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Automatic Generation Control by Hybrid Invasive Weed Optimization and Pattern Search Tuned 2-DOF PID Controller

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Abstract: A hybrid invasive weed optimization and pattern search (hIWO-PS) technique is proposed in this paper to design 2 degree of freedom proportional-integral-derivative (2-DOF-PID) controllers for automatic generation control (AGC) of interconnected power systems. Firstly, the proposed approach is tested in an interconnected two-area thermal power system and the advantage of the proposed approach has been established by comparing the results with recently published methods like conventional Ziegler Nichols (ZN), differential evolution (DE), bacteria foraging optimization algorithm (BFOA), genetic algorithm (GA), particle swarm optimization (PSO), hybrid BFOA-PSO, hybrid PSO-PS and non-dominated shorting GA-II (NSGA-II) based controllers for the identical interconnected power system. Further, sensitivity investigation is executed to demonstrate the robustness of the proposed approach by changing the parameters of the system, operating loading conditions, locations as well as size of the disturbance. Additionally, the methodology is applied to a three area hydro thermal interconnected system with appropriate generation rate constraints (GRC). The superiority of the presented methodology is demonstrated by presenting comparative results of adaptive neuro fuzzy inference system (ANFIS), hybrid hBFOA-PSO as well as hybrid hPSO-PS based controllers for the identical system.
Keywords: Automatic generation control, interconnected power system, governor, dead - band non linearity, 2 degree of freedom PID controller, invasive weed optimization, pattern search.

1 Introduction

Automatic generation control (AGC) loop in a power system calculates the required change in the generation based on the system frequency and tie-line flow deviations, and adjusts the set position of the generators in each area to maintain the time average of frequency and tie-line power changes at a low value [11], [5]. The researchers in the world over are developing a number of control strategies for AGC to keep the tie-line flow system and frequency at their desired values both in normal and disturbed conditions [29]In recent times, soft computing based methods have been applied to tune the parameters of the controller [25] [1] ; [28]; [19]. [14] applied DE to tune the controller parameters for a multi-source power system and relative performances of different classical controllers were compared. [2] employed teaching learning based optimization (TLBO) technique for the design of I/PID controllers for a multi-units multi-sources power system and superiority of TLBO algorithm was demonstrated over DE and optimal output feedback controller. [6] proposed an intelligent controller based on emotional learning for LFC of an interconnected power system with generation rate constraint (GRC) and demonstrated the advantage their approach over PI, fuzzy logic, hybrid Neuro Fuzzy (HNF) controller. A Firefly Algorithm (FA) with on line wavelet filter was employed by [15] for AGC of inter connected unequal three area power system. [8] employed artificial bee colony (ABC) algorithm for AGC and superiority of the approach was demonstrated over PSO algorithm. [22] used gravitational search algorithm (GSA) to optimize PI/PIDF controller parameters with conventional integral based objective functions for AGC system and compared the results with DE, BFOA and GA to show the superiority. A Teaching Learning Based Optimization algorithm has been applied by [24] for Automatic generation control of multi-area power systems with diverse energy sources.

It is seen in literatures that the performance of power system depends on the tuning technique, controller structure and choice of cost function. In this regard, it is observed that, a two degree of freedom controllers provide better performance than a single degree of freedom controller [21]. Having known all this, in the present work, an ideal 2 degree freedom of PID (2-DOF-PID) controller for AGC of multi-area power systems. Generally, all population centered heuristic optimization techniques offer acceptable results but there is no guarantee that a particular technique will give a better performance than other techniques in all optimizing problems [30] . Hence, suggesting and realizing novel heuristic techniques are always desired. Each heuristic technique has its own advantages and disadvantages. Hybrid algorithms taking the advantage of two or more algorithms have been recently proposed in literature. [16] proposed a hybrid BFOA-PSO algorithm to tune the controller parameters for AGC systems. A hybrid PSO-PS algorithm is proposed by [23] to tune the fuzzy PI parameters. A modified DE optimized fuzzy PID controller for load frequency control with thyristor controlled series compensator has been proposed by [20].

In recent times, invasive weed optimization (IWO), a novel biologically motivated optimization technique was proposed by [12]. IWO is a robust, stochastic and derivative free optimization algorithm for the solution of complex real world problems. It is based on the invasive habits of growth of weeds in nature and having excellent exploration and exploitation ability in the search area. IWO has been successfully employed to a number of engineering problems such as recommender system design [18], antenna system design [10], state estimation of nonlinear systems [13] , unit commitment problem solution [27] and economic load dispatch of power systems [3]. To get excellent performance using any optimization technique, a balance of exploitation as well as exploration throughout the search procedure is to be maintained. IWO being a global search technique, searches the wide search area and may not give best solution if employed alone. Alternatively, local search methods such as Pattern Search (PS) exploits the local but cannot perform extensive search [4] . Owing to their individual strengths, there is a scope for hybridization of these algorithms [31]. In view of the above, a hybrid IWO-PS technique is suggested in this work for tuning the parameters of 2-DOF-PID controller for AGC of interconnected systems.

In the present study, a two area thermal as shown in Figure 1 is considered as the system under study. The same system is extensively used in literature for proposing new AGC approaches [1]; [19]; [17]; [23].

In Figure 1,B_1 & B_2 represent the frequency bias parameters;ACE_1 & ACE_2 stands for area control errors;u_1 & u_2 are the control outputs;R_1 & R_2 represent the regulation parameters in pu Hz;T_{G1} & T_{G2} are the time constants of governor in sec; ΔP_{G1}&ΔP_{G2} are the incremental valve positions (pu); T_{T1}&T_{T2} are the time constant of turbine in sec;ΔP_{T1}&ΔP_{T2} are the incremental

