Application of Pattern Search Algorithm based Automatic Generation Control of an Interconnected Power System

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Abstract: This paper demonstrates the advantage of the selection of the Pattern Search algorithm (PS) in the design of a Proportional-Integral controller used in Automatic Generation Control for a two area non-reheat interconnected thermal system. The design problem involves the implementation of PS algorithm to find out the value of parameters of the controller of the proposed power system. Here we have implemented three objective functions by using ITAE, damping ratio of dominant eigenvalues and settling time with weight coefficients for the design problem to get an optimized parameter of the Proportional Integral controller. The robustness of the designed PI controller using the Pattern search algorithm has been demonstrated after comparing other PI controllers using various optimization techniques like Genetic Algorithm, Bacteria Foraging Optimization Algorithm for the system under study. Further, best objective function uses the PS optimization algorithm in PI/PID controller parameters, tunning is obtained in presence of physical constraints like governor dead band non linearity of the proposed two area power system. The modified model to test the sensitivity analysis of PI/PID controller by using different loading condition to show the PID controller performance of frequency and tie line power deviation improved better as compared to the PI controller of the same power system. Further, it is extended to multi-area multi-source power for effectiveness and robustness of the system under different disturbances to check the transient stability.

Keywords: Automatic Generation Control (AGC), two-area power system, PI/PID controller, Pattern Search (PS) algorithm. Governor dead band

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1. Introduction

The objective of the interconnected power systems to maintain the continuous power supply with good quality to all the consumer in the system. There for it need the steady operation of an interconnected power systems, constant tie-line power exchange and constant frequency is required. An automatic generation controller (AGC) helps to keep frequency of the system and also tie-line power flow of each area in desirable limit. It also helps to reduce area control error-ACE due to the frequency and tie line power deviations at low value [1-2]. For this reason, an Automatic Generation Control output is considered to a linear combination of power interchange and frequency variation. Generally, AGC drives ACE to zero which infers that variation of frequency and tie-line power flows are made zeros [3-4]. Automatic Generator Control is showing controlling the control function making the difference between the generation of an area and the randomly changing the load of that area to zero. This makes the frequency of system and tie-line power flow to be in satisfactory limiting value. The different type of control strategies has been considered in AGC for maintaining the tie line power and frequency of the system at their desired value during normal and fault conditions. A classical PI and PID controller are the best choices of engineer' due to simplicity in structure, reliability, less cost, development effort is very nominal and it needed lower user skill and also it overs simplified dynamic model. The may artificial intelligence optimizations are available in the present day for the optimization of PI and PID controller of AGC in interconnected power system In the literature survey on AGC with various control aspects affecting the smooth functioning of AGC has been carried out for frequency stability analysis [5]. Furthermore, researchers have attempted various AGC strategies using BES/SMES, FACTS devices, PV systems. Significant research work is being carried out to design an efficient AGC systems implementing control theory, Fuzzy logic, ANN and ANFIS approach [6-8]. It is also found that optimization method can be used to tune PI controller to improvise the performance of an Automatic Generator Controller. As a result, numerous optimization techniques have been implemented for comparative studies on the performance of AGC. The use of artificial intelligent techniques is not based on any model theory and arithmetic equations and hence, it is wide open to the knowledge of experts in problem formulation. On the other hand, various modern optimization techniques involve in models for any problem in the power systems [8-9]. For controller design, particle swarm optimization [10-11], multi-objective evolutionary algorithm, bacterial foraging and many more has been implemented to get an improvised performance of integral controller [12-17]. The PI controller based bacterial foraging optimization algorithm (BFOA) has a good performance as compared with PI controller with GA optimized in the same two area power system[18].The design and analysis of differential evolution algorithm based automatic generation control for interconnected power system has attempted for the load frequency control under different perturbation of load and variation of parameter to check the sensitivity analysis for frequency stability improvement of the power system[19].This paper attempted the Pattern search (PS) based algorithm for optimization of controller parameters of the proposed power system for the frequency stability analysis. The Pattern Search (PS) which is also called as derivative free search optimization algorithm which do not require any gradient. Hence it can be used for functions not continuous or differentiable. This optimization technique is used to find the best match in a space of multidimensional analysis. In this technique the objective is to obtain pattern or substring from another bigger string. The main objective in designing this optimization technique is to reduce the time complexity. This paper presents the optimal design of pattern search-based PI controller for load frequency control of a two-area interconnected network of an electric system has been applied and their performance has been compared for an AGC system. The main aim of the present work can be summarized as to illustrate the proposed pattern search algorithm advantages over BFOA and GA optimization algorithm of the published article and to study the effect different objective function the advantages of implementing modified objective function like Integral Time Absolute Error (ITAE), damping ratio of dominant eigenvalues and settling times for deviation in frequency and tie line power flow in the design of PI controller for a two-area system under study. The performances of interconnected power system depend on the type of objective function, controller structure and also optimization techniques employed for tunning the controllers are analyzed in the literature survey of the different articles. Therefore, in the analysis of load frequency control for stability enhancement of frequency new optimization and hybrid optimization always preferable for different power system model. Therefore, design of proposed controller of the system is considered to be an optimization problem which employing the pattern search optimization algorithm. The dynamic behavior of the above power system under study has been highly improvised by reducing the variation in frequency and tie line power flow, damping ratio and settling times. Simulation results shows that the proposed controller is able to provide good damping characteristics to system oscillations owing to different loading condition and variation in system parameters. It is demonstrated that the designed controller of the proposed system has been superior performances as compared with the same structure and controller by employing the optimization techniques like BFOA and GA [18]. The proposed system which is extended by considering the physical constraint of Governor dead band non linearity to demonstrated the effect of the performance of the system in term of settling time, overshoot and undershoot of frequency deviations and tie line power deviation. It is further investigated the sensitivity analysis under extensive changes in operation condition changes from nominal value to ±50 % and ±25% in step of the power system of PI and PID controller to test the robustness of the power system in presence of physical constraint of governor dead band. It dynamic results shows the PID controller performance of improved better as compared to PI controller of the same system in term of settling time, overshoot and undershoot in frequency and tie line power deviation of the system.

2. System Under Study

2.1 Two-area Power System

In Fig. 1 of two are interconnected system having B_1 and B_2 represents the frequency bias parameters of area-1 and area-2 respectively, AEC_1 and AEC_2 represents area-1 area control errors and area-2 area control errors respectively, u_1 and u_2 denotes controller outputs of area 1 and area 2 respectively, R_1 and R_2 represents the governor speed regulation parameters of area 1 and area 2 respectively in pu Hz, T_{G1} and T_{G2} represents time constants of speed governor of area-1 and area-2 respectively in sec, ΔP_{G1} and ΔP_{G2} denotes the change in position of governor valve of area-1 and area-2 respectively (pu), T_{T1} and T_{T2} denotes time constant of turbine of area 1 and area 2 respectively in sec, ΔP_{T1} and ΔP_{T2} represents variation of turbine power outputs of area-1 and area-2 respectively, ΔP_{D1} and ΔP_{D2} represents the change in load demand of area 1 and area 2 respectively, ΔP_{Tie} represents the cumulative variation in tie line power flow of area 1 and area 2 respectively (p.u), K_{PS1} and K_{PS2} denotes the gains of power system of area-1 and area-2 respectively, T_{PS1} and T_{PS2} represents the time constant of power system of area-1 and area-2 respectively in sec, T_{12} represents the synchronizing coefficient, Δf_1 and Δf_2 represents deviation in area 1 system frequency and deviation in area 2 system frequency respectively in Hz. The values of these parameters are summarized later in appendix.A.

The Area Control Error (ACE) given by as in equation (1) where generator frequency deviation (ΔF) and frequency bias parameters(B)

$$AEC = B\Delta F + \Delta P_{Tie} \tag{1}$$

The transfer functions are used in the proposed model of each component of the two-area power system for the simplicity of frequency-domain analysis as per references of load frequency control [3] which are given as follows:
The transfer function of the Turbine can be represented as in equation (2)

$$G_T(s) = \frac{\Delta P_T(s)}{\Delta P_V(s)} = \frac{1}{1+sT_T} \tag{2}$$

The transfer function of governor is given as in equation (3)

$$G_G(s) = \frac{\Delta P_V(s)}{\Delta P_G(s)} = \frac{1}{1+sT_G} \tag{3}$$

The frequency domain from of output of speed governing system is given as in equation (4)

$$\Delta P_G(s) = \Delta P_{ref}(s) - \frac{1}{R}\Delta F(s) \quad (4)$$

Where ΔP_{ref} and ΔF are the speed governor of input signals

The generator and load transfer function *Gp*(s) is given as in equation (5)

$$G_P(s) = \frac{K_P}{1+sT_P} \quad (5)$$

Where $K_P = 1/D$ and $T_P = 2H/fD$.

The output of Generator $\Delta F(s)$ represented as in Eq. (6)

$$\Delta F(s) = G_P(s)[\Delta P_T(s) - \Delta P_D(s)] \quad (6)$$

Where inputs of generator load are $\Delta P_T(s)$ and $\Delta P_D(s)$

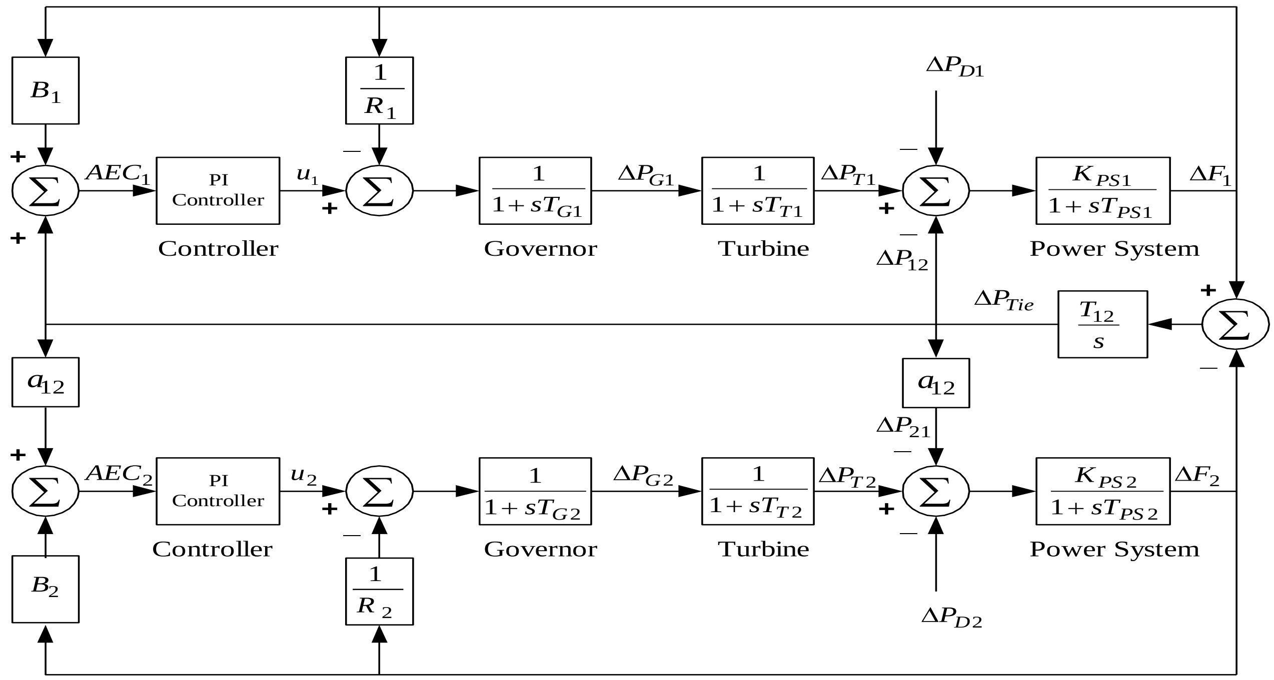


Fig.1. A two-area interconnected non-reheat power plant

3. The Proposed Approach

3.1 Controller

The PI and PID controller are the highly popular controllers generally employed in different process industries. The main advantages of proportional controller that it can decreases the rise time but steady state error does not give satisfactory value of the dynamic performances. similarly in the case of integral controller it can reduces the steady state error but transient performance very worse result. In case of the derivative control which can improving the transient stability and decreases the overshoot of the system responses. Therefore, Proportional Integral (PI) type controller one of the most suitable controllers adopted in the industry due to the above advantages. It is also used in industries PID controllers due to transient stability is better and give the fast responses of the steady sate value and also reduces the overshoot. The derivative controller mode which increases stability of the power system and it is allow the increasing in proportional gain and decrease in integral gain which in turn increases speed of the controller response. After comparing the advantages of different modes, in this article a PI and PID controller has been implemented for the stability analysis. The PI and PID controller design are based on gains of Proportional, Integral and derivative (K_P, K_I and K_P, K_I, K_D). The identical PI /PID controller is considered for both the areas of the proposed power system. The gains of the PI/PID controller are taken as ($K_{P1} = K_{P2} = K_P$, $K_{I1} = K_{I2} = K_I$ and $K_{D1} = K_{D2} = K_D$)The error inputs to the controllers are the respective area control errors (ACE) given by:

$$e_1(t) = AEC_1 = B_1\Delta f_1 + \Delta P_{Tie} \quad (7)$$

$$e_2(t) = AEC_2 = B_2\Delta f_2 - \Delta P_{Tie} \quad (8)$$

The control inputs u_1 and u_2 of the power system are the outputs of the controllers as given in equation (9) and (10)

$$u_1 = K_{P1}AEC_1 + K_{I1}\int AEC_1 \quad (9)$$

$$u_2 = K_{P2}AEC_2 + K_{I2}\int AEC_2 \quad (10)$$

3.2 Objective Function

The first step to design a proposed model with PI controller is to define an objective function which is based upon the essential specifications and desirable constraints of the system. The selection of an objective function for tuning Proportional Integral controller is basically dependent upon performance index of the response of complete closed loop system. The settling time, rise time, overshoot and steady state error are most important for time domain of the system. Mostly 4 types of objective function considered for the performance criteria are studied while designing a controller. These objective functions are ITAE, ISE, ITSE and IAE. From [21], ITAE was found to give better responses as compared to other performance criteria. The system modes and eigen value of three type objective function is provided for analyzing low frequency oscillations found in the power system. The performance stability analysis of the power system is studied using eigen value analysis under various frequencies modes. All the modes should be stable in a power system. Also, all the oscillations should quench immediately and it must have maximum damping ratios of dominant eigenvalues as per the literature of frequency stability analysis. In the AGC for frequency stability for the few essential control specifications enlisted are (i) After a load change, the frequency error must return to zero (ii) The frequency error should be marginal for integral value (iii) under the normal operating criteria load should be carrying itself by each area [3]. Keeping in mind all the above points, three different types of objective functions are considered in this analysis which are given by in Eq. (11), (12) and (13). The ITAE objective function(J1) as in Eq. (11) is a standard objective function and widely used frequently in many literatures. It helps to achieve the control specifications (i) and (ii) as explained in the above analysis. In order to achieve damping of oscillating modes with some degree of stability, the objective function(J2) is considered in Eq. (12) in the proposed analysis. The aim of this function(J2) is minimization of ITAE and maximization of the minimum damping ratio of dominant eigenvalues. Here to quickly minimize the error , the settling times of frequency deviations (Δf_1, Δf_2) and change in tie line power (ΔP_{Tie}) are also considered in the objective function (J3) as in given Eq. (13).In equation 12 and 13 , n and ζ_i are the total number of dormient eigenvalues and damping ratio respectively and also ω_1 to ω_5 are weighting factors taken in the objective functions of J2 and J3.

$$J_1 = \int_0^{t_{sim}} \left(|\Delta f_1| + |\Delta f_2| + |\Delta P_{Tie}|\right) \cdot t \cdot dt \qquad (11)$$

$$J_2 = \int_0^{t_{sim}} \omega_1 \cdot \int_0^{t_{sim}} \left(|\Delta f_1| + |\Delta f_2| + |\Delta P_{Tie}|\right) \cdot t \cdot dt + \omega_2 \cdot \frac{1}{\min\left(\sum_{i=1}^{n}(1-\zeta_i)\right)} \qquad (12)$$

$$J_3 = \int_0^{t_{sim}} \omega_3 \cdot \int_0^{t_{sim}} \left(|\Delta f_1| + |\Delta f_2| + |\Delta P_{Tie}|\right) \cdot t \cdot dt + \omega_4 \cdot \frac{1}{\min\left(\sum_{i=1}^{n}(1-\zeta_i)\right)} + \omega_5 \cdot T_S \qquad (13)$$

Where t_{sim} and T_S are simulation time range and sum of settling time value (frequency and tie line power deviations) respectively. The addition of appropriate individual terms of weighting factors of RHS of equations (12) and (13) leads to competition in each term in optimization process. On the other hand, if the weighting factors are wrongly chosen, to incompatible numerical values gets assigned to each term of the fitness function which in turn will give deceptive result. The weights are chosen in such a way that all the terms in RHS of equations (12) and (13) lie in the same range of the numerical value. Repetitive trial run of this optimization algorithms is select the ITAE value to be in the range of 1.25 to 2.5, minimum damping ratio can be select in the range 0.02 to 0.3 and total setting times of Δf_1, Δf_2 and ΔP_{Tie} to be in the range of 2 to 50. To include competition in each term while the optimization process, the following weights are assigned as: ω_1 =1.0, ω_2 =10, ω_3 =1.0, ω_4 =1.0 and ω_5 =0.05.The problem constraints are PI/PID controller parameter bounds in the optimization technique. Hence, PI controller design for this system can be considered as an optimization problem as follows:

Minimize J (14)

Subject to

PI controller: $K_{P\min} \le K_P \le K_{P\max}$ and $K_{I\min} \le K_I \le K_{I\max}$

and PID controller: $K_{P\min} \le K_P \le K_{P\max}$, $K_{I\min} \le K_I \le K_{I\max}$, $K_{D\min} \le K_D \le K_{D\max}$ (15)

Where J represents the objective functions : (J_1, J_2 and J_3) , $K_{P\min}$, $K_{P\max}$ $K_{I\min}$, $K_{I\max}$ and $K_{PID\min}$ and $K_{PID\max}$ are the minimum value and maximum value of the proportional, integral and derivative control parameters respectively. Here the minimum and maximum value of controller parameters can be taken in the range [-1 1] during the searching of optimal control parameters of the

4. Pattern Search Algorithm

The Pattern Search (PS) which is also called as derivative free search optimization algorithm which do not require any gradient [20]. Hence it can be used for functions not continuous or differentiable. This optimization technique is used to find the best match in a space of multidimensional analysis. In this technique the objective is to obtain pattern or substring from another bigger string. The main objective in designing this optimization technique is to reduce the time complexity. In the available optimization technique is of traditional one and takes a lot of times to finish the pattern search task. Here we have a string and pattern string. So, the objective is to match the pattern string with the text string with each occurrence. The text string size is always greater than the pattern string size. The algorithm will give the output index of the string where it matches the pattern string with the text string. Let us suppose I have a text string of size 16 and pattern string of size 4 then we need to take a window size of 4 which is the size of pattern string. When we start running the window over the text string starting from index zero. The window in text screen is compared with the pattern string and if both the string found to be equal then we say that the pattern has been found at that particular index string. After this again we move the window further and again compare the window with the pattern string. Similarly, we keep moving the window until we reach, the last window. Hence, it can be observed that if text string size is 16 and pattern string size is 4 then the last index where the window should be there is given as 16-4 which is equal to 12 and the window runs from zero to 12. So, while developing the algorithm there are two loops considered. One is the outer loop and for each window there is an inner loop. One of the things that is ignored is the partial matches means the entire pattern must match the text string. The PS optimization algorithm started at the point of initial X_0 for the searching of pattern for the beginning with first iteration mesh size scalar value is taken as 1 for the proposed algorithm. The pattern vectors created as [0 1], [1 0], [-1 0] and [0 -1] and added the point of initial X_0 for the computation by the mesh points is given as X_0 + [0 1], X_0 + [1 0], X_0 + [-1 0] and X_0 + [0 -1] which are represented as shown in Fig.2. The PS optimization algorithm is computed the objective function as per the first order of initial mesh point X_0 of the pattern search. It will be computing the given objective function till the new one obtained which is less than the mesh point value X_0. The new objective function X1 is obtained successfully from poll which are decreases the value as compared to X_0. From the poll of pattern search effectively obtained the objective function of PS algorithm the steps to iteration 2 which is mesh size of present value 2 is multiplied the pattern vectors and this multiplying factor 2 is called as expansion factor. The next new iteration the new pattern vectors are X1 + 2 *[0 1], X1 + 2 * [1 0], X1 +2 * [-1 0] and X1 + 2 *[0 -1], it will be continuing until stopping criteria researched.

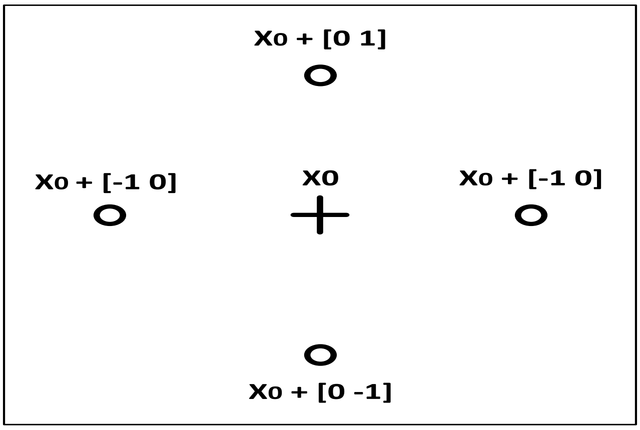


Fig. 2. Pattern vectors with Search mesh points

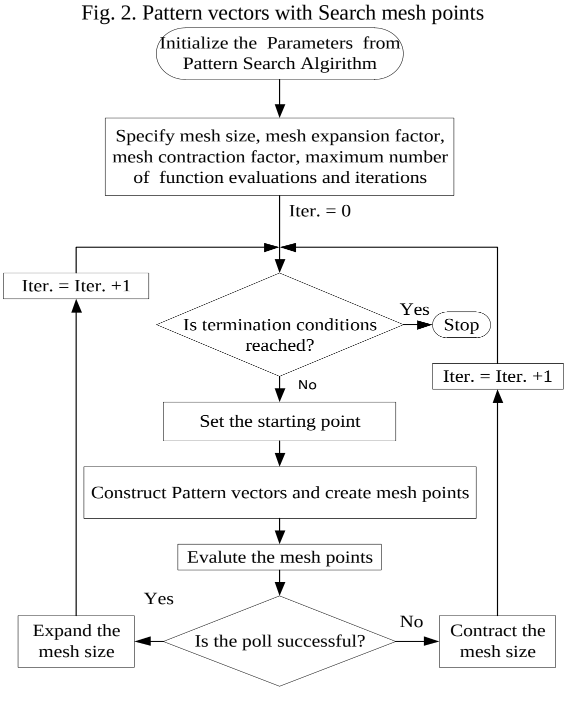


Fig.3. Flowchart of Pattern Search Algorithm

If any objective function value is obtained from the poll of pattern search which is more than the initial mesh point then current point of iteration unsuccessful and it is automatically procced to the next iteration until successful one is obtained which are multiplied the mesh size by 0.5 called a contraction factor. The contraction factor 0.5 multiplied due to smaller the next iteration and it will be continued until stopping criteria is reached. The flow chart of the above process of pattern search optimization algorithm as shown in Fig.3.

5. Results and Discussions

5.1 Application of Pattern Search Algorithm in Controller Design

The system has been modelled in MATLAB/SIMULINK environment and Pattern Search Algorithm written in (.m file). The developed simulation model having same type of PI controllers are considered in both the areas of the power system. The simulation model is taking with 0.1pu step load change of area 1. The calculation of the objective function is carried out in MATLAB code to be used in optimization algorithm. Here, Pattern Search Algorithm is implemented by taking with mesh size value=1, mesh expansion factor=2 and mesh contraction factor taken as 0.5. The optimal generation and evaluation of objective function taken 10 per each set value. Termination of the optimization is carried out by number of generations specified by as before value taken in the number of generations. The repetition of the program has set to 50 and the best final solution obtained from this algorithm at the end of the loop is considered as the final value of controller gains and initial value for Pattern Search technique. The results of optimal tunning parameters are obtained by using PS algorithm over 50 independent runs are shown in Table I.

TABLE I
TUNING OF CONTROLLER FOR THREE DIFFERