

METAHEURISTIC OPTIMIZED PID TUNING FOR LOAD FREQUENCY CONTROL OF MULTI- AREA MULTI- SOURCE POWER SYSTEM WITH AND WITHOUT HVDC LINK

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Abstract: In this paper a hybrid Bacterial Foraging Optimization Algorithm - Particle Swarm Optimization (hBFOA-PSO) tuned Proportional Integral Derivative (PID) controller is proposed for Load Frequency Control (LFC) of an interconnected power system. A novel attempt is also made to extend the proposed approach further for a multi- area multi- source power system with/without High Voltage Direct Current (HVDC) link. The modifications in the objective function are also introduced in this paper and better output results are exhibited compared to conventional objective functions. To demonstrate the ability of the proposed approach to handle nonlinearity and physical constraints, the phenomena such as the load changes and Governor Dead Band (GDB) nonlinearity are included in the system model. The superiority of the proposed hBFOA-PSO tuned PID controller are verified by comparing its results with the designed Bacterial Foraging Optimization Algorithm (BFOA), Particle Swarm Optimization (PSO) approaches as well as the results of recently documented optimization methodologies for the same interconnected system. All the simulation results clearly reveal that, the proposed approach has better transient performances, robustness and convergence characteristics in both single- source and multi- source power systems over other alternatives.

Key words: Bacterial foraging optimization algorithm, Governor dead band nonlinearity, hybrid Bacterial Foraging Optimization Algorithm - Particle Swarm Optimization, Load Frequency Control, Particle swarm optimization algorithm, PID tuning.

1. Introduction

The main aim of power generating system is to deliver adequate, high quality, reliable and efficient power to the load. LFC is one of the most important research problems in power systems operation and control for supplying sufficient and reliable electric power with good quality. However, the increased size and complexity of modern interconnected power systems and the dynamics in load requires increased intelligence and flexibility in LFC system to ensure the capability of maintaining a generation-load balance [1].

Normally, the primary means of frequency control in a LFC loop is executed with the governor mechanism, and the supplementary control is offered with the controllers like Proportional (P), Integral (I), Proportional Integral (PI) and Proportional

Integral Derivative (PID) controller [2, 3]. It is obvious from the literatures that, the performance of power system mainly depends on the types of controllers used. In general, the PID controllers are largely preferred as the most adopted controllers in industrial settings because of the advantageous cost/benefit ratio they are able to provide. This controller is also used in the fields, where fast and stable output responses of system are required.

However, tuning the gain parameters of PID controller is always a challenging task. The early research works were mainly focused to design the classical tuning methodologies with small load perturbations. The conventional ways of tuning provides fixed gain parameters. These fixed gain controllers fail to provide best control performances under wide range of operating conditions. To overcome these drawbacks, many heuristic algorithm-based optimal tuning of controllers such as Imperialist Competitive Algorithm [4, 5], Bacteria Foraging Optimization Algorithm (BFOA) [6], Differential Evolution (DE) [7, 8], Artificial Bee Colony Algorithm [9], Fuzzy Gain Scheduling [10] and Cuckoo Search algorithm [11] are developed nowadays in order to control the frequency of the generating system within the permissible limit.

Recently, it has been reported in many researches that, the development of hybrid algorithms combines the effectiveness of two intelligent approaches and pledge to overcome the difficulties of single classic intelligent approach. Accordingly, the performance of LFC has been greatly improved with hybrid algorithms such as hybrid DEPS optimized fuzzy PI/PID [12], hybrid BFOA-PSO [13], hybrid PSO and PS [14], hybrid FA and PS [15] compared to individual intelligent approaches.

In the view of above, a maiden attempt has been made in this paper to design an hBFOA-PSO tuned PID controller for LFC system. In all intelligent controllers, the objective function is first defined based on the desired specifications and constraints. The conventional objective functions normally considered in the control design are Integral Square Error (ISE), Integral Time Square Error (ITSE) and Integral Time Absolute Error (ITAE). To enhance the performance of LFC, a novel objective function is also proposed in this paper that includes the

minimization of fundamental time domain specifications such as steady state error, maximum peak, settling time, rise time and peak time in addition to the error minimization. The superiority of the proposed hBFOA-PSO approach employed with proposed objective function is proved over the alternate PSO and BFOA tuned PID controllers developed in this article and recently published modern heuristic optimization approaches [7, 13] for the same system configurations.

To prove the ability of the proposed approach in way of handling nonlinearity and physical constraints, the system model is subjected to the, load changes, parameter changes and Governor Dead Band (GDB) nonlinearity. The proposed hBFOA-PSO approach with proposed fitness function is further tested in two-area interconnected LFC system with GDB nonlinearity and the dominance is proved over craziness based particle swarm optimization (CBPSO) approach [16].

In virtually interconnected power systems, the power generation normally comprises of a mix of thermal, hydro, nuclear and gas power plants. In most of the literature reviews AC tie lines are used for the interconnection of multi-area multi-source power systems and lesser attention is given to AC-DC parallel tie lines. Recent researches have obviously proved that the HVDC link is connected in parallel with the existing AC tie lines of multi-source LFC system for stabilizing frequency oscillation and used an optimal output feedback controller for frequency stabilization [8, 17, and 18]. It is also proved in recently published article that, the incorporation of DC link in parallel with AC link as an area interconnection enables the system to have an appreciable improvement in stability margins [19]. Also the performance index value of the system has been reduced when parallel AC/DC links are used. Also, it has been proved that the use of DC link not only improves the dynamic stability of the system but also lowers the cost index. Keeping in view, the study on the proposed approach is further extended to multi-area, multi-source power system including thermal-hydro-gas systems with/without HVDC link. The supremacy of the proposed hBFOA-PSO tuned PID controller in multi-area multi-source system is also confirmed by comparing the results with DE algorithm for same system configurations [8].

In this research work, the proposed hBFOA-PSO approach is tested in various LFC system models such as two area interconnected LFC system with and without GDB nonlinearity, multi source single area system, multi-source multi-area system with and without HVDC link. Furthermore, detailed analyses such as transient analysis, convergence analysis and robustness analysis are carried out in this article. All these analyses undoubtedly reveal that, the proposed hBFOA-PSO tuned PID controller is suitable for all

types of LFC structures and outperforms established approaches under both linear and nonlinear conditions of the power system.

2. Materials and methods

2.1. Description of LFC in a Two Area Thermal Power System

A widely used standard two-area thermal power system [7, 13, and 18] is considered in this research work and its linearised model is shown in Fig. 1. Each area of the power system consists of speed governing system, hydraulic valve actuator, turbine, generator and load with a rating of 2000 MW and a nominal load of 1000 MW. During load change/uncertainties the initial frequency control is offered by its own governor-turbine mechanism and a supplementary control is supplied with PID controllers for tuning the frequency error to zero. In this paper, enhancing the performance of LFC with optimal tuning of PID controller is designed as an optimization problem. The three intelligent algorithms named PSO, BFOA and hBFOA-PSO are designed and prescribed in this report for effective tuning of the PID controller parameters and a comparative analysis is also made between them.