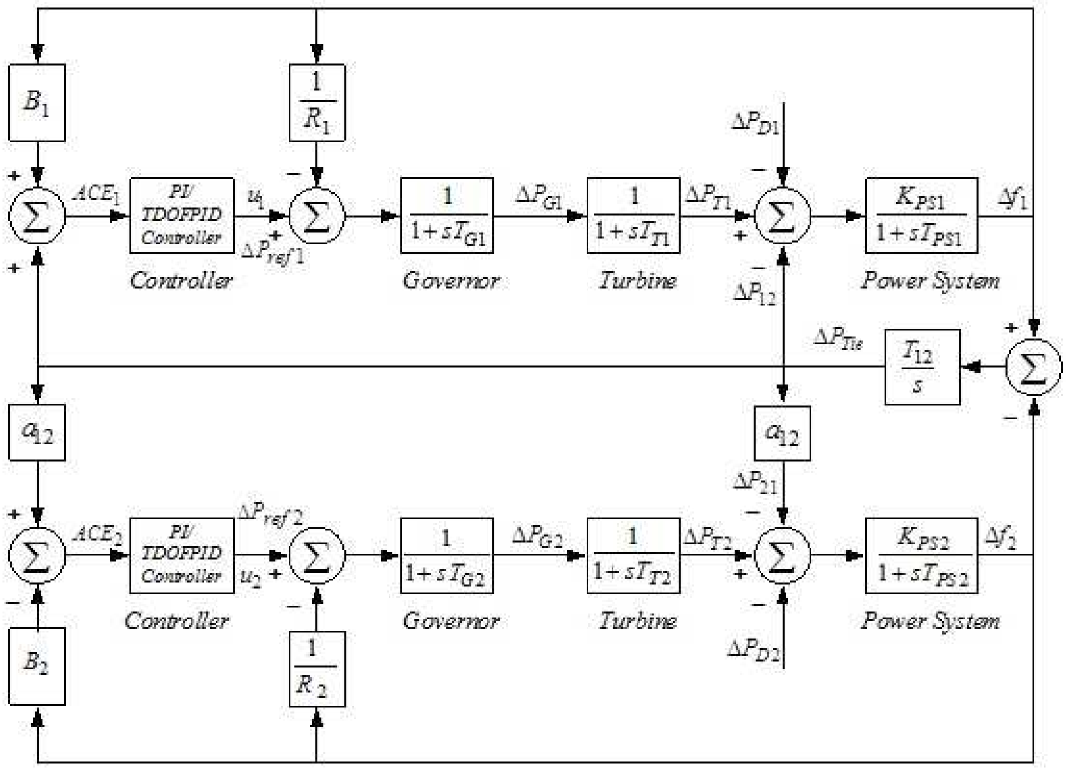

Figure 1: Transfer function model of two-area non reheat thermal system

turbine powers; $\Delta P_{D1}\&\Delta P_{D2}$ are the step load perturbations;ΔP_{tie} is the incremental tie-line power (p.u);K_{ps1} & K_{ps2} are the power system gains; T_{ps1} & T_{ps2} are the time constants of power system in sec; T_{12} represent the synchronizing coefficient in p.u. and Δf_1 and Δf_2 are the incremental frequency changes in Hz. The parameters of the system are specified as shown. Nominal parameters of the two area thermal power system are: $P_R = 2000MW(rating); P_L = 1000MW(nominal\ loading); f = 60\ Hz;$
$B_1 = B_2 = 0.425p.u.MW/Hz; R_1 = R_2 = 2.4Hz/p.u.; T_{G1} = T_{G2} = 0.08s; T_{T1} = T_{T2} = 0.3s; K_{PS1} = K_{PS2} = 120Hz/p.u.MW; T_{PS1} = T_{PS2} = 20s; T_{12} = 0.545pu$
The area control errors (ACE)of each area are given [5]:

$$ACE_1 = B_1\Delta f_1 + DeltaP_{Tie} \tag{1}$$

$$ACE_2 = B_2\Delta f_2 - DeltaP_{Tie} \tag{2}$$

In the present study, each component of the power system are represented by appropriate transfer functions. The transfer function of turbine is given by:

$$G_T(s) = \frac{\Delta P_T(s)}{\Delta P_V(s)} = \frac{1}{1 + sT_T} \tag{3}$$

Governor transfer function is given by:

$$G_G(s) = \frac{\Delta P_v(s)}{\Delta P_G(s)} = \frac{1}{1 + sT_G} \tag{4}$$

The output of speed governing system $\Delta P_G(s)$ is given by:

$$\Delta P_G(s) = \Delta P_{ref}(s) - \frac{1}{R}\Delta F(s) \tag{5}$$

The transfer function generator and load is given by:

$$G_p(s) = \frac{K_p}{1 + sT_p} \tag{6}$$

Where $K_p = \frac{1}{D}$ and $T_p = \frac{2H}{fD}$
The output $\Delta f(s)$ of generator load system has two inputs $\Delta P_T(s)$ is given by:

$$\Delta f(s) = G_p(s)[\Delta P_T(s) - \Delta PG(s)] \tag{7}$$

2 Ideal two degree of freedom PID controller

Depending on the number of closed-loop transfer functions which can be controlled individually, the degree of freedom of a control system is classified. In a control system design problem, numerous performance criteria are to be satisfied thus a 2-degree-of-freedom (2-DOF) controller offers some advantages over the single degree of freedom control system [26]. The 2-DOF controller calculates a weighted difference signal for each of the control actions as per the set point weights and gives an output signal which is the sum of the control actions on the respective difference signals [21]. A derivative filter is used for improved system performance in presence of noise or random error in the measured process variable. It also limits the huge controller output changes which derivative action causes due to presence of measurement noise and helps to lessen the controller output variations which may result in wear in the control parts. The structure of proposed ideal 2-DOF-PID controller is given in Figure 2 where R(s) represents the reference signal, Y(s) is the feedback signal and U(s) represents the output signal,$K_p, K_i \& K_d$ are the controller gains, PW & DW are the set point weights, and N is the filter coefficient of derivative term. A 2-DOF-PID control system is given in Figure 3 where C(s) a one degree

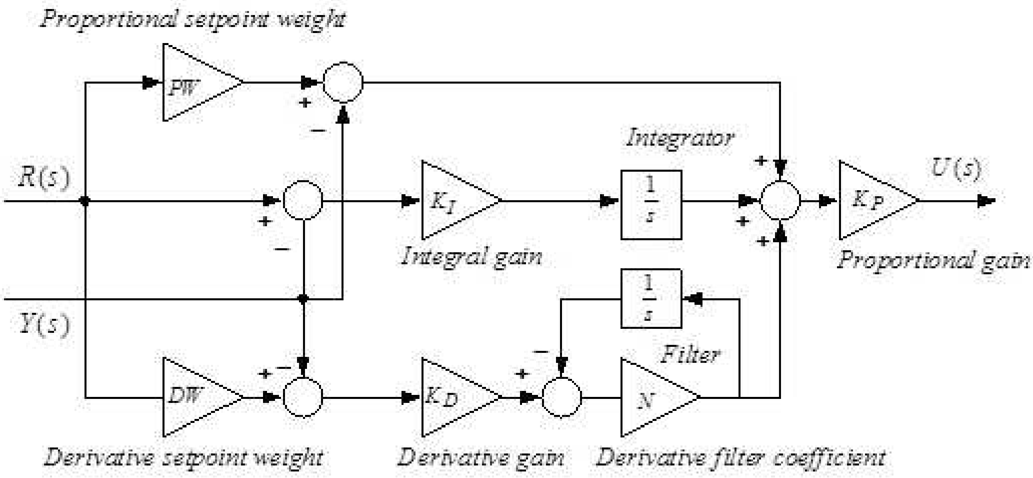

Figure 2: Two degree of freedom (TDOF) PID control structure

of freedom controller,D(s) is the load disturbance and F(s) is the filter acting on the reference signal. In an ideal 2-DOF-PID controller, and are specified by:

$$F(s) = \frac{(PW + DWK_D)s^2 + (PWN + K_I)s + (K_IN)}{(1 + K_DN)s^2 + (N + K_I)s + (K_IN)} \tag{8}$$

