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Hybrid Bacterial Foraging Enhanced PSO Algorithm for Load Frequency Control of Hydro-Thermal Multi-Area Power System and Comparative analysis

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Abstract: This work proposes the hybrid Bacterial Foraging enhanced Particle Swarm Optimization (BF-PSO) tuned proportional-integral (PI) controller for load frequency control (LFC) of interconnected 3-area power system comprising diverse sources of power. Area 1 of the 3-area power system is a thermal system with governor dead-band nonlinearity, area 2 is a reheat thermal system, whereas, area 3 is a hydro system with mechanical hydraulic governor. The multi area power system is investigated for frequency regulation under the effect of varying step load disturbance applied in all the three areas besides the reheat non linearity in one thermal area, dead band non linearity in second thermal area and different head levels in the hydro area. The simulation results clearly bring out the enhanced performance of the hybrid BF-PSO algorithm as against the BF, PSO, and conventional Ziegler-Nichols (ZN) algorithms, also implemented in this work for comparative analysis. The frequency and tie-line power deviations, peak overshoot, settling time, and minimum value of performance index are used as the performance measures. Simulations are carried out using MatLab/Simulink.

Keywords: Load frequency control (LFC), Bacterial forging (BF) algorithm, Particle swarm optimization (PSO), Multi-area power system, Integral time absolute error (ITAE)

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1. INTRODUCTION

For stable operation of interconnected power systems, perfect balance between generation and consumption of power should be maintained at any point in time because even a small mismatch would cause the nominal system frequency to vary, besides the flow of tie-line power between different areas, thus degrading the system performance. Therefore, to ensure efficient and reliable operation of interconnected power systems, the system frequency needs to be regulated under varying operating conditions. This is where load frequency control (LFC) mechanism comes to use in each area [1, 2].

The literature on LFC of interconnected power systems is voluminous as many strategies have been proposed by researchers over the past many decades [3]. The LFC studies have been conducted on hybrid power systems with and without non linearity [4-8]. Advanced control concepts have been employed to obtain improved LFC performance [9]. Various biologically inspired computing techniques such as artificial neural network (ANN) [10], fuzzy logic [11, 12], reinforcement learning [13], bat inspired algorithm based dual mode gain scheduling of PI controllers [14], and adaptive neuro fuzzy inference system (ANFIS) [15] have been reported for LFC problem. Besides, many evolutionary optimization algorithms such as Genetic algorithm (GA) [16,17], novel hybrid optimization method based on artificial bee colony algorithm and Taguchi method [19], hybrid bee colony [20], grey wolf optimizer algorithm [21], and novel hybrid gravitational search and pattern search algorithm [22] have been applied for optimal tuning of controller parameters. As a recent proposition, the hybrid BF-PSO algorithm has been used for optimization purpose where, the foraging behavior of bacteria forms the basis of the optimization process [23-29].

The novelty of this work lies in the use of hybrid BF-PSO algorithm for optimal tuning of the PI controllers employed for LFC in a three-area power system comprising diverse generating sources. The investigations are carried out under the effect of varying load conditions and also with and without the nonlinearity. The comparative analysis of the LFC performance of the hybrid BF-PSO algorithm as against the other algorithms is presented qualitatively as well as quantitatively.

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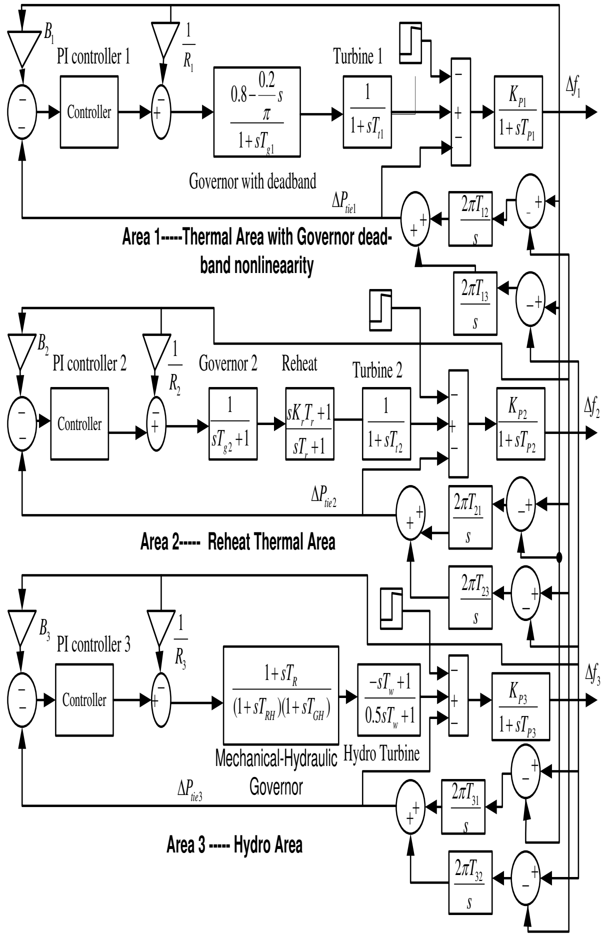
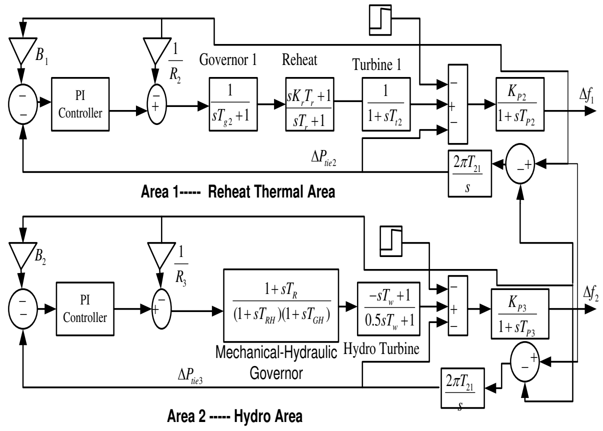
2. SYSTEM DESCRIPTION

