower ITAE is realized with hADE-PS based FOFPID (ITAE $= 0.49 \times 10^{-2}$) than with hDE-PS (ITAE $= 3.24 \times 10^{-2}$), ADE (ITAE $= 3.68 \times 10^{-2}$) [16], hSFS-LUS (ITAE $= 6.8131 \times 10^{-2}$) [17], SFS (ITAE $= 7.0879 \times 10^{-2}$) [17], and TLBO (ITAE $= 9.6124 \times 10^{-2}$) [15] tuned PID controllers. In addition the smallest settling times are acquired with our suggested hADE-PS tuned FOFPID controller. With 1 % SLP in area-1 at $t = 0$ s, the system responses are exposed in Figs. 16–18. The outcomes show that system responses are handled better by hADE-PS based FOFPID than by hADE-PS, ADE [16], hSFS-LUS [17], and TLBO [15] tuned PID controllers. Table 5 makes it clear that for the same system and control structure, ADE-PS offers better results compared to hFA-PSO, hDE-PS, hMOL-GSA, and hSFLA-PS optimisation techniques. The proposed ADE-PS shows minimal ITAE (0.49×10^{-2}) and T_s (0.5, 0.16) values compared to the competition for the same system and control structure as mentioned in Table 5. Table 5 shows that the ITAE value with ADE-PS is reduced by 10.9 %, 14.03 %, 32.87 %, and 22.22 % compared to hFA-PSO, hDE-PS, hMOL-GSA, and

Table 5: *Controller gains and performance index of six-unit two area system (third system).*

Technique		Controller parameters								Performance		
		K_1	K_2	K_P	K_I	K_D	λ_1	μ	λ_2	ITAE $\times 10^{-2}$	Settling Time ΔF_1	Settling Time ΔF_2
Proposed hADE-PS: FOFPID	Thermal	0.9291	0.8528	3.2198	4.9251	4.8949	0.6829	0.7857	0.4744	0.49	0.50	0.16
	Hydro	0.7807	0.0474	3.2648	3.7856	0.6495	0.9823	0.4163	0.4071			
	Gas	0.7829	0.4338	2.8818	3.2527	0.1660	0.4046	0.9590	0.5959			
hFA-PSO: FOFPID	Thermal	0.4641	0.9881	4.5392	4.2113	4.8574	0.1437	0.8571	0.7623	0.55	0.81	0.18
	Hydro	0.7605	0.4600	4.9210	4.5380	2.2779	0.1481	0.2943	0.3810			
	Gas	0.9246	0.1943	3.2756	3.9717	0.9682	0.0327	0.8020	0.3140			
hDE-PS: FOFPID	Thermal	0.8303	0.2949	3.8834	3.6657	2.6345	0.2700	0.7681	0.9545	0.57	1.23	0.19
	Hydro	0.1186	0.0259	4.1108	4.3229	4.6289	0.0933	0.2335	0.2120			
	Gas	0.6102	0.3951	3.6338	4.8065	3.7513	0.0797	0.8681	0.3634			
hMOL-GSA: FOFPID	Thermal	0.7270	0.4640	4.6547	3.7841	4.0144	0.8033	0.8768	0.0884	0.73	1.02	0.38
	Hydro	0.6682	0.5029	1.6785	4.9432	1.7603	0.2075	0.2629	0.0996			
	Gas	0.1509	0.3217	2.9724	4.7695	0.3141	0.0088	0.7745	0.6824			
hSFLA-PS: FOFPID	Thermal	0.9421	0.9478	4.2232	4.6291	0.8950	0.5180	0.6274	0.9133	0.63	1.57	0.26
	Hydro	0.6643	0.6398	3.7003	4.0884	3.0021	0.0859	0.9224	0.0545			
	Gas	0.5275	0.1197	1.9013	4.0643	1.2212	0.8845	0.7129	0.8788			
ADE-PS: PID [16]	Thermal	–	–	9.2509	1.2641	6.7215	–	–	–	3.24	0.53	0.16
	Hydro	–	–	9.4782	0.0299	1.2710	–	–	–			
	Gas	–	–	9.1693	6.7215	1.1388	–	–	–			
ADE: PID [16]	Thermal	–	–	9.8856	0.0643	6.2166	–	–	–	3.68	1.49	0.93
	Hydro	–	–	4.8682	3.048	1.4609	–	–	–			
	Gas	–	–	9.5551	9.6049	8.7385	–	–	–			
hSFS-LUS: PID [17]	Thermal	–	–	4.9985	4.9912	2.443	–	–	–	6.8131	1.57	0.97
	Hydro	–	–	4.984	0.8881	0.552	–	–	–			
	Gas	–	–	4.975	4.6494	3.678	–	–	–			
TLBO: PID [15]	Thermal	–	–	4.1468	4.0771	2.0157	–	–	–	9.6124	2.11	1.57
	Hydro	–	–	1.0431	0.603	2.2866	–	–	–			
	Gas	–	–	4.7678	3.7644	4.9498	–	–	–			