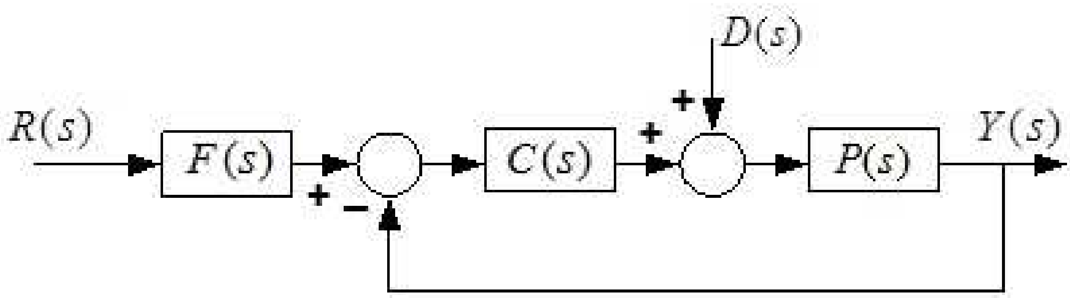

Figure 3: TDOF control system

$$C(s) = K_p \frac{(1 + K_D N)s^2 + (N + K_I)s + (K_I N)}{s(s + N)} \tag{9}$$

An integral of time multiplied absolute error (ITAE) based objective function given in Eq. (10) is chosen in this paper to design the proposed controllers. ITAE is chosen over other integral based objective functions because it gives less over shoots and settling times compared to other criterion such as integral of squared error (ISE), and integral of absolute error (IAE). Other integral squared criteria such as integral of time multiplied squared error (ITSE) and integral of squared time multiplied error (ISTE) based design produces huge controller output when there is a sudden variation in reference which is not desirable.

$$J = ITAE = \int_0^{t_{sim}} \omega_1(|\Delta f_1| + |\Delta f_2| + |\Delta P_{tie}|)t.dt \tag{10}$$

Where, and are the system frequency changes; is the change in tie-line power and is the simulation time. The optimization problem can be expressed as:

$$Minimize \quad J \tag{11}$$

Subject to

$$K_{pmin} \leq K_p \leq K_{pmax}, K_{Imin} \leq K_I \leq K_{Imax}, K_{Dmin} \leq K_D \leq K_{Dmax}$$

$$PW_{min} \leq PW \leq PW_{max}, DW_{min} \leq DW \leq DW_{max}, N_{min} \leq N \leq N_{max} \tag{12}$$

Where K_{pmin},K_{pmax} ; K_{Imin},K_{Imax} and K_{Dmin},K_{Dmax} are the lower and upper bounds of the control parameters. PW_{min},DW_{min} and PW_{max},DW_{max} are the lower and upper bounds of set point weights,N_{min},N_{max} and are lower and upper bounds of derivative filter coefficient. The bounds of controller parameters, set point weights and filter coefficient are taken as -2 & 2, 0 & 5 and 10 & 300 respectively.

3 Overview of invasive weed optimization technique

Invasive weed optimization (IWO) is a novel population based stochastic, derivative free optimization technique inspired from the biological growth of weed plants. It was first developed and designed by [12]. The IWO algorithm is based on the colonizing actions of weed plants [18]. Some of the interesting characteristics of weed plants that are invasive, fast reproduction and distribution, robustness and self adaptation to the changes in climate conditions.

The significant characteristic of the IWO algorithm is that it lets all the plants to contribute in the reproduction procedure. Fitter plants yield more seeds than less fit plants and this results in the algorithm to converge. Additionally, it is still probable that some of the less fit plants carry beneficial information in iteration process as compared to the some fitter plants. Thus IWO algorithm provides an opportunity to the lesser fit plants to participate in reproduction process. If the seeds formed by lesser fit plants have better fitness in the colony, they can survive [12]. Another significant characteristics of IWO algorithm is that reproduction is done without mating and every weed can yield new seeds, individually. This reproduction without mating characteristics augments a new quality to the technique as each agent may have not the same number of variables during the optimization process and the number of variables can be selected as one of the optimization parameters in IWO. Also, IWO algorithm has more chance to avoid local minima points compared to GA and PSO due to its continuous and normally distributed dispersal structure over search space which has a decreasing variance parameter centered on each parent plant [18]. The steps of the proposed approach are mentioned below:

Step 1: Based on the number of chosen variables (d) of the assumed problem, the seeds are initialized. The initial seed are distributed uniformly over the entire solution space.

Step 2: Create each seed set, after generating all the selected variables of the given problem randomly within their effective lower and upper limits. Thus, in the search space, each seed contains random values for all variable. Each seed set represents a potential solution of the given problem. Generate several seed set to create a Seed matrix (S) of size ($Pop_{max}xd$). The total number of plants in the population is selected as (Pop_{max}) after satisfying their limits.

Step 3: The fitness value of all individuals of the current seed set (S) (each row (plant) of S) is calculated according to the cost function considered in the given problem. These individuals evolve into weed plants which are capable of creating new units.

Step 4: As per the fitness value of each plant with respect to others, each plant is ranked. Then, every weed yields new seeds depending on its rank in the set of seed. All plants are participating in reproduction process which adds a new attribute to the optimization providing chances to contribute useful information (good result) by less fit plants during iterative process.

Step 5: The number of seeds to be produced by all weed changes linearly from N_{min} to N_{max} which can be calculated by:

$$Seed\ \ number = \frac{F_i - F_{worst}}{F_{best} - F_{worst}}(N_{max} - N_{min}) + N_{min} \tag{13}$$

Where,F_i is the fitness associated with i^{th} weed,F_{worst} and F_{best} denotes the worst and best fitness in weed population. The created seeds are normally distributed over the field with zero average and variable standard deviation of σ_{iter} defined by

$$\sigma_{iter} = [\frac{iter_{max} - iter}{iter_{max}}]^n(\sigma_0 - \sigma_f) + \sigma_f \tag{14}$$

Where, $iter_{max}$ and $iter_{min}$ are the maximum number of iteration and current iteration, respectively. $\sigma_0\ and\ \sigma_f$, are the predefined initial and final standard deviations and n represent the modulation index.

Step 6: The new seeds breed to the flowering plants when all seeds found their positions over the search area. Next, they are ranked together with their parents in the seed set matrix. Plants with lower ranking in the colony are removed and the maximum number of plants in the colony (Pop_{max}) is maintained.

Step 7: Survived plants can yield new seeds as per their ranking. The fittest individual (plant) is selected from the seed-parent combination of current seed set. If the stopping criterion is satisfied, the iterative process is terminated and the results (gain schedule) are displayed, otherwise go to Step 3 for continuation.

4 Overview of pattern search algorithm

Pattern search (PS) algorithm is an effective but simple technique applicable to the complex problems which cannot be solved by conventional optimization techniques. It has a flexible operator to fine tune the local explore capability [23]. The PS method consists of a series of polls x_k $k \in N$. A number of trial steps with $i = 1, 2, ...p$ are added to the polls x_k to get trial points $x_k^i = x_k + s_k^i$ at each poll. At these trial points the objective function value is calculated through a sequence of exploratory steps and compared with its previous value $J(x_k)$. The trial step s_k^* corresponding to least value of $J(x_k + s_k^i) - J(x_k) < 0$ is then selected to produce the subsequent estimation of the patterns polls $x_{k+1} = x_k + s_k^*$. The trial steps s_k^i are produced by a step length parameter $\Delta_k \in R_{in}^+$. The Δ_k value is updated in subsequent polls as per x_{k+1} value. The improvement of Δ_k , help the algorithm to converge. These elements are explained in more details in reference [4].