The system considered for investigation is the thermal-thermal-hydro type three-area interconnected power system whose transfer function model is as shown in Figure 1 (a), where, Δf_i is the system frequency deviation in Hz, $ACE_i$is the area control error, $\Delta P_{Di}$is the load demand change, ΔP_{Gi} is the change in governor valve position $(p.u.)$, and ΔP_{tie} is the change in tie line power $(p.u.)$. The relevant parameters, with their usual meanings, are given in appendix-A.

As shown in Figure 1 (a), the thermal subsystem in area-1possesses the speed governor dead band non-linearity, modeled using the describing function approach [8-9, 29] whereas, the thermal subsystem in area-2 has a single reheat steam turbine and area 3 comprises hydro system.



(a)



(b)

Figure 1 (a) Transfer function model of three –area hydro-thermal system (b) Block diagram representation of two area hydro-thermal power system.

For the i^{th}area, the area control error ACE_i signal is expressed as under:

$$ACE_i = B.\Delta f_i + \Delta Ptie_i \tag{1}$$

Where, symbols have their usual meaning.

Further, the system of Figure 1(b) is also simulated here, with parameters of PI controller being optimized using BF-PSO algorithm and also other optimization algorithms already implemented by other authors on the same system, merely for comparative analysis to demonstrate the supremacy of the hybrid BF-PSO algorithm.

3. CONTROL STRATEGY AND OPTIMIZATION ALGORITHMS

3.1. PI controller

The control strategy used in the present work is conventional PI control in each area. For the i^{th}area, the combined gain of the PI controller, $K_i(s)$, is given by the following equation:

$$K_i(s) = K_{Pi} + \frac{K_{Ii}}{s} \tag{2}$$

Where, K_{Pi} and K_{Ii} are the proportional and integral gains of the PI controller.

The controller output signal can be expressed as:

$$U_i(s) = -K_i(s)ACE_i(s) \tag{3}$$

3.2. Optimization Algorithms

The controller gain parameters are optimally tuned using BF-PSO, PSO, and the conventional ZN methods. The performance index, J , used in the process of optimization is formulated as the minimization of the integral of time multiplied absolute error (ITAE) as given by following equation:

$$J = \int_0^T \left(|\Delta f_i| + |\Delta P_{tiejk}|\right).t.dt \tag{4}$$

Where, j is area number $(1\ 2)$, and $k = 2$ (for $j \neq k$), 3

3.2.1. *PSO algorithm*

The PSO algorithm is well established as the tool used for optimization [23, 24]. This work also implements PSO algorithm for optimally tuning the gains of PI controller with the implementation process of the algorithm being described by the flow chart as given in Figure 2. The parameters chosen in this work for implementing the algorithm are as under:

Max generation =50
Population in swarm=50
$c_1 = 1.2$
$c_2 = 0.12$
$w = 0.9$

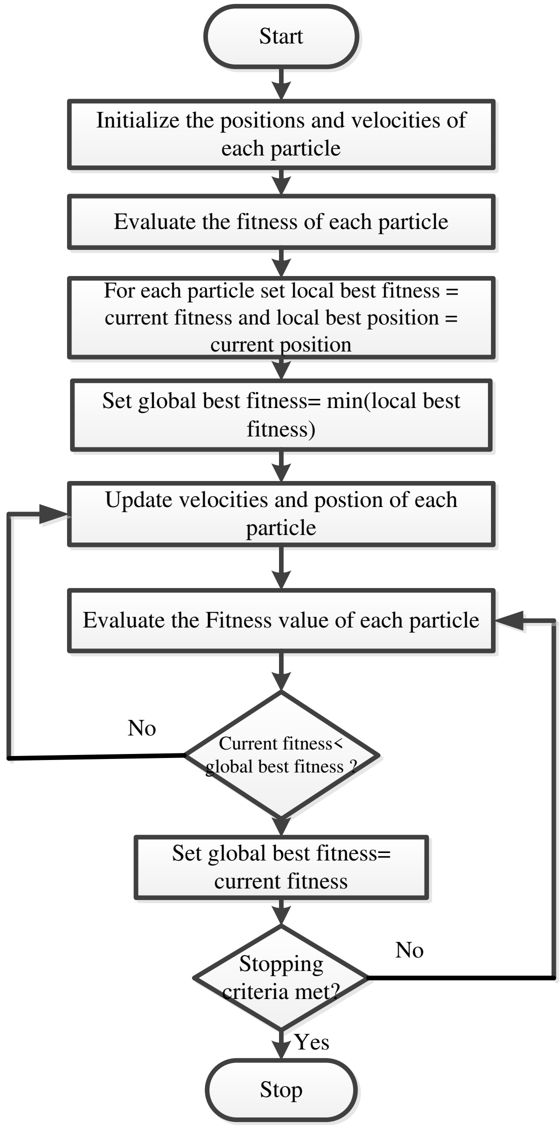


Figure 2. Flow chart of PSO algorithm.