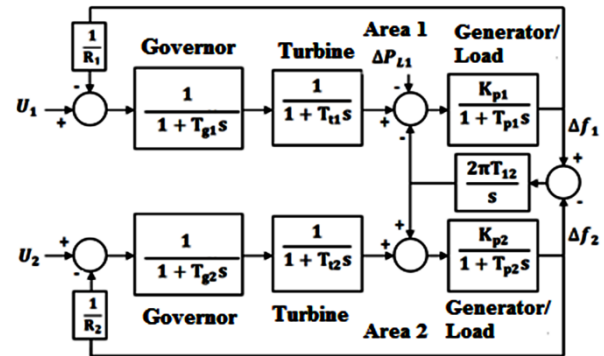


Fig. 1. Linearised model of two area LFC system.

In Fig. 1, u_1 and u_2 are the control outputs from the controller; R_1 and R_2 are the governor speed regulation parameters in p.u. Hz; T_{g1} and T_{g2} are the speed governor time constants in seconds; T_{t1} and T_{t2} are the turbine time constants in seconds; ΔP_{L1} and ΔP_{L2} are the step load demand changes; K_{p1} and K_{p2} are the power system gains; T_{p1} and T_{p2} are the power system time constants in seconds; T_{12} is the synchronizing coefficient and Δf_1 and Δf_2 are system frequency deviations in Hz. The relevant parameters are given in Appendix A.

2.2. Objective function

In the design of any optimally tuned controller, the objective function is first defined based on the desired specifications and constraints. The three commonly used conventional minimization objective functions (1) for effective convergence of the solution to an optimal point are ISE, ITSE and

ITAE respectively (2-4)

$$\text{Fitnessfunction} = \text{Min}(J) \quad (1)$$

$$\text{ISE} = \int_0^{t_{\text{sim}}} (\Delta F_1^2) + (\Delta F_2^2) + (\Delta P_{\text{Tie}}^2) \cdot dt \quad (2)$$

$$\text{ITSE} = \int_0^{t_{\text{sim}}} [(\Delta F_1^2) + (\Delta F_2^2) + (\Delta P_{\text{Tie}}^2)] \cdot t \cdot dt \quad (3)$$

$$\text{ITAE} = \int_0^{t_{\text{sim}}} (|\Delta F_1| + |\Delta F_2| + |\Delta P_{\text{Tie}}|) \cdot t \cdot dt \quad (4)$$

In above equations, ΔF_1 is the absolute value of frequency deviation error in area 1, ΔF_2 is the absolute value of frequency deviation error in area 2, ΔP_{tie} is the absolute value of tie line power deviation error, t_{sim} is the time range of simulation.

However, these three objective functions only focus on error minimization in frequency deviations in area-1 and 2 (ΔF_1 and ΔF_2) and tie line power deviation (ΔP_{tie}) of the LFC system. Hence, to enhance the control performances, the LFC is considered as a multi-objective optimization problem and a maiden attempt is also made to design a new objective function (5) which includes minimization of fundamental time domain specifications in addition to the error minimization. The proposed multi-objective function (J_R) is designed with one of the popular classical weighted-sum approach where, a single objective function is formulated as a weighted sum of the individual objectives. But the problem lies in the correct selection of the weights and their values are problem dependant. The values of weighting factors for this research work are chosen by trial and error method.

$$J_R = w_1 \Delta e_T + w_1 P_m + w_3 T_s + w_4 T_r + w_5 T_p \quad (5)$$

In the above equation, Δe_T is the total output error and can be termed as, $\Delta e_T = |\Delta F_1| + |\Delta F_2| + |\Delta P_{\text{tie}}|$. Likewise, J is the fitness value of particle, P_m is the maximum peak of the output wave form, T_s and T_r are the settling time and rise time respectively and w_1, w_2, w_3, w_4 and w_5 are the weighting factors.

3. Intelligent tuning of PID controller

A The PSO is a population based search algorithm where each individual is referred to as particle and represents a candidate solution. Each particle in PSO flies through the search space with an adaptable velocity that is dynamically modified according to its own flying experience and also to the flying experience of the other particles [20].

In PSO algorithm, the ability of exchanging social information with personal best and global best solutions seems to be more beneficial compared to BFOA. Nevertheless, in PSO algorithm the solutions may trap in past optimal or local minima depends on the speeds of particles.

The BFOA, mimics the foraging (locating, handling, ingesting food) strategy of E.Coli bacteria

in a nutrient search space. It has been widely accepted as a global optimization algorithm of current interest for distributed optimization and control. Normally, the E.Coli bacteria undergo four stages during the foraging strategy. They are chemotaxis, swarming, reproduction and elimination- dispersal correspondingly [13, 21].

However, the reproduction and elimination - dispersal steps in BFOA approach prevents the solution being trapped in local optima and makes the algorithm to produce global optimal solutions. Hence, the hBFOA-PSO algorithm is designed in this paper, to combine the merits and to overcome the drawbacks of both PSO and BFOA. The procedural steps of hBFOA-PSO algorithm are as follows:

Step 1: All the essential parameters of both PSO and BFOA techniques are initialized for hBFOA-PSO algorithm [6, 13, and 20].

Step 2: The initial chemotactic movement of particles can be computed using BFOA approach as follows:

Let, the index of Number of bacteria (S) be represented as i , Number of chemotaxis (N_c) denoted as j , Number of reproduction steps (N_{re}) indicated by k and Number of elimination-dispersal events (N_{ed}) represented as l and the iterations are framed with these indexes. Initially, S number of random control parameters for area-1 and area-2 as a set of positional values (P) within a specified range (6) for area-1 and area-2 are generated in a search space. The fitness value (J) of every particle and their positional values (P) are computed in consecutive iteration (7).

$$0 \leq K_{p1}, K_{i1}, K_{d1}, K_{p2}, K_{i2}, K_{d2} \leq 1 \quad (6)$$

$$J(i, j, k, l) = \text{Function}(P(i, j, k, l)) \quad (7)$$

The excellent solution is then located with the minimum fitness value employing with the proposed objective function (4) described in section 2. In computational programming it is just done by sorting all the fitness values in descending order and selecting the last one (8). Then, each particle makes a chemotactic movement in random direction as indicated in (9)

$$J_{\text{last}} = J(i, j, k, l) \quad (8)$$

$$P(i, j+1, k, l) = P(i, j, k, l) + C(i)\phi(j) \quad (9)$$

where, $C(i)$ for $i=1,2,\dots,S$ is the size of step taken in random direction $\phi(j)$. The value of $\phi(j)$ can be calculated with a random vector (10).

$$\phi(j) = \frac{\Delta(i)}{\sqrt{\Delta^T(i) \cdot \Delta(i)}} \quad (10)$$

where, Δ indicates a vector in random direction whose elements are in the range of $[-1, 1]$. After the chemotactic movement the particles reach a new position $P(I,j+1,k,l)$ in search space. The fitness value for this new position can be evaluated (11) and the best fitness value is again computed and stored

as J_{last} (8).

$$J(i, j+1, k, l) = \text{Function}(P(i, j+1, k, l)) \quad (11)$$

When, the fitness value J evaluated for the current chemotactic step $J(i, j+1, k, l)$ is less than the previous one $J(i, j, k, l)$, another step will be taken by every particle in the same direction. Otherwise, the bacterium will tumble in random direction. This consecutive movement lead the particles to move towards the direction of decreasing the fitness function and finally to reach the best fitness value.