5 Results

5.1 Application of hIWO-PS algorithm

As the two areas are assumed identical, similar controllers are assumed in each area. The objective function is calculated by applying a 10percent step load disturbance in area-1. A series of runs are executed to properly select the algorithm parameters. Number of search agents and iterations are taken as 20 and 50 respectively. The optimization process was repeated 10 times and the best solution obtained in 10 runs is selected as final controller parameters. In the next step, the proposed hIWO-PS algorithm is applied to optimize the controller parameters. In hIWO-PS algorithm, initially optimal IWO is executed for 40 iterations and then PS is employed for 10 iterations. The final solution corresponding to the minimum objective function value provided by optimal IWO is used as the beginning points of PS algorithm. For the implementation of PS algorithm, the following parameters are used: mesh size=1, mesh expansion factor=2, mesh contraction factor= 0.5, max. no. of function estimations=10, max. no. of iterations = 10. The optimized 2-DOF-PID parameters are provided in Table 1. For comparison, the optimized PI controller parameters are also specified in Table 1.

Table 1: Tuned controller parameters

Controller Technique	Controller parameters
IWO: PI	KP=-0.3005, KI=0.4551
hIWO-PS	KP =-0.3106, KI =0.4524
IWO: 2-DOF-PID	KP =1.764, KI =1.764, KD =0.4785, PW =7.201, DW =4.3767, N =298.2108
hIWO-PS: 2-DOF-PID	KP =1.889, KI =1.9398, KD =0.4941, PW =7.2088, DW =2.7742, N =318.1317

5.2 Result analysis

A 10 percent step load disturbance in area-1 is considered at t=0.0 sec. The ITAE values with IWO and hIWO-PS optimized PI/2-DOF-PID controllers are shown in Table 2.

To demonstrate the efficiency of the proposed hIWO-PS technique, results are compared with genetic algorithm: GA, bacteria foraging optimization algorithm: BFOA [1], differential evolution: DE [19], particle swarm optimization: PSO, hybrid BFOA-PSO cite16, non dominated shorting GA-II: NSGA-II optimized PI controllers, NSGA-II optimized PID Controller with derivative filter cite17, pattern search: PS, PSO, and hybrid PSO-PS cite23 optimized fuzzy PI controllers for the same interconnected power system. It is obvious from Table 2 that

Table 2: ITAE values with different controllers and optimization techniques

Controller	Tuning method/ Optimization technique	ITAE Value
PI	Hybrid Invasive Weed Optimization (IWO)- Pattern Search	1.1761
PI	Invasive Weed Optimization (IWO)	1.1763
PI	Ziegler Nicholas (Ali, & Abd-Elazim, 2011)	3.7568
PI	GA (Ali, & Abd-Elazim, 2011)	2.7475
PI	BFOA (Ali, & Abd-Elazim, 2011)	1.7975
PI	DE (Rout, Sahu, & Panda, 2013)	1.2551
PI	PSO (Panda, Mohanty, & Hota, 2013)	1.2142
PI	Hybrid BFOA-PSO (Panda, Mohanty, & Hota, 2013)	1.1865
PI	NSGA-II (Panda, & Yegireddy, 2013)	1.1785
2-DOF-PID	Hybrid IWO-PS	0.1037
2-DOF-PID	IWO	0.1311
PIDF	NSGA-II (Panda, & Yegireddy, 2013)	0.387
Fuzzy PI	PS (Sahu, Panda, & Sekher, 2015)	0.6334
Fuzzy PI	PSO (Sahu, Panda, & Sekher, 2015)	0.4470
Fuzzy PI	Hybrid PSO-PS (Sahu, Panda, & Sekher, 2015)	0.1438

with the same PI controller, tuned using the same ITAE objective function, lowest ITAE value is obtained with proposed hIWO-PS technique (ITAE=1.1761) compared to IWO (ITAE=1.1763), Z-N tuning (ITAE=3.7568), GA (ITAE=2.7475), BFOA (ITAE=1.7975), DE (ITAE=1.2551), PSO (ITAE=1.2142), Hybrid PSO-PS technique (ITAE=1.1865) and NSGA-II (ITAE=1.1785). In the above evaluation, identical interconnected power system with two similar PI controllers is assumed and the controller parameters are tuned using an ITAE objective function. Therefore, it can be concluded that proposed hIWO-PS technique provides better performance than IWO, GA, BFOA, DE, PSO, Hybrid PSO-PS NSGA-II techniques as lowest ITAE value is achieved using hIWO-PS technique. From Table 2, it is furthermore apparent that, value of ITAE is considerably reduced (ITAE=0.1311) with IWO tuned 2-DOF-PID controller. The ITAE value is reduced (ITAE=0.1037) with hIWO-PS tuned 2-DOF-PID controller. It is also evident from Table 2 that hIWO-PS tuned 2-DOF-PID controller gives minimum ITAE value compared to IWO optimized 2-DOF-PID controller (ITAE=0.1349), Pattern Search (PS) tuned fuzzy PI controller (ITAE=0.6334), PSO tuned fuzzy PI controller (ITAE=0.447), Hybrid PSO-PS tuned fuzzy PI controller (ITAE=0.1438) and NSGA-II tuned PIDF controller (ITAE=0.387).

In the next step, a Step Load Perturbation (SLP) of 10 percent is applied at t = 0 sec in area-1 and time domain simulation results are plotted. The system dynamic responses are shown in Figures 4-6. The results of some recently published approaches like DE cite19, BFOA cite1, hBFOA-PSO cite16 tuned PI controller and PSO fuzzy PI, PS fuzzy PI & hPSO-PS fuzzy PI cite23 controllers for the identical system are also provided in Figures 4.

It can be seen from Figure 4 that, considerable improvement is achieved with hIWO-PS tuned 2-DOF-PID controller compared other methods. For a better illustration of advantage of proposed approach over various approaches proposed in recent times, ITAE values as well as settling times in tie-line power and frequency deviations for the above disturbance is summarized in Table 3. It is evident from Table 3 that best system performance in terms of minimum ITAE values and settling times are obtained with proposed hIWO-PS tuned 2-DOF-PID controller as related to other recent methods.

The dynamic response of the system for a concurrent 10percent SLP in area 1 as well as 20 percent SLP in area 2 at t = 0 s is assumed and the system dynamic responses are shown in

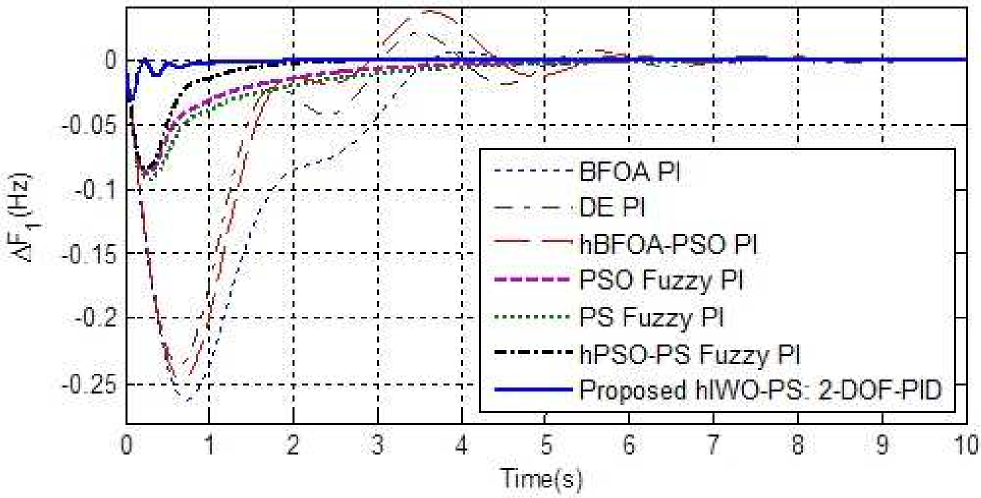

Figure 4: Change in frequency of area-1 for 10% step load increase in area-1

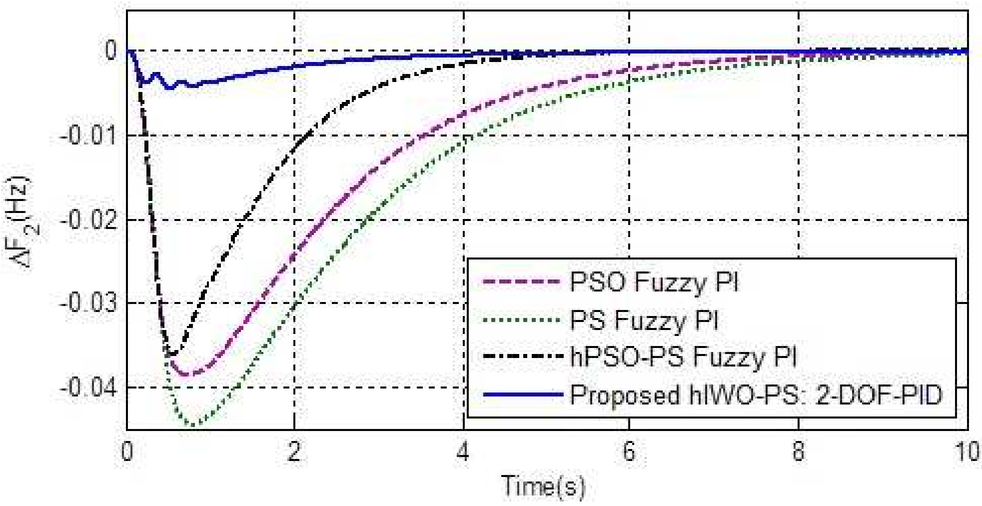

Figure 5: Change in frequency of area-2 for 10% step load increase in area-1

Figures 7-9. It is obvious from Figures 7-9 that the proposed controllers perform satisfactorily with change in the location and step size of the disturbance. Better dynamic responses are obtained with proposed hIWO-PS tuned 2-DOF-PID controller as compared to other recently reported methods in all the cases.

Robustness analysis is done to investigate the usefulness of the system when there are wide deviations in the loading conditions and parameters of the system. These parameters (loading condition and time constants) of speed governor, turbine, tie-line power are varied one after another from their initial values by +50 percent to -50 percent in steps of 25percent. The performance index under changed conditions are provided in Table 4. The above sensitivity analysis is performed by assuming a SLP of 10 percent in area-1 at t=0 sec. To demonstrate the advantage of the proposed approach, results are compared with hPSO-PS tuned fuzzy PI controller [23] under the same varied conditions. In this comparison, hPSO-PS tuned fuzzy PI controller values are selected for comparison as least ITAE value is attained with, hPSO-PS

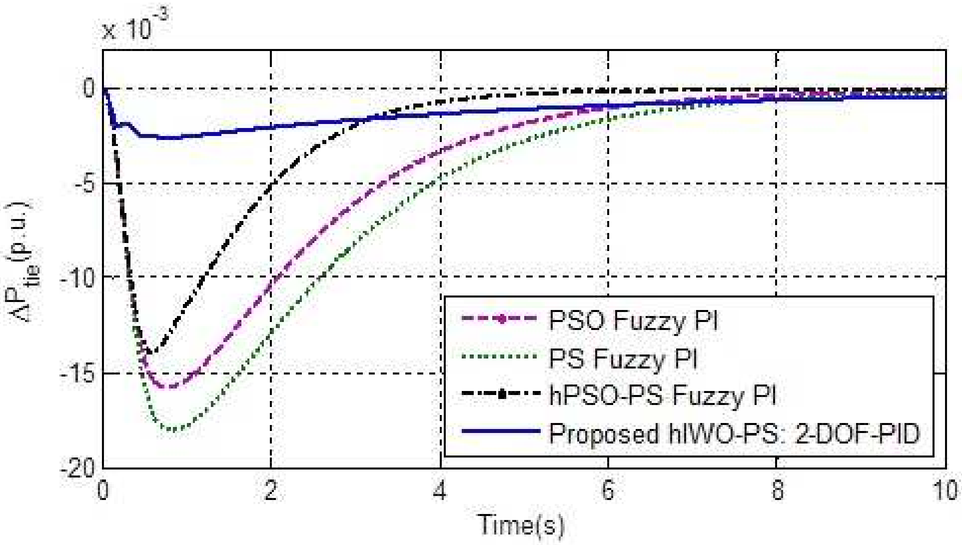

Figure 6: Change in tie line power for 10% step load increase in area-1

Table 3: Performance comparison with recent AGC approaches

Performance	ITAE Value	Settling Time ΔF_1	ΔF_2	ΔP_{tie}
Conventional ZN: PI(Ali, & Abd-Elazim, 2011)	3.7568	45	45	28
GA: PI (Ali, & Abd-Elazim, 2011)	2.7475	10.59	11.39	9.37
BFOA: PI (Ali, & Abd-Elazim, 2011)	1.7975	5.52	7.09	6.35
DE: PI (Rout, Sahu,& Panda, 2013)	0.9911	8.96	8.16	5.75
PSO: PI (Panda, Mohanty, & Hota, 2013)	1.2142	7.37	7.82	5.0
hBFOA-PSO: PI (Panda, Mohanty, & Hota, 2013)	1.1865	7.39	7.65	5.73
NSGA-II: PI (Panda, & Yegireddy, 2013)	1.1785	6.49	7.54	5.79
NSGA-II: PIDF (Panda, & Yegireddy, 2013)	0.387	3.03	4.86	4.34
PS: Fuzzy PI (Sahu, Panda, & Sekher, 2015)	0.6334	6.05	7.10	5.56
PSO: Fuzzy PI (Sahu, Panda, & Sekher, 2015)	0.4470	5.13	6.22	4.83

tuned fuzzy PI controller related to other methods. It is obvious from the simulation results that the system performances remain more or less the same with varied loading condition and system parameters. Thus it can be concluded that, the hIWO-PS tuned 2-DOF-PID controller offers a robust and efficient control strategy. Also, the controller parameters which are tuned at the nominal system conditions, need not be retuned when there are wide variations in the system parameters.

5.3 Extension to three unequal area non-liner hydro thermal power system

To establish the capability of the proposed method to deal nonlinearity and several tie-lines, the method is applied to a unequal three area non-linear thermal hydro power system ([16]; [10]; [23] as shown in Figure 10. In this case different controllers are assumed in each area as the areas are unequal. A GRC (Generation Rate Constraints) of 3% min is assumed for thermal units. A GRC of 270%min for rising and 360% min for lowering generation are considered for hydro unit. The related system parameters are specified.
Three-area hydro thermal power system with generation rate constraints:
$B_1 = B_2 = B_3 = 0.425 pu\ MW/Hz; R_1 = R_2 = R_3 = 2.4 Hz/pu\ MW; T_{G1} = T_{G2} =$

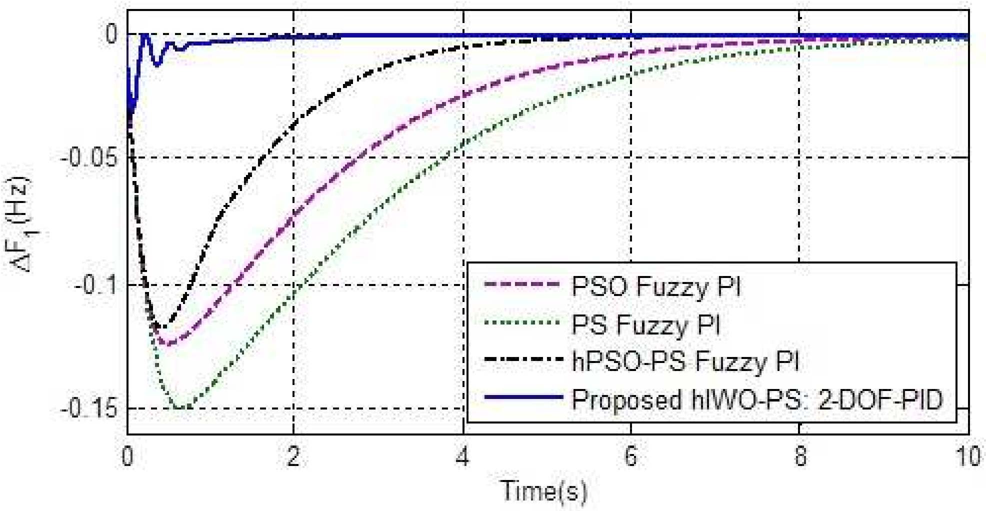

Figure 7: Change in frequency of area-1 for 10% step load increase in area-1 and 20% step load increase in area-2

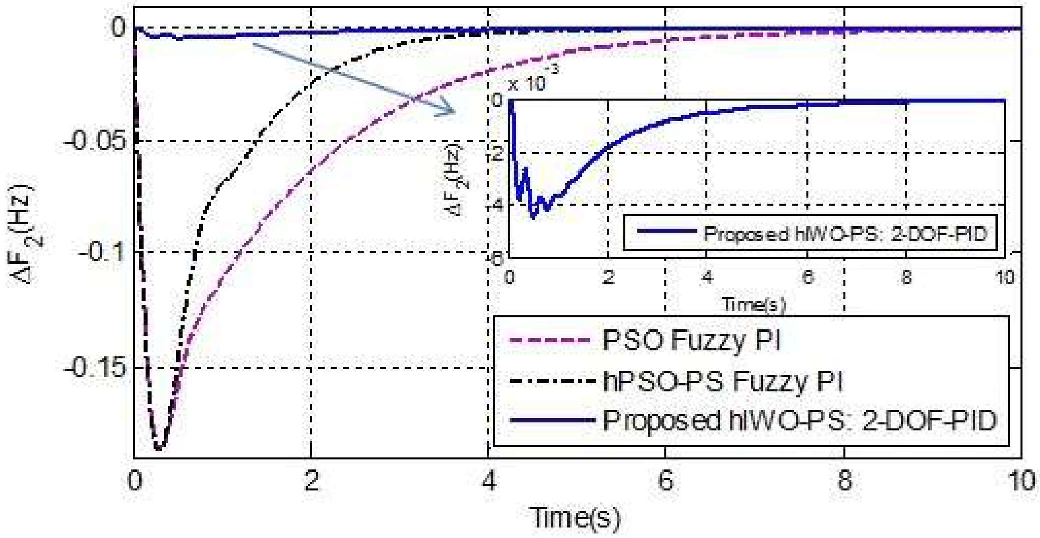

Figure 8: Change in frequency of area-2 for 10% step load increase in area-1 and 20% step load increase in area-2

$0.08s; T_{r1} = T_{r2} = 10.0s, T_{T1} = T_{T2} = 0.3s; T_W = 1.0s; T_R = 5s; K_{PS1} = K_{PS2} = K_{PS3} = 120Hz/p.u.MW; T_{PS1} = T_{PS2} = T_{PS3} = 20s; T_{12} = T_{23} = T31 = 0.086pu; a_{12} = a_{23} = a_{31} = -1$

The objective function in this case is defined by:

$$J = ITAE = \int_0^{t_{sim}} (|\Delta f_1| + |\Delta f_2| + |\Delta f_2 + |\Delta Pt_{12}| + |\Delta Pt_{13}| + |\Delta Pt_{23}|)t.dt \qquad (15)$$

Where $\Delta f_1, \Delta f_2$ *and* Δf_3 are the frequency devotions and $\Delta Pt_{12}, \Delta Pt_{13}$ *and* ΔPt_{23} are the tie-line power deviations between individual areas. The final parameters obtained using proposed hIWO-PS algorithm are:

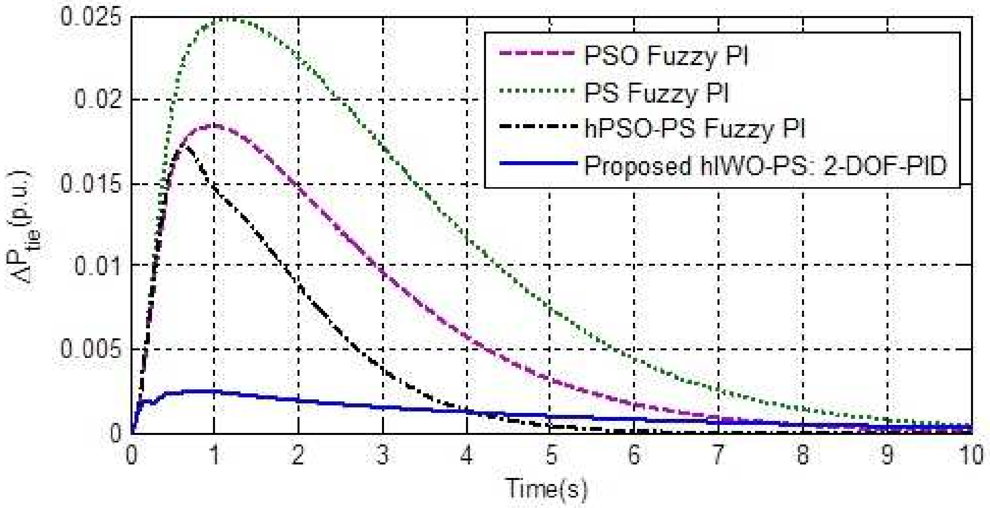

Figure 9: Change in tie line power for 10% step load increase in area-1 and 20% step load increase in area-2

Table 4: Robustness analysis for two area two unit system

Parameter Variation	Percent Change	Performance index with hPSO-PS optimized fuzzy PI (Sahu, Panda, & Sekher, 2015)				Performance index with Proposed hIWO-PS optimized 2-DOF-PID			
		Settling time Ts(Sec)			ITAE	Settling time Ts(Sec)			ITAE
		ΔF_1	ΔF_2	ΔP_{tie}	Value	ΔF_1	ΔF_2	ΔP_{tie}	Value
Nominal	0	2.26	3.74	2.94	0.1438	1.39	1.97	2.01	0.1037
Loading condition	+50	2.26	3.75	2.94	0.1438	1.39	1.97	2.01	0.1037
	+25	2.26	3.75	2.94	0.1438	1.39	1.97	2.01	0.1037
	-25	2.26	3.74	2.94	0.1437	1.39	1.97	2.01	0.1037
	-50	2.26	3.74	2.94	0.1437	1.39	1.97	2.01	0.1037
T_g	+50	2.21	3.64	2.81	0.1321	1.29	1.9	1.99	0.1029
	+25	2.22	3.70	2.88	0.1386	1.44	1.96	2.0	0.1034
	-25	2.28	3.76	2.96	0.1460	1.39	1.97	2.01	0.1046
	-50	2.31	3.77	2.97	0.1469	1.41	1.99	2.03	0.1053
T_t	+50	1.98	3.61	2.80	0.1348	1.02	1.81	1.89	0.991
	+25	2.16	3.69	2.88	0.1409	1.21	1.86	1.92	0.1015
	-25	2.33	3.76	2.95	0.1422	1.48	2.03	2.06	0.1064
	-50	2.39	3.74	2.91	0.1354	1.58	2.12	2.13	0.1089
T_{12}	+50	2.73	3.51	2.70	0.1361	1.42	1.89	2.08	0.0919
	+25	2.56	3.60	2.80	0.1399	1.39	1.92	2.05	0.0967
	-25	1.92	3.98	3.14	0.1513	1.4	2.0	1.87	0.1163
	-50	3.02	4.48	3.53	0.1917	1.51	1.97	1.87	0.1403

$K_{P1} = 1.8539, K_{I1} = 1.7880, K_{D1} = 0.1682, PW_1 = 14.5646, DW_1 = 11.2175, N_1 = 495.2406$
$K_{P2} = 1.6238, K_{I2} = 1.8195, K_{D2} = 0.2642, PW_2 = 10.1788, DW_2 = 14.7692, N_2 = 125.3624$
$K_{P3} = 0.0711, K_{I3} = 1.9101, K_{D3} = 0.0240, PW_3 = 0.0122, DW_3 = 18.9549, N_3 = 139.4454$
A 1% SLP is applied at the same time in all the three areas at t=0 sec. The system dynamic responses are given in Figures 11-13.

The responses with ANFIS based controller [10], hBFOA-PSO tuned PI controller [16] and hPSO-PS based fuzzy PI controller [23] are also shown in Figures 11-13 for comparison. Figures 11-13 clearly establishes that system performance is appreciably enhanced with hIWO-PS tuned

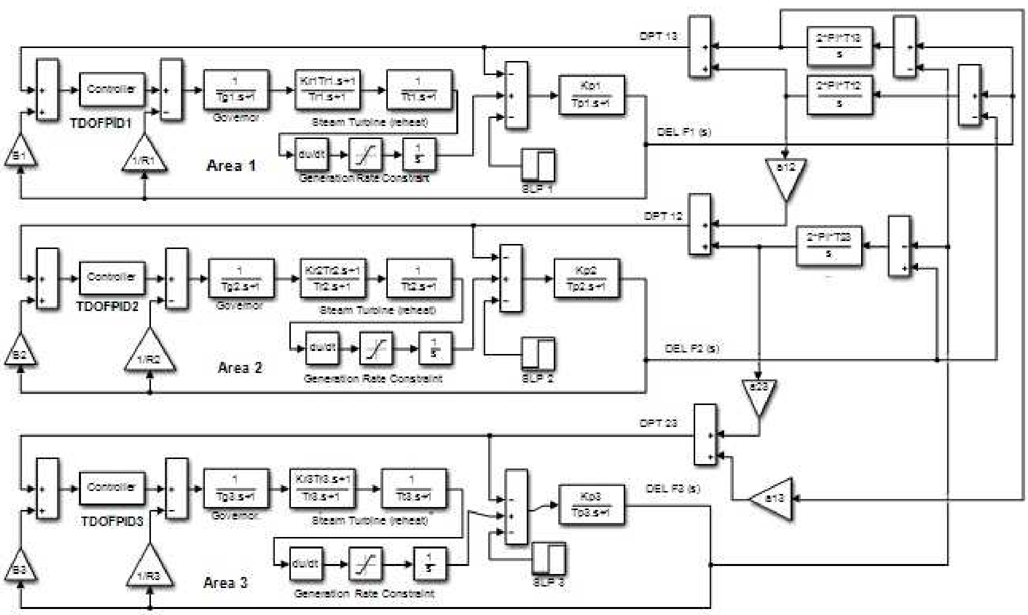

Figure 10: Transfer function model of model of three-area hydro-thermal system with generation rate constraint

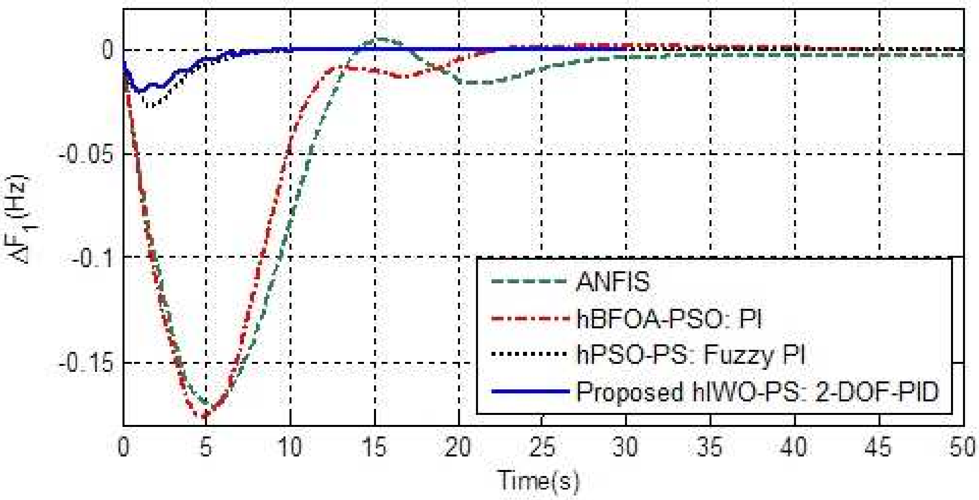

Figure 11: Change in frequency of area-1 for 1% step load increase in all areas

2-DOF-PID controller compared to ANFIS based controller, hBFOA-PSO tuned PI controller and hPSO-PS based fuzzy PI controller. Finally, to demonstrate the advantage of the hIWO-PS tuned 2-DOF-PID controller, ITAE values are compared with some recently reported optimization approaches [23]. In all the cases 1% SLP is applied in all the areas at the same time. The results are briefed in Table 5. It is obvious from Table 5 that least ITAE value is achieved with proposed hIWO-PS tuned 2-DOF-PID controller (ITAE=0.8378) compared to hPSO-PS technique (ITAE=1.3999), RCGA (ITAE=2.4873), GSA (ITAE=1.7805), DE (ITAE=1.6857) and FA (ITAE=1.5344) algorithms. It is evident from Table 9 that, hIWO-PS algorithm out

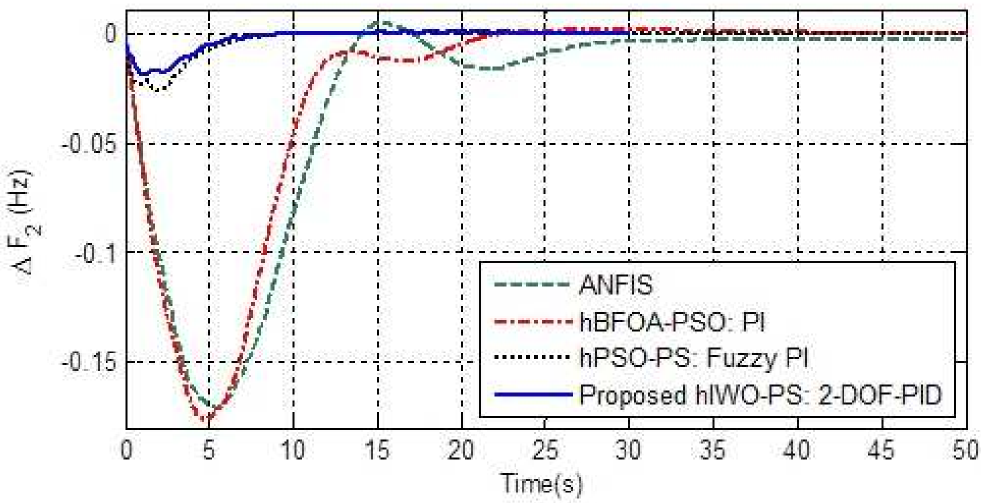

Figure 12: Change in frequency of area-2 for 1% step load increase in all areas

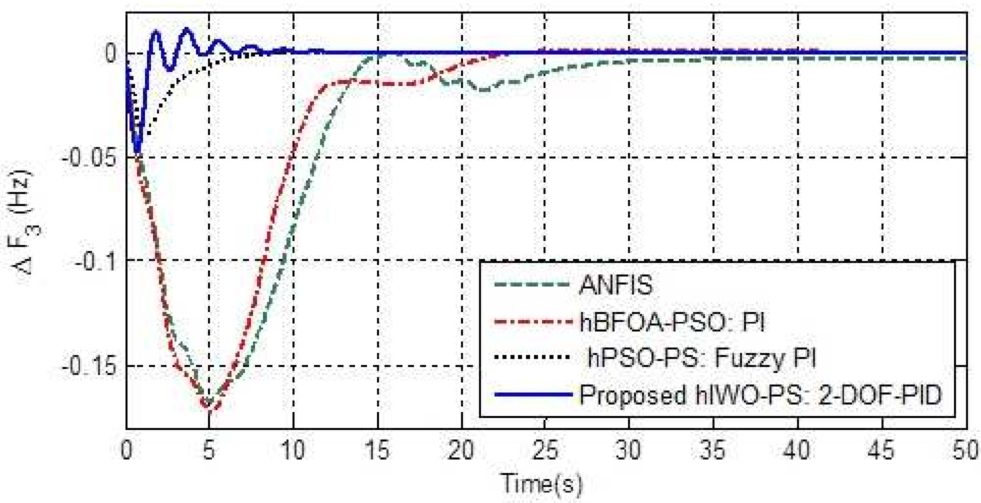

Figure 13: Change in frequency of area-3 for 1% step load increase in all areas

Table 5: Comparison of ITAE values with different approaches for three area system

Techniques	Controller ITAE	Value
GA (Sahu, Panda, & Sekher, 2015)	Fuzzy PI	2.4873
GSA (Sahu, Panda, & Sekher, 2015)	Fuzzy PI	1.7805
DE (Sahu, Panda, & Sekher, 2015)	Fuzzy PI	1.6857
FA (Sahu, Panda, & Sekher, 2015)	Fuzzy PI	1.5344
hPSO-PS (Sahu, Panda, & Sekher, 2015)	Fuzzy PI	1.3999
hIWO-PS	2-DOF-PID	0.8378

performs RCGA, GSA, DE, FA and hPSO-PS techniques.

6 Conclusion

A 2 degree freedom of PID (2 - DOF - PID) controller for automatic generation control (AGC) of multi-area power systems is presented in this paper. The controller parameters are tuned tuned by hybrid invasive weed optimization and pattern search (hIWO - PS) technique. An extensively used standard two area thermal system test system which is considered at the first instance for the AGC design. At the outset, the superiority of hIWO-PS over IWO, Ziegler Nichols (ZN), genetic algorithm (GA), bacteria foraging optimization algorithm (BFOA), differential evolution (DE), particle swarm optimization (PSO), hybrid BFOA - PSO, hybrid PSO - PS and non-dominated shorting GA - II (NSGA - II) is established. It is observed that proposed hIWO - PS tuned 2-DOF-PID controller achieves better system dynamic performances compared to several AGC approaches reported in recent times. Furthermore, robustness analysis is carried out and it is shown that the hIWO - PS tuned 2-DOF-PID controller perform satisfactorily when there are extensive variations in system parameters and operating load conditions. Lastly, the proposed method is applied to three unequal area non-liner hydro thermal system. It is observed that proposed hIWO - PS tuned 2- DOF - PID controller gives better dynamic response than ANFIS, hybrid hBFOA- PSO and hybrid hPSO - PS based approaches for the same power system.

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