3.2.2. *BF Algorithm*

The BF algorithm derives its inspiration from the searching and optimal foraging based decision making capabilities of the Escherichia coli (E coli) bacteria [25-28]. This algorithm has found numerous applications of optimization. In the present study also, the BF algorithm has been implemented on the similar lines as explained in [26-28] with the parameters as under:

Number of bacteria=10
Number of chemotactic steps=5
Limit of the length of a swim=4
Number of elimination-dispersal events=2
Probability that each bacteria will eliminated/dispersed=0.25

3.2.3. *Hybrid BF-PSO Algorithm*

The hybrid BF-PSO is the synergetic use of BF and PSO where the combined strengths of both the algorithms i.e. the ability of PSO to exchange social information and the ability of BF in finding a new solution by elimination and dispersal have been utilized. The algorithmic steps involved in the implementation of the hybrid algorithm for optimal tuning of PI controller are as explained in the form of flow chart given in Figure 3 [29]. The parameters of hybrid BF-PSO algorithm as used for simulation are as under:

Dimension of search space=6
Number of bacteria=10
Number of chemotactic steps=10
Limits the length of a swim=4
Number of reproduction steps=4
Number of elimination-dispersal events=2
Probability of each bacteria getting eliminated/dispersed=0.25.

4. RESULTS AND DISCUSSIONS

The model of the system under study is developed in SIMULINK with the optimization algorithms being implemented with the help of programs written in .m files. The controller gain parameters are optimally tuned, using various algorithms implemented in this study, with ITAE as the performance index. The results are compared qualitatively and quantitatively in respect of the minimum value of ITAE, rise time, settling time, peak overshoot, and peak time besides the nature of oscillations in the frequency as the performance measures.

The simulation results are discussed under the following four case studies:

Case-1. Equal step load increase in all areas

In this case, the perturbation applied in all the three areas is same- 1% step load increase- and the corresponding frequency deviation responses are shown in Figures 4 to 12 and the Tables 1 & 2 with different heads of hydro turbine. It is evident from these figures and the Tables that the hybrid BF-PSO algorithm provides the less oscillatory response with least settling time compared to all other algorithms wherein not only the frequency oscillations are poorly damped but also take large time to settle. The superior performance of the hybrid BF-PSO algorithm can also be established quantitatively by the values of the performance index, given in Table 1, which in case of hybrid BF-PSO algorithm are the minimum among all algorithms for different heads. Likewise, the other performance measures viz. the settling time, rise time, peak overshoot, and peak time, as given in Table 2, also indicate the superior performance of the hybrid BF-PSO algorithm resulting in lowest values.

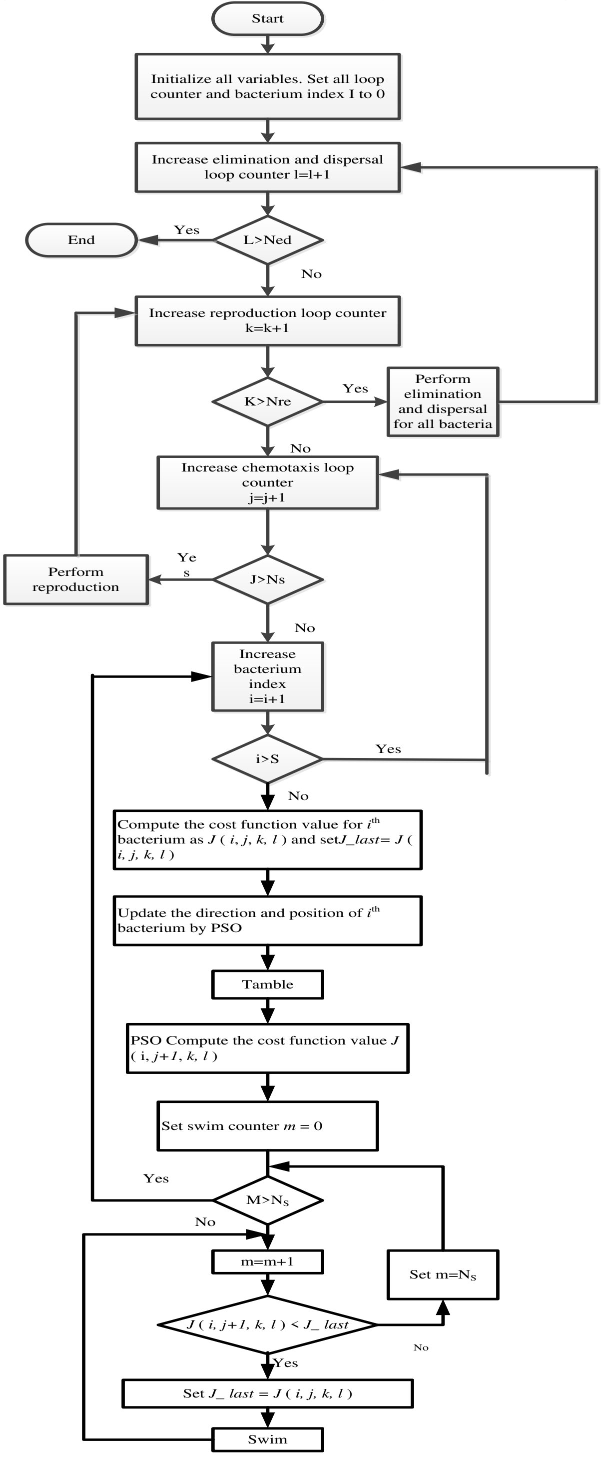


Figure 3. Flow chart of hybrid BF-PSO algorithm.