Step 3: For each particle i , at each chemotactic movement j , compute the best fitness value as local best with the index of J_{local} (12) and the corresponding positions with a set of control parameters (K_p, K_i, K_d) are predicted as local best positions P_{local} (13).

$$J_{local}(j) = J(i, j+1, k, l) \quad (12)$$

$$P_{local}(j) = P(i, j+1, k, l) \quad (13)$$

Step 4: At the end of each chemotactic movement, best fitness among J_{local} is evaluated and stored as J_{global} and the corresponding position of the particle is stored as P_{global} .

Step 5: During the next iteration, the position of each particle will be changed (14) with the velocity equation (15, 16) designed using PSO algorithm.

$$\phi(j+1) = v(j+1) \quad (14)$$

$$v_i^{t+1} = wv_i^t + c_1 * r_1 (P_{local} - P_i) \quad (15)$$

$$+ c_2 * r_2 (P_{global} - P_i) \\ P_i^{t+1} = P_i^t + v_i^{t+1} \quad (16)$$

Step 6: Substitute (14) in (9) and repeat the algorithmic steps 2- 6 over the specified number of chemotactic movements.

Step 7: Extend the algorithm with the significant reproduction operation and elimination- dispersal event of BFOA approach.

4. Results and Discussions

4.1. Transient Analysis of two area LFC

In this section, the output responses of the LFC test system is studied with PSO, BFOA and hBFOA-PSO tuned PID controller, employing proposed (J_R) objective function by considering 10 % Step Load Perturbation (SLP) at area-1.

A comparative analysis is made among all the approaches in view of, fundamental time domain specifications of the output responses. The fitness values of all the optimization approaches are also computed with the optimal values of control parameters. The simulated results are plotted as shown in Fig. 2. In addition, for detail analysis all the transient parameters such as steady state error, settling time, peak, rise time and peak time of the output responses are measured from Fig. 2 are also depicted in Table 1.

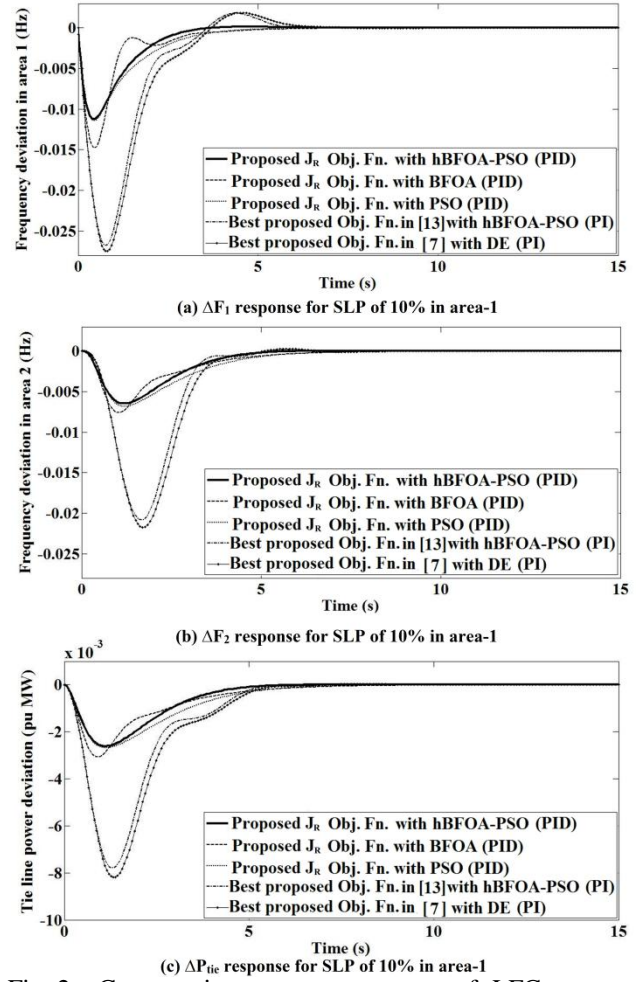


Fig. 2. Comparative output responses of LFC system with proposed (J_R) objective function.

To demonstrate the effectiveness of the proposed objective function J_R , the output performances of the LFC test system with proposed hBFOA-PSO tuned PID controller employing J_R are compared with the dominant system performances obtained with best proposed objective functions in hBFOA-PSO tuned PI controller [13] and DE tuned PI controller [7] approaches documented earlier. These best proposed objective functions termed in references [7, 13] have already been proven as a prominent one compared to conventional ITAE objective function. This comparative analysis is also clearly illustrated in Table 1. It is evidently proved from Fig. 2 and Table 1 that, the output responses of LFC system corresponding to the proposed hBFOA-PSO tuned PID controller employing J_R objective function are enormously better from the point of view of steady state error, settling time, magnitude of oscillations and peak deviations compared to other objective functions published in earlier literatures.