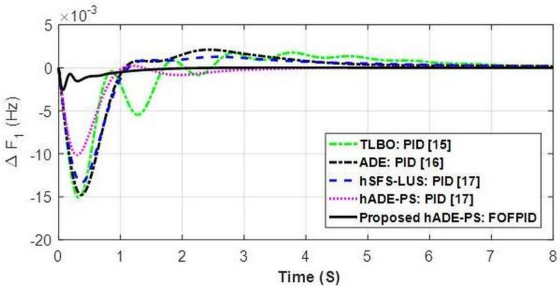

Fig.16: ΔF_1 *for the third system.*

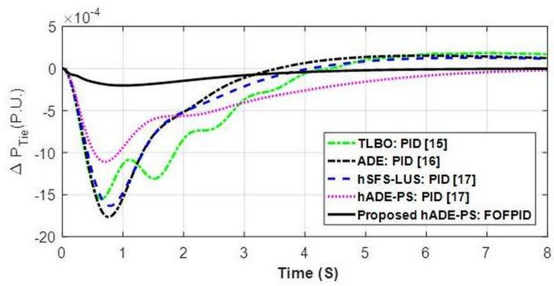

Fig.18: ΔP_{tie} *for the third system.*

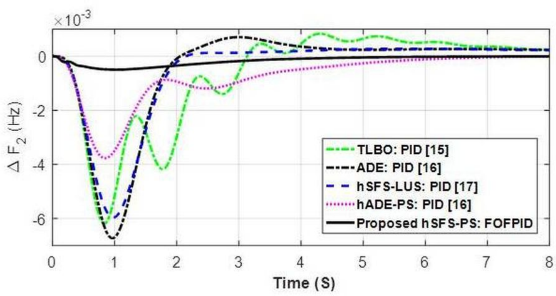

Fig.17: ΔF_2 *for the third system.*

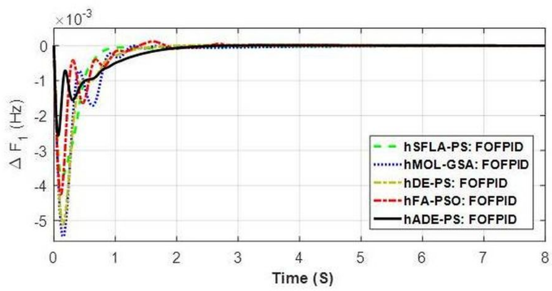

Fig.19: ΔF_1 *for FOFPID controller (third system).*

Table 6: *Robustness analysis for the third system.*

Parameter	% Change	Settling Time (ΔF_1)	ISE $\times 10^{-7}$	ITSE $\times 10^{-7}$	IAE $\times 10^{-4}$	ITAE $\times 10^{-4}$
Nominal	0	0.5	19.5121	12.5459	32.0954	49.4511
Loading condition	+25	0.52	19.4829	12.5316	32.0790	48.4405
	−25	0.491	28.4411	27.7682	53.8921	179.5463
T_{12}	+25	0.972	36.7283	38.4285	45.3932	151.1866
	−25	0.9670	37.1908	40.3801	44.8266	148.0099
T_t	+25	0	19.7177	29.7831	52.5470	184.5068
	−25	0	19.7232	29.8235	52.5498	184.5606
T_{SG}	+25	0	20.8301	25.5407	51.4064	176.6832
	−25	0	20.8268	25.5510	51.4073	176.6966

Fig.20: *Experimental setup based on OPAL-RT.*

hSFLA-PS, respectively. The comparative results are shown in Fig. 19, which proves the effectiveness of the ADE-PS method.

4. SENSITIVITY ANALYSIS

A sensitivity study was executed to validate the robustness of the suggested FOFPID under a large variation of parameters [12, 24, 25]. The loading condition and time constants of the system were changed from their nominal values for the third test system. The outcomes are gathered in Table 6. For ΔF_2 and ΔP_{tie}, settling times are not shown in Table 6 as the transient responses lie within the tolerance band throughout the simulation time. It can be seen from Table 6 that the suggested controllers are robust and the performance index remains almost constant under varied conditions.

5. EXPERIMENTAL VALIDATION

The experimental validation by OPAL-RT was performed for the real-time application of the recommended approach and the results are displayed in Fig. 20. The OPAL-RT includes the inherent delays and errors which are neglected in the usual off-line simulations [24]. The area-1 frequency deviation responses of OPAL-RT based Real-Time Simulator and MATLAB and are revealed in Figs. 21–23 for all systems. The MATLAB results closely match the OPAL-RT results.

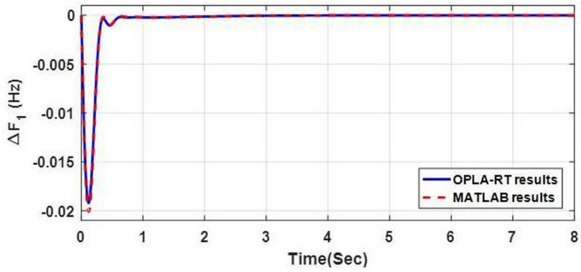

Fig.21: *ΔF_1 for the first system (OPAL-RT vs. MATLAB results).*

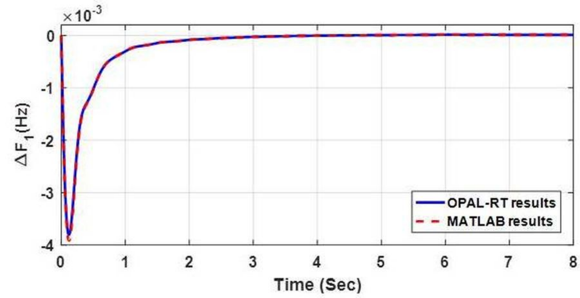

Fig.22: *ΔF_1 for the second system (OPAL-RT vs. MATLAB results).*

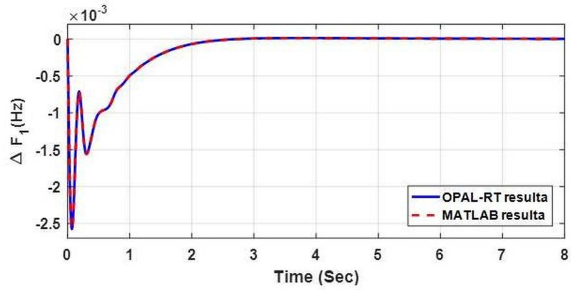

Fig.23: *ΔF_1 for the third system (OPAL-RT vs. MATLAB results).*

6. CONCLUSION

This work presents a comparative analysis of transient responses of various test systems having a new controller structure called FOFPID for AGC. The optimal values of our suggested FOFPID are determined by using hADE-PS. First, an interconnected two-area power system (non-reheat type) was examined in the MATLAB/Simulation. The superiority of our hADE-PS based FOFPID controller was confirmed by equating the outcomes for the identical test system with various recent publications. Our suggested hADE-PS tuned FOFPID gives superior characteristics with minimal performance index values when compared to some recently proposed methods such as PSO based FPI, TLBO based PID, JA based PIDN, hPSO-PS based FPI, BFOA, GA, and hBFOA-PSO based PI. The analysis was then extended to investigate an interconnected thermal power system reheat type and 2-area six-unit thermal- hydro-gas system. Improved results of our suggested method were observed by comparing it with ABC, SOSA, and FA approaches for the second test system and ADE, hSFS-LUS, and TLBO approaches for the third test system. The ITAE value with proposed ADE-PS was reduced by 11.70 %, 17 %, 40.28 %, and 51.17 % compared to hFA-PSO, hDE-PS, hMOL-GSA, and hSFLA-PS, respectively for the first system. For the second test system, the ITAE value with proposed ADE-PS was reduced by 16 %, 26.31 %, 37.31 %, and 40 % compared to hFA-PSO, hDE-PS, hMOL-GSA, and hSFLA-PS, respectively. The reduction in ITAE value with our proposed ADE-PS compared to hFA-PSO, hDE-PS, hMOL-GSA, and hSFLA-PS was 10.9 %, 14.03 %, 32.87 % and 22.22 %, respectively. Sensitivity of the suggested method was confirmed by changing the loading condition and parameters. It is noticeable that our recommended FOFPID is robust and attains acceptable performance under varied conditions. The experimental investigation shows the MATLAB results closely match OPAL-RT results.

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