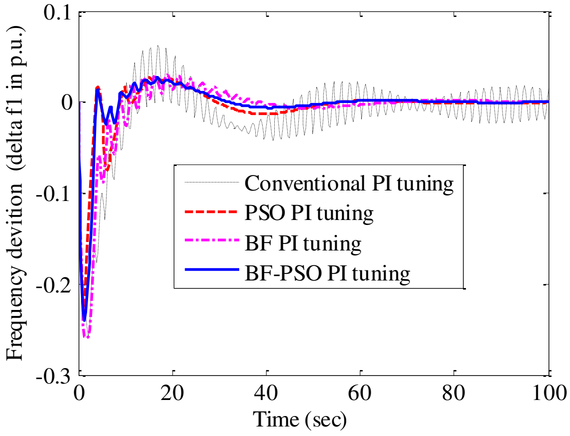


Figure 4. Area-1 frequency deviation to low head hydro turbine

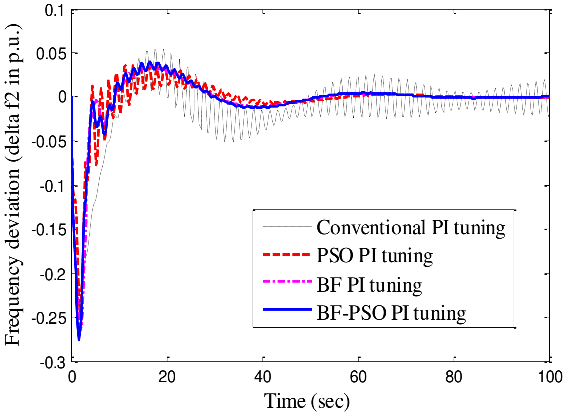


Figure 5. Area-2 frequency deviation to low head hydro turbine

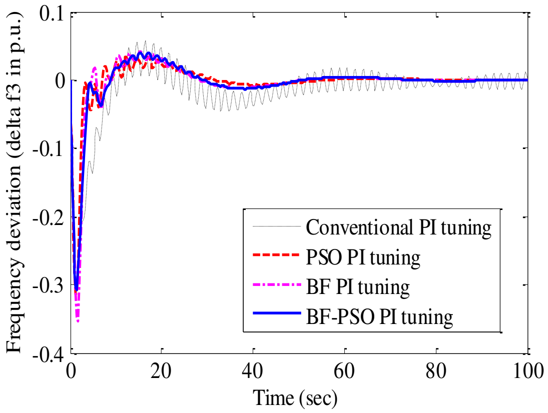


Figure 6. Area-3 frequency deviation to low head hydro turbine

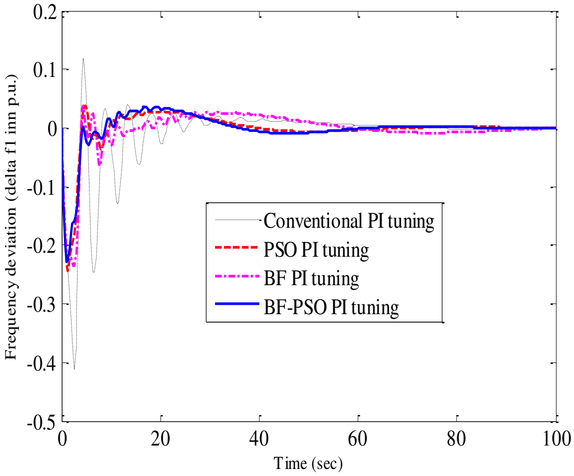


Figure 7. Area-1 frequency deviations to medium head hydro turbine

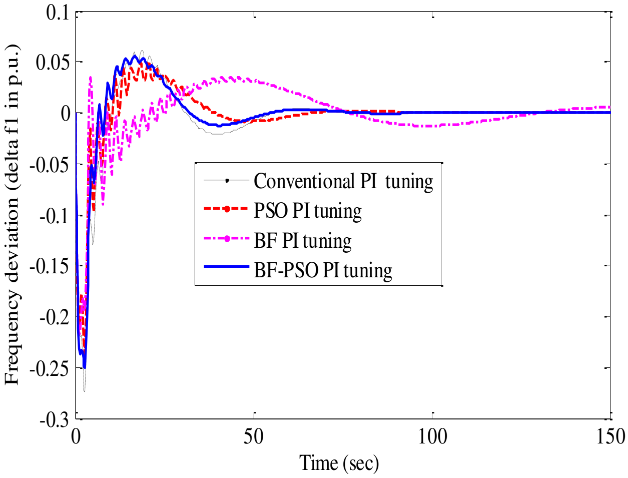


Figure 10. Area-1 frequency deviations to high head hydro turbine

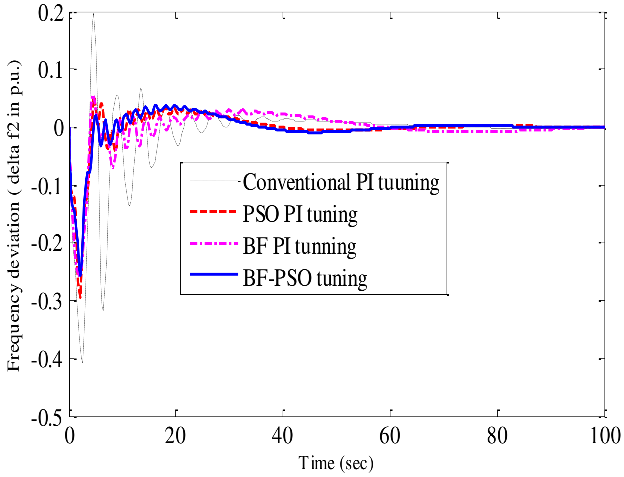


Figure 8. Area-2 frequency deviations to medium head hydro turbine

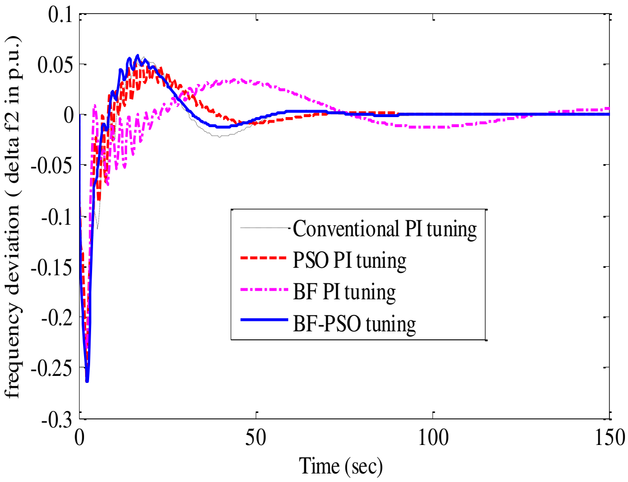


Figure 11. Area-2 frequency deviations to high head hydro turbine

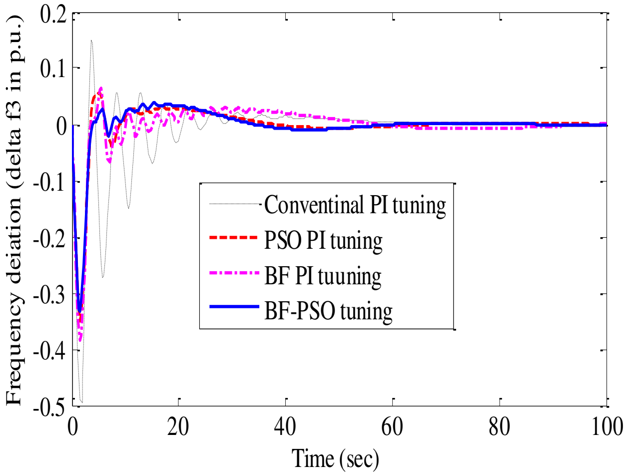


Figure 9. Area-3 frequency deviations to medium head hydro turbine

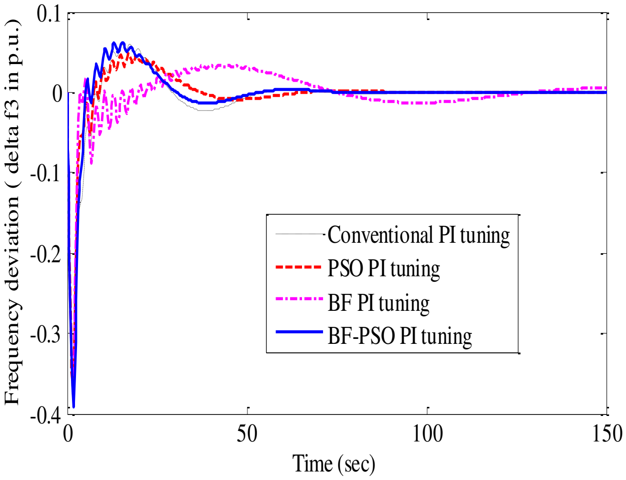


Figure 12. Area-3 frequency deviations to high head hydro turbine

TABLE I. VALUES OF ITAE PERFORMANCE INDEX FOR DIFFERENT ALGORITHMS AND HYDRO HEAD LEVELS

Algorithms	**Hydro head level**		
	Low	**Medium**	**High**
Conventional ZN	17.95	19.95	10.3586
PSO	6.7468	6.4624	8.7675
BF	5.6409	6.4300	8.9303
BF-PSO	**4.5960**	**5.6682**	**5.9053**

Case-2. Different step load increase in all areas

In this case, a simultaneous step increase in load of 5% in area-1, 4% in area-2, and 2% in area-3 is considered and the corresponding frequency deviation responses of area-1, as a representative case, with varying head of hydro turbine are shown in figures 13 to 15. As can be seen in these figures, the hybrid BF-PSO tuned controller achieves best dynamic performance in respect of less oscillatory response and the transients getting died down faster compared to the other algorithms. Further, it is clearly visible from the figures that the settling time and peak overshoot are least as well in case of hybrid BF-PSO algorithm. This establishes the superiority of the proposed scheme.

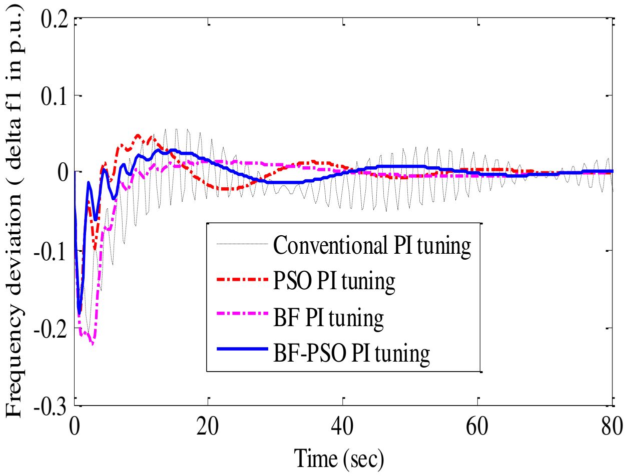


Figure 13. Area-1 frequency deviations to low head hydro turbine

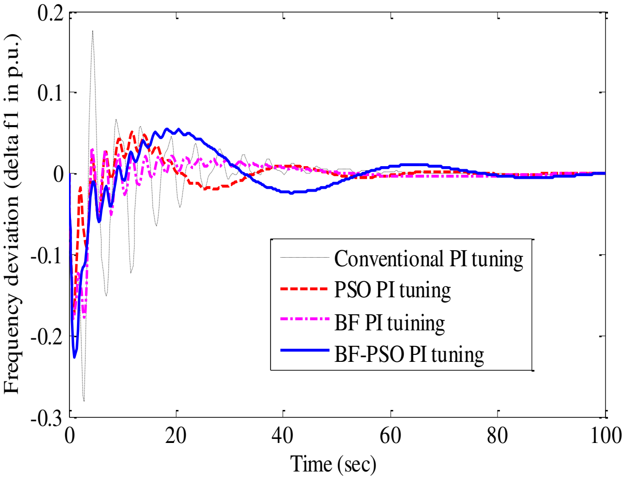


Figure 14. Area-1 frequency deviations to medium head hydro turbine

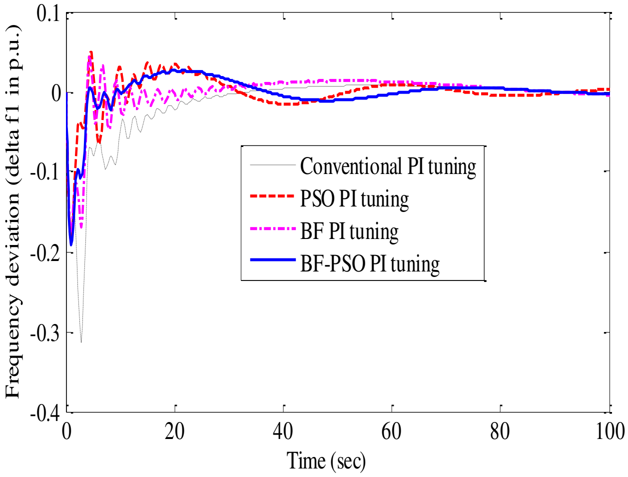


Figure 15. Area-1 frequency deviations to high head hydro turbine

Case-3. Random step load disturbance

To illustrate the dynamic response of the system under realistic load variations, the system is investigated under the effect of random step load disturbance the pattern of which is as depicted in figure 16. The corresponding system frequency deviation responses with varying head of hydro turbine are shown in Figures 17 to 19. As can be observed from the figures, the hybrid BF-PSO tuned controller regulates the system frequency, following a disturbance, quite better than the other implemented algorithms and provides the best response in respect of performance measures like less oscillatory response, least oscillation peaks, least settling time. Apart from this, the hybrid BF-PSO algorithm follows the random load variations and responds to those effectively.

TABLE II. Rise time (tr), Settling time (ts), Peak overshoot and Peak time of each system state variable for different algorithms in different Head of hydro system