Table 1. Transient performance analysis of LFC employing J_R objective function

| Control and Measuring parameters | hBFOA-PSO tuned PID controller (J_R) | BFOA tuned PID controller (J_R) | PSO tuned PID controller (J_R) | hBFOA-PSO tuned PI controller with best proposed obj.fun in [13] | DE tuned PI controller with best proposed obj.fun in [7] |
|--|--|-------------------------------------|------------------------------------|--|--|
| K_{p1} | 0.3693 | 0.5041 | 0.3797 | -0.4383 | -0.4741 |
| Area 1 K_{i1} | 0.8312 | 0.7630 | 0.6771 | 0.3349 | 0.3047 |
| K_{d1} | 0.4338 | 0.1545 | 0.4175 | 0 | 0 |
| K_{p2} | 0.7718 | 0.2747 | 0.8168 | -0.4383 | -0.4741 |
| Area 2 K_{i2} | 0.3585 | 0.3538 | 0.6075 | 0.3349 | 0.3047 |
| K_{d2} | 0.7931 | 0.6412 | 0.5619 | 0 | 0 |
| Fitness Value (J_R) | 0.22406 | 0.59439 | 0.55992 | 1.4933 | 0.9911 |
| Frequency deviation in area-1 (ΔF_1) | | | | | |
| Steady state error | 2.32×10^{-5} | -7.79×10^{-5} | 8.64×10^{-6} | -8.41×10^{-5} | 1.28×10^{-4} |
| Settling Time | 6.2116 | 6.7741 | 6.2479 | 6.5486 | 6.8407 |
| Peak | 0.1087 | 0.1432 | 0.1103 | 0.2543 | 0.26099 |
| Rise Time | 0.0087 | 0.0001 | 0.6277 | 0.0001 | 0.0001 |
| Peak Time | 0.4102 | 0.4448 | 0.4270 | 0.6830 | 0.79158 |
| Frequency deviation in area-2 (ΔF_2) | | | | | |
| Steady state error | 4.10×10^{-5} | -2.08×10^{-4} | -4.82×10^{-5} | 1.47×10^{-4} | 8.54×10^{-5} |
| Settling Time | 5.5283 | 8.3538 | 7.9923 | 6.9729 | 6.1101 |
| Peak | 0.0680 | 0.0819 | 0.0719 | 0.2172 | 0.2259 |
| Rise Time | 0.0447 | 0.0339 | 0.0244 | 0.0091 | 0.0047 |
| Peak Time | 1.0830 | 0.9477 | 1.0827 | 1.5867 | 1.5895 |
| Tie line power deviation (ΔP_{tie}) | | | | | |
| Steady state error | 7.16×10^{-7} | -1.18×10^{-4} | -3.44×10^{-5} | 6.37×10^{-5} | 1.0163×10^{-4} |
| Settling Time | 5.7595 | 8.5496 | 8.2208 | 6.3852 | 6.4003 |
| Peak | 0.0274 | 0.0332 | 0.0280 | 0.0824 | 0.0861 |
| Rise Time | 0.0033 | 0.0163 | 0.0099 | 0.0347 | 0.0663 |
| Peak Time | 1.0039 | 0.8205 | 1.0062 | 1.1872 | 1.1896 |

4.2. Convergence analysis

All the optimization problems are targeted to have better convergence characteristics with a minimum convergence time along with an optimal solution. The evolutionary tendency of optimization algorithms can only be investigated with the convergence of output, and is measured through the fitness value of system response over consecutive iterations. Moreover, the convergence can also be visualized through the positional values of particles over number of iterations.

The comparison of fitness values evaluated through hBFOA-PSO, BFOA and PSO tuned PID controllers with J_R objective function over consecutive iterations are illustrated in Fig. 3. It is apparent from this figure that faster convergence can be obtained with the proposed hBFOA-PSO optimized PID controller compared to PSO and BFOA employing J_R objective function. Also it is confirmed that the final fitness value corresponding to the proposed hBFOA-PSO approach is minimum

compared to other optimization approaches.

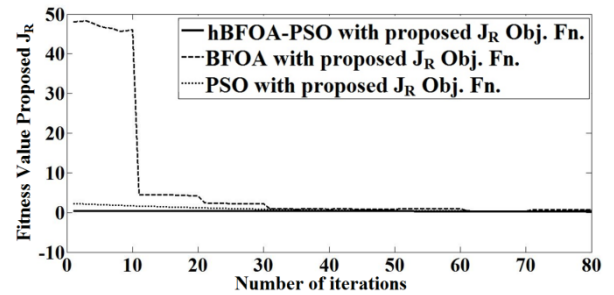


Fig. 3. Convergence analysis of optimization approaches with fitness values.

Likewise, the positional values of the control parameters (K_{p1} , K_{i1} , K_{d1} , K_{p2} , K_{i2} and K_{d2}) over consecutive iterations are depicted in Fig. 4. And it clearly illustrates that, the positional values of both PSO and BFOA algorithms are erratic and the hBFOA-PSO possesses stable positional values. In view of above, it is clear that, the proposed hBFOA-

PSO with proposed J_R objective function exhibits preferable convergence characteristics compared to other optimization approaches.

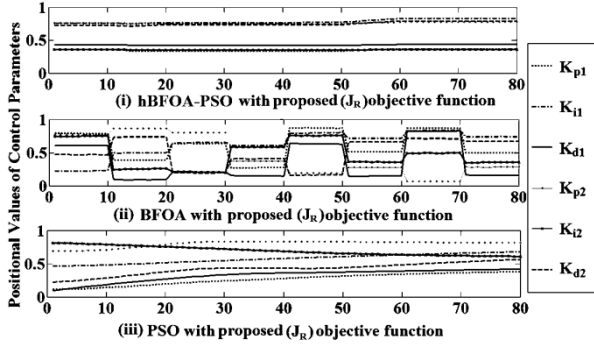


Fig. 4. Convergence analysis with positional values of control parameters.

4.3. Robustness analysis under load variations

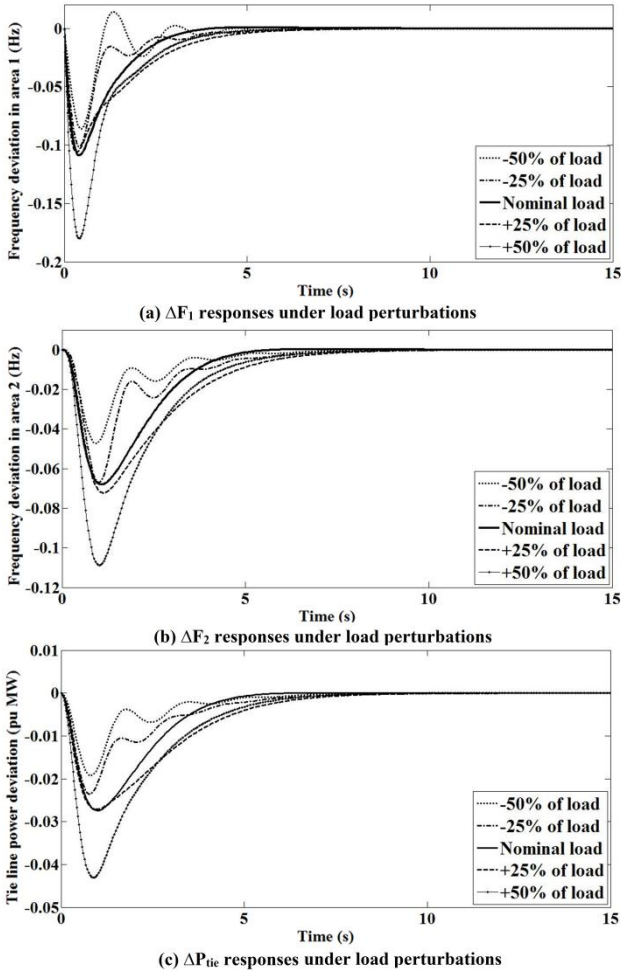


Fig. 5. Robustness analysis of the LFC system with variable load perturbations.

Generally, the frequency deviation and tie line power deviation responses in LFC system changes according to load fluctuations. To analyse these changes, the operating load conditions are changed by $\pm 50\%$ from their nominal values and related

control parameters are optimized with the proposed approach.