Different head of hydro	System state variable	Algorithms	Performance parameters			
			t_r	t_s	Peak overshoot	Peak time
Low head	Δf_1	Conventional ZN	0.1093	165.5350	0.3498	1.3172
		PSO	8.9246×10^{-4}	50.1057	0.2369	1.2018
		BF	5.6576×10^{-4}	55.3043	0.2599	1.7903
		BF-PSO	**4.0755×10^{-4}**	**46.1636**	**0.2402**	**1.2336**
	Δf_2	Conventional ZN	0.1115	138.3684	0.2321	2.2003
		PSO	8.2982×10^{-4}	49.1838	0.2751	1.9989
		BF	3.9592×10^{-4}	52.6951	0.3026	2.2700
		BF-PSO	**2.6541×10^{-4}**	**49.1166**	**0.2793**	**2.0569**
	Δf_3	Conventional ZN	0.1140	137.4431	0.3489	1.3172
		PSO	6.3545×10^{-4}	47.2847	0.3201	1.4424
		BF	2.6505×10^{-4}	49.1166	0.3712	1.4223
		BF-PSO	**2.4841×10^{-4}**	**40.1503**	**0.3267**	**1.4882**
Medium Head of hydro	Δf_1	Conventional ZN	4.7467	99.9878	2.8064×10^{-19}	100
		PSO	2.7224×10^{-4}	56.3932	0.2435	1.2422
		BF	4.6318×10^{-4}	88.1009	0.2361	2.6262
		BF-PSO	**1.900×10^{-4}**	**54.3482**	**0.2281**	**1.0338**
	Δf_2	Conventional ZN	4.7467	99.7934	1.9555×10^{-19}	99.8116
		PSO	2.6231×10^{-4}	52.8701	0.2936	2.0652
		BF	4.6284×10^{-4}	87.1097	0.2575	1.8460
		BF-PSO	**1.900×10^{-4}**	**53.5446**	**0.2577**	**2.1963**
	Δf_3	Conventional ZN	4.8388	99.9919	5.8628×10^{-18}	99.3774
		PSO	5.3523×10^{-4}	33.1989	0.3488	1.4988
		BF	0.0053	79.5793	0.3848	1.4508
		BF-PSO	**1.900×10^{-4}**	**49.9484**	**0.3337**	**1.6027**
High Head of hydro	Δf_1	Conventional ZN	3.4752×10^{-4}	52.0489	0.2745	2.8180
		PSO	3.1604×10^{-4}	42.0278	0.2805	1.4223
		BF	0.0049	40.6676	0.2182	1.0811
		BF-PSO	**2.0265×10^{-4}**	**38.0612**	**0.2505**	**2.8218**
	Δf_2	Conventional ZN	3.8846×10^{-4}	52.5899	0.2547	2.5314
		PSO	3.7315×10^{-4}	49.1354	0.3246	2.5351
		BF	0.0049	44.3268	0.2326	2.0586
		BF-PSO	**2.0746×10^{-4}**	**40.9296**	**0.2639**	**2.530**
	Δf_3	Conventional ZN	3.4258×10^{-4}	49.4852	0.3828	1.6298
		PSO	3.2959×10^{-4}	46.0620	0.4359	1.6909
		BF	0.0052	41.0671	0.3685	1.6450
		BF-PSO	**2.6379×10^{-4}**	**40.3473**	**0.3913**	**1.6483**

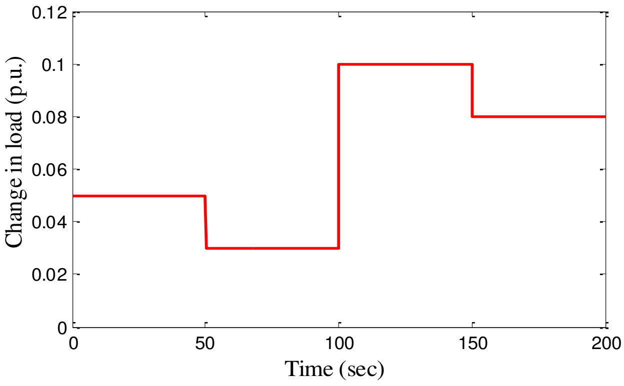


Figure 16 Random step load disturbances

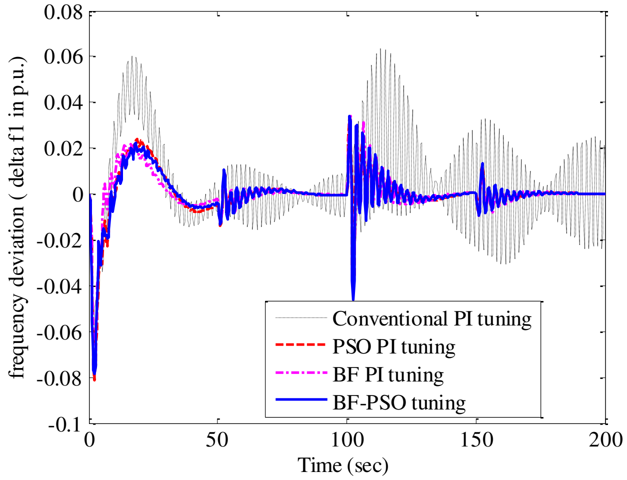


Figure 17 Area-1 frequency deviations to the low head hydro turbine

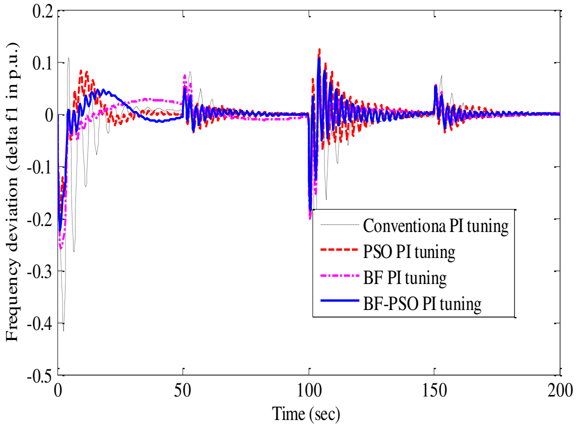


Figure 18 Area-1 frequency deviations to medium head hydro turbine

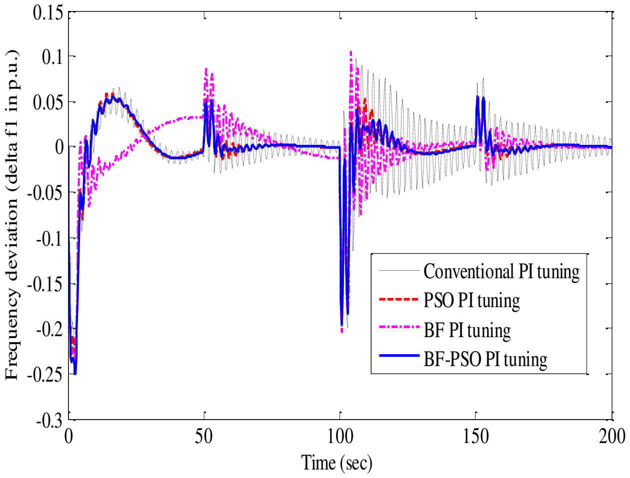
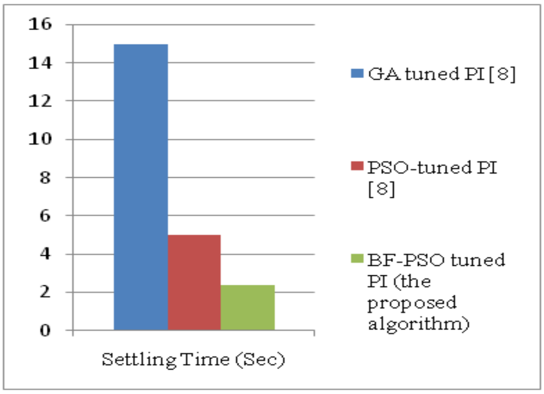


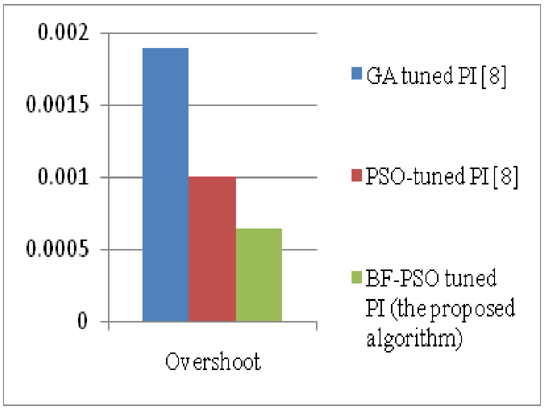
Figure 19 Area-1 frequency deviations to high head hydro turbine

Case-4. Comparative performance analysis with the existing works

This case study is conducted just to demonstrate the relative supremacy of the hybrid BF-PSO algorithm over other evolutionary algorithms employed in similar studies earlier. The exact same system could not be traced as implemented earlier, however, the system considered for this case (Figure 1(b)) is the nearest possible system [8]. So, this system is simulated here with parameters of PI controller optimized using hybrid BF-PSO algorithm and also with other optimization algorithms already implemented by authors on the same system [8], merely for comparative analysis to demonstrate the supremacy of the BF-PSO algorithm. A 1% step load is applied to area-1 at t=0 s and the settling time and peak overshoot values are obtained as shown in Figures 20 (a) and (b), respectively as against the reported works of other authors for the similar study but with different optimization algorithms. As is evident from Figures 20 (a & b), the hybrid BF-PSO algorithm provides the best results compared to other algorithms.



(a)



(b)

Figure 20. Comparative (a) settling times and (b) peak overshoot values

5. CONCLUSIONS

The hybrid BF-PSO tuned PI controller is implemented in this paper for frequency regulation in a three area power system consisting of diverse sources. For comparative analysis, other evolutionary algorithms namely, BF, PSO, and conventional ZN are also implemented. An ITAE of the frequency deviation of three areas and tie line power deviation is taken as the objective function for tuning the controller gain parameters. The system performance is analyzed in terms of minimum values of performance index, rise time, settling time, peak overshoot, peak time and the extent of mitigation of oscillations in the frequency deviations. The system is investigated under three different test cases and the simulation results established the supremacy of hybrid BF-PSO tuned controller compared to conventional ZN, PSO and BF tuned controller in all the three test cases. The BF-PSO algorithm has proved to be superior in mitigating the oscillations of frequency deviations and is very effective in regulating the frequency with load variations and varying head of hydro turbine. Besides, a comparative performance analysis vis-a-vis the existing works is also carried out which as well reinforced the superiority of the hybrid BF-PSO algorithm.

APPENDIX-A: SYSTEM PARAMETERS[9, 29]

The typical values of parameters of system under study are shown below:

$$f = 60Hz, P_R = 2000\, W(rating), P_L = 1000\, MW\ (norminal\ loading)$$

A.1. Nominal parameter of Area-1 system with governor dead band nonlinearity is

$$T_{g1} = 0.2\, s, T_{t1} = 0.3\, s$$

A.2. Nominal parameter of Area-2 reheat thermal power system is

$$T_{g2} = 0.08, T_r = 10\, s, K_r = 0.5\, s, T_{t2} = 0.3\, s$$

A.3. Parameters of different head of hydro turbine

Head	**T_w (Sec)**	**T_R (Sec)**	**T_{RH} (Sec)**	**T_{GH} (Sec)**
Low	1.0	5	28.75	0.2
Medium	2.2	9.68	112.87	0.3
High	4.0	14	259	0.3

$$B_1 = B_2 = B_3 = 0.425, R_1 = R_2 = R_3 = 2.4 \frac{Hz}{p}.u.MW$$

$$K_{P1} = K_{P2} = K_{P3} = 120\, Hz/p.u.MZ, T_{P1} = T_{P2} = T_{P3} = 0.086\, p.u.$$

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