The output performances of LFC system simulated with these optimal control parameters are presented in Fig. 5. It is well-understood from this figures that, maximum frequency deviations in area 1 and area 2 are very less over entire load variations and they are around 0.0951Hz and 0.005Hz. Similarly, the deviation in tie line power over these load variations are around 0.007Hz. In the same way, the maximum deviation in settling time of ΔF_1 , ΔF_2 and ΔP_{tie} responses are within 1.5s. This ensures the robustness and stable control performances of LFC system with the proposed HBFOA-PSO approach employing J_R objective function against the load variations.

4.4. Extension to non-linear power system

To analyse the practical establishment of the proposed approach, the study is further extended by introducing non-linearity in the power system model by considering the effect of Governor Dead Band (GDB) in speed governor of the system [16] as shown in Fig. 6 and the configurations are shown in Appendix B.

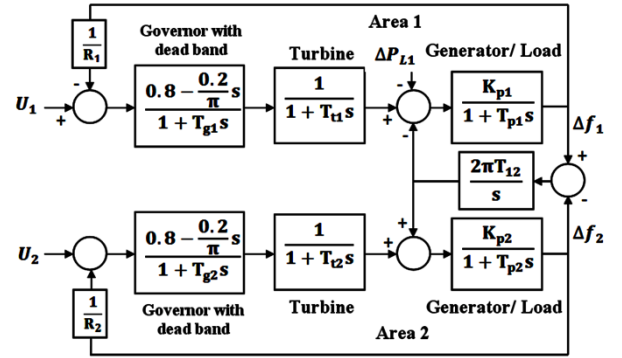


Fig. 6. Linearised model of two area LFC system with governor dead band nonlinearity.

Normally, GDB is the hysteresis effect mainly arises due to the mechanical friction, backlash and valve overlaps in hydraulic relays. The GDB will make significant disturbances on the governor's performance and also on the transient performances like amplitude and settling time of the oscillations [16, 22]. Hence, the effect of GDB nonlinearity is considered in this paper. The Fourier expansion of the transfer function of GDB is represented in equation (17) below.

A step change in load perturbation of 1% is applied to the area 1 of the LFC system with GDB nonlinearity and the PID controller is optimized with proposed hBFOA-PSO tuned PID with J_R objective function. The simulated performances of test system corresponding to these optimal control parameters are shown in Fig. 7. The tuned control parameters and the output measurements of these figures are tabulated in Table 2.

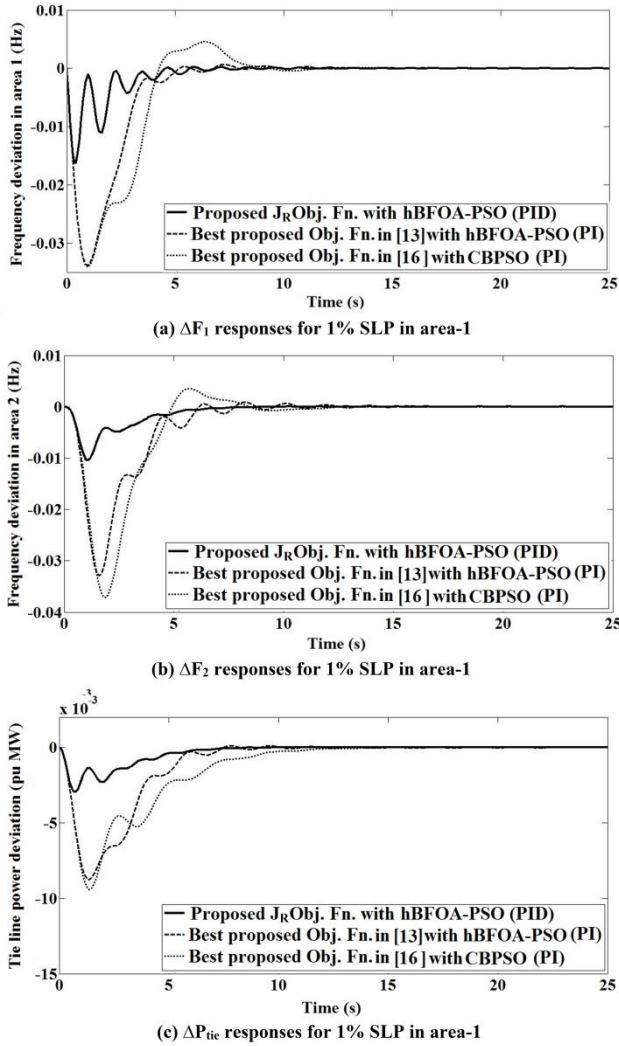


Fig. 7. Output responses of LFC employing J_R objective function with GDB nonlinearity.

Table 2. Comparative output response of LFC with GDB nonlinearity

| Parameters | | A* | B* [13] | C* [16] |
|--------------------|------------------|--------|---------|---------|
| Control parameters | K_{p1} | 0.7357 | -0.5484 | -0.5762 |
| | K_{i1} | 0.7473 | 0.2277 | 0.1962 |
| | K_{d1} | 0.8288 | - | - |
| | K_{p2} | 0.2864 | -0.5484 | -0.5762 |
| | K_{i2} | 0.0127 | 0.2277 | 0.1962 |
| | K_{d2} | 0.1717 | - | - |
| Maximum peak | ΔF_1 | 0.0162 | 0.0337 | 0.0339 |
| | ΔF_2 | 0.0104 | 0.0362 | 0.0372 |
| | ΔP_{tie} | 0.0030 | 0.0091 | 0.0093 |
| Settling time | ΔF_1 | 8.396 | 10.85 | 9.65 |
| | ΔF_2 | 7.5407 | 10.95 | 10.98 |
| | ΔP_{tie} | 8.3304 | 9.43 | 13.16 |

A* - Proposed hBFOA-PSO tuned PID controller with J_R objective function

B* - hBFOA-PSO tuned PI controller with best proposed objective function in reference [13]

C* - CBPSO tuned PI controller with best proposed objective function in reference [16]

To demonstrate the effectiveness, the simulated performances of the proposed hBFOA-PSO tuned PID controller with GDB employing J_R objective function, are compared with the documented results of hBFOA-PSO tuned PI controller [13] and CBPSO tuned PI controller [16] employing their best proposed objective functions which has been proven as a prominent one in those references [13, 16].

The Table 2 distinctly proves that, the output frequency responses of the system in both areas (ΔF_1 , ΔF_2) and tie line power responses (ΔP_{tie}) of two area LFC system with GDB nonlinearity are tremendously improved with minimum overshoot and faster settling time by the proposed hBFOA-PSO tuned PID controller compared to other approaches.

4.4. Extension to multi-source multi-area system

To demonstrate the effectiveness of the proposed hBFOA-PSO tuned PID controller, the study is further extended to a multi-area multi-source interconnected power system with/without HVDC link. In multi-source power system under consideration each area comprises reheated thermal, hydro and gas generating units.

4.5.1 Multi-source single-area power system

The single area multi-source power system including thermal-hydro-gas generation is considered in this section. A step change in load demand of 1% is applied to the system under consideration. The upper and lower limits of the controller gains are chosen as (0, 1). The integral and PID controller for single area multi-source power system are effectively tuned with the proposed hBFOA-PSO algorithm employing ITAE objective function and the tuned controller parameters are listed in Table 3.

The frequency deviation responses corresponding to the tuned integral and PID controller parameters of the system are plotted as shown in Fig. 8 and Fig. 9. To show the dominance of the proposed hBFOA-PSO approach, the results are compared with DE algorithm for the same power system [8] as scheduled in Table 4. The enlarged portion A and B of Fig. 8 and Table 4 clearly illustrate that, the proposed hBFOA-PSO optimized integral controller gives better output performances in single area multi-source power system compared to DE optimized integral controller in terms of minimum settling time, less steady state error and minimum peak.

Correspondingly, it is clear from the Fig. 9 and Table 4 that, the proposed approach gives preeminent dynamic response having relatively smaller peak overshoot, lesser settling time and low steady state error as compared to DE tuned integral controller. The Table 4 also reveals that the ITAE value also much reduced with the proposed approach compared to DE approach.

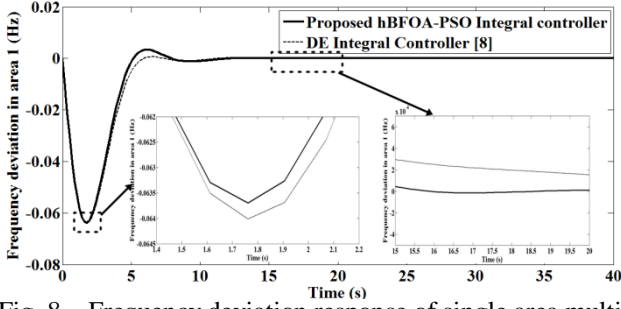


Fig. 8. Frequency deviation response of single area multi source power system employing Integral controller

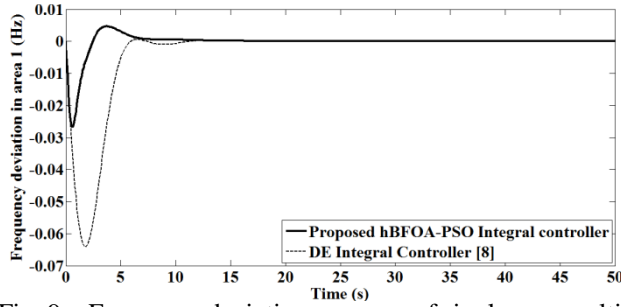


Fig. 9. Frequency deviation response of single area multi source power system employing PID controller

Table 3. Proposed hBFOA-PSO tuned controller parameters for various configurations of multi source power system

| Type of System | Thermal | Hydro | Gas |
|--------------------------|---|---|---|
| Single area multi source | $K_i=0.042361$ | $K_i=0.013989$ | $K_i=0.22136$ |
| | $K_p=0.57719$ | $K_p=0.49050$ | $K_p=0.78743$ |
| | $K_i=0.99137$ $K_d=0.46626$ | $K_i=0.07411$ $K_d=0.87988$ | $K_i=0.93730$ $K_d=0.50787$ |
| Two area AC tie-line | $K_p=0.81828$ $K_i=0.99818$ $K_d=0.99999$ | $K_p=0.78890$ $K_i=0.45170$ $K_d=0.38499$ | $K_p=0.70674$ $K_i=0.77714$ $K_d=0.44776$ |
| | $K_p=1.99070$ $K_i=1.99183$ $K_d=0.77645$ | $K_p=1.31860$ $K_i=0.74462$ $K_d=0.44997$ | $K_p=0.75605$ $K_i=1.97850$ $K_d=0.15790$ |

4.5.1 Multi-area multi-source power system with/without HVDC link

The linearised model of multi-area multi-source power system is shown in Fig. 10. Each area of this system comprises reheat thermal, hydro and gas generating units with equal system configurations in both areas.

The HVDC transmission lines are mostly used in parallel to the AC tie line due to its remarkable features such as fast controllability of power in HVDC lines through converter control, ability to reduce transient stability problems associated with AC lines, and some other economical advantages. Hence, this paper also preferred HVDC in parallel to the AC tie line that already existed on the

interconnected multi-area multi-source system under consideration.

The PID controllers of all generating unit in each area with AC tie line and with AC-DC parallel tie lines are tuned with proposed hBFOA-PSO approach and the tuned parameters are listed in Table 5. The frequency deviation responses of area 1, area 2 and tie line power deviation responses of multi- area multi-source power system with AC tie line are shown in Fig. 11, Fig. 12 and Fig. 13. To show the superiority of the proposed approach, the results are compared with a recently published DE approach as depicted in Table 5.

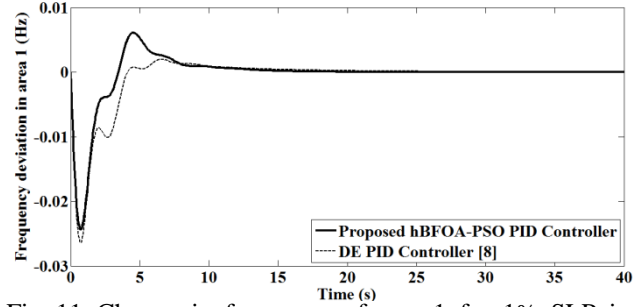


Fig. 11. Change in frequency of area-1 for 1% SLP in area-1 with AC tie line only.

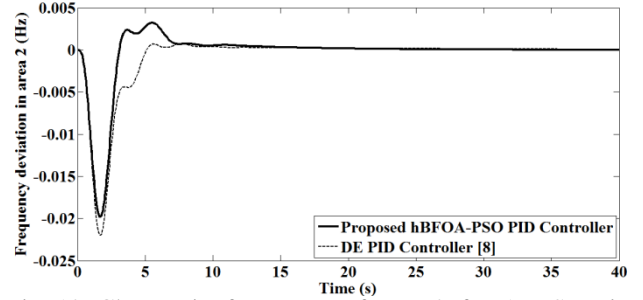


Fig. 12. Change in frequency of area-2 for 1% SLP in area-1 with AC tie line only.

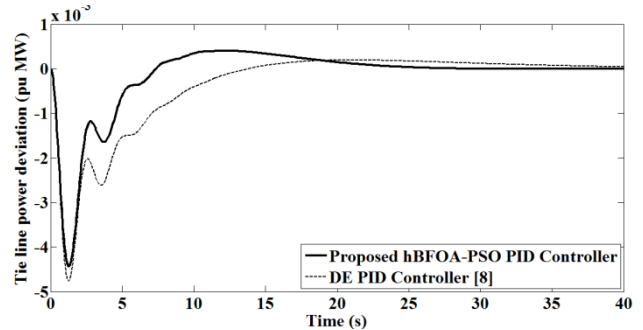


Fig. 13. Change in tie line power for 1% SLP in area-1 with AC tie line only

Similarly, the frequency deviation responses of area 1, area 2 and tie line power deviation responses of multi- area multi-source power system with AC-DC parallel tie lines are shown in Fig. 14, Fig. 15 and Fig. 16.

Table 4. Comparative output response of single area multi-source system

| Parameters | Proposed hBFOA-PSO optimized Integral Controller | Proposed hBFOA-PSO optimized PID Controller | DE optimized Integral Controller [8] |
|--------------------|--|---|--------------------------------------|
| | Value | % Improvement | Value |
| ITAE | 0.452878 | 12.38 | 0.132184 |
| Settling time | 11.3851 | 25.62 | 15.29306 |
| Maximum peak | 0.063697 | 0.48827 | 0.026716 |
| Rise time | 3.07×10^{-05} | 94.12 | 9.88×10^{-05} |
| Steady state error | -2.30×10^{-06} | 94.12 | 1.01×10^{-06} |

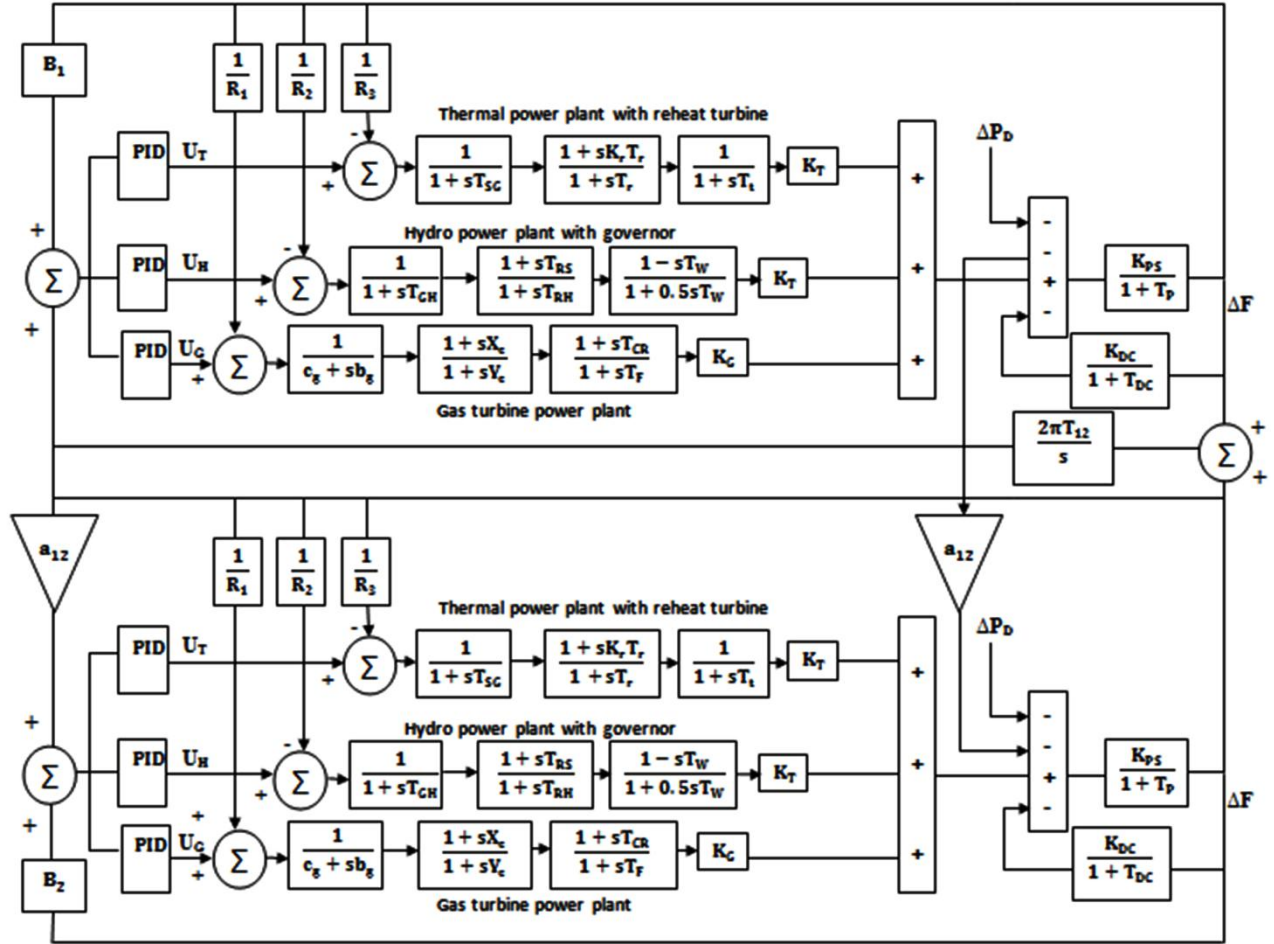


Fig. 10. Linearised model of multi area multi source LFC system with PID controller.

Table 5. Comparative output response of multi-area multi-source system

| Parameters | Proposed hBFOA-PSO optimized PID controller with AC tie line | | | Proposed hBFOA-PSO optimized PID controller with AC-DC tie line | | |
|---------------|--|---------------|----------|---|---------------|----------|
| | Value | % Improvement | Value | Value | % Improvement | Value |
| ITAE | 0.31366 | 37.29 | 0.500203 | 0.164878 | 0.11 | 0.165073 |
| Settling time | ΔF_1 | 15.90591 | 30.09 | 22.75435 | 23.97035 | 0.74 |
| | ΔF_2 | 22.21775 | 16.96 | 26.75852 | 28.73844 | 0.60 |
| | ΔP_{tie} | 25.54193 | 37.34 | 40.76511 | 19.96541 | 0.06 |
| Maximum peak | ΔF_1 | 0.024326 | 7.89 | 0.02641 | 0.011686 | 0.16 |
| | ΔF_2 | 0.019793 | 9.99 | 0.021992 | 0.00251 | 0.40 |
| | ΔP_{tie} | 0.004435 | 6.93 | 0.004766 | 0.001797 | 1.04 |

The settling time and maximum peak measured from these figures are also listed in Table 5. The improvement of system performances are also evaluated compared to documented results of DE approach and portrayed in Table 5.

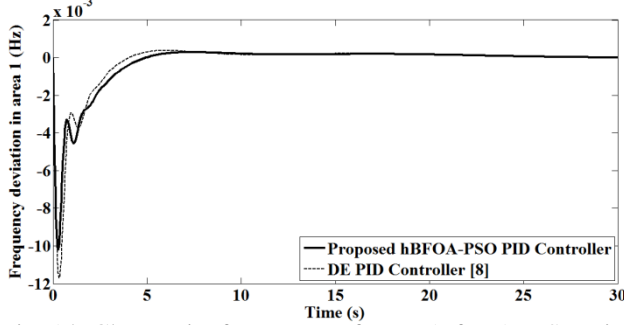


Fig. 14. Change in frequency of area-1 for 1% SLP in area-1 with AC-DC parallel tie lines.

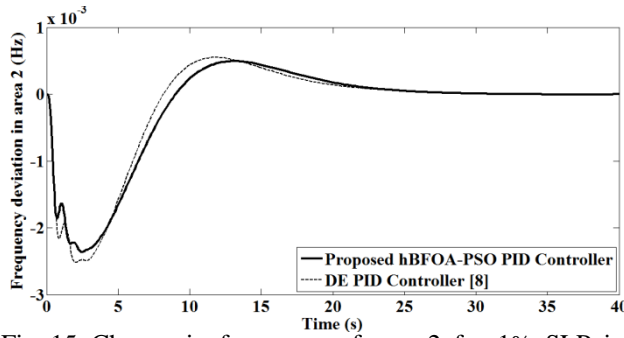


Fig. 15. Change in frequency of area-2 for 1% SLP in area-1 with AC-DC parallel tie lines

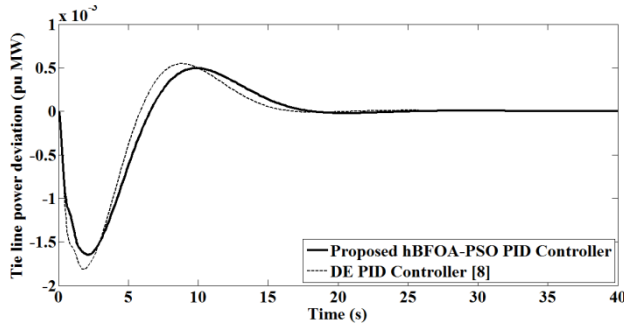


Fig. 16. Change in tie line power for 1% SLP in area-1 with AC-DC parallel tie lines.

This table clearly reveals that in both AC and AC-DC tie lines criterion the system output performance is much improved with the proposed hBFOA-PSO approach in terms of minimum ITAE, less oscillations, minimum overshoot and minimum settling time compared to DE approach. In addition, the Table 5 obviously exemplified that the maximum peak overshoot of the frequency deviation responses in area 1 and 2 are improved by 51.96 % and 87.32% respectively and the tie line power deviation responses are improved by 59.47 % in AC-DC parallel tie line compared to AC tie line performances. The ITAE also improved by 47.43%

in AC-DC parallel tie line compared to AC tie line interconnected system. Hence, the recognition of using HVDC in interconnected areas is again confirmed in this paper.

5. Conclusion

A novel attempt to design a hybrid Bacterial Foraging Optimization Algorithm - Particle Swarm Optimization (hBFOA-PSO) tuned PID controller of LFC systems has been carried out in this article. Initially a two area thermal power system is considered and the gain parameters of PID controller are simultaneously optimized using a proposed hBFOA-PSO algorithm. Further a novel objective function is proposed in this paper to enhance the dynamic performance of the system and the supremacy is also proved over conventional objective functions. Three significant analysis named, transient analysis, convergence analysis and robustness analysis are conducted on the test system. With these analyses the supremacy of proposed hBFOA-PSO algorithm has been proved over individual PSO and BFOA approaches. All the simulation results are also compared with the documented results of hBFOA-PSO tuned PI controller and DE tuned PI controller to prove the dominance of the proposed approach for the same interconnected power system. The convergence analysis carried out in this research work also confirmed that, consistent convergence characteristics with faster convergence and minimum fitness values can be obtained through the proposed hBFOA-PSO tuned PID controller with proposed objective function. Additionally, the robustness analysis carried out on the system exemplified that, the proposed controllers are quite robust for varying operating load conditions from their nominal values. As a special mention, the robustness analysis is carried out by introducing GDB nonlinearity to the system and remarkable system performances are obtained with the proposed approach compared to the reported results of CBPSO tuned PI controller. The proposed approach is further extended to multi-area multi-source power system with/without HVDC link. Results are compared with some recently published approach named DE tuned integral/PID controller for the identical power systems to show the superiority of proposed approach. From the simulation study it is revealed that, the proposed hBFOA-PSO tuned PID controller out performs some recently proposed approaches and may become a very promising algorithm for solving more complex engineering optimization problems in future research.

Appendix A: Two area interconnected system—system parameters

$P_{r1} = P_{r2} = 1000$ MW; $f = 60$ Hz; $T_{g1} = T_{g2} = 0.03$ s; $T_{11} = T_{12} = 0.3$ s; $T_{p1} = T_{p2} = 20$ s; $K_{p1} = K_{p2} = 120$ Hz/

pu; $R_1 = R_2 = 2.4 \text{ Hz/pu MW}$; $2\pi \cdot T_{12} = 0.545$; $B_1 = B_2 = 0.425 \text{ pu MW/Hz}$.

Appendix B: Dead zone nonlinearity configurations
 $P_{r1} = P_{r2} = 1000 \text{ MW}$; $f = 60 \text{ Hz}$; $T_{g1} = T_{g2} = 0.2 \text{ s}$; $T_{11} = T_{12} = 0.3 \text{ s}$; $T_{p1} = T_{p2} = 20 \text{ s}$; $K_{p1} = K_{p2} = 120 \text{ Hz/pu}$; $R_1 = R_2 = 2.4 \text{ Hz/pu MW}$; $T_{12} = 0.0731$; $B_1 = B_2 = 0.425 \text{ pu MW/Hz}$.

Appendix C: Multi-area multi-source power system – system parameters

$B_1 = B_2 = 0.4312 \text{ pu MW/Hz}$; $P_{r1} = 2000 \text{ MW}$; $P_L = 1840 \text{ MW}$; $R_1 = R_2 = R_3 = 2.4 \text{ Hz/p.u.}$; $T_{SG} = 0.08 \text{ s}$; $T_T = 0.3 \text{ s}$; $K_R = 0.3$; $T_R = 10 \text{ s}$; $K_{PS1} = K_{PS2} = 68.9566 \text{ Hz/p.u. MW}$; $T_{PS1} = T_{PS2} = 11.49 \text{ s}$; $T_{12} = 0.0433$; $a_{12} = -1$; $T_W = 1 \text{ s}$; $T_{RS} = 5 \text{ s}$; $T_{RH} = 28.75 \text{ s}$; $T_{GH} = 0.2 \text{ s}$; $X_C = 0.6 \text{ s}$; $Y_C = 1 \text{ s}$; $c_g = 1$; $b_g = 0.05 \text{ s}$; $T_F = 0.23$; $T_{CR} = 0.01 \text{ s}$; $T_{CD} = 0.2 \text{ s}$; $K_T = 0.543478$; $K_H = 0.326084$; $K_G = 0.130438$; $K_{DC} = 1$; $T_{DC} = 0.2 \text{ s}$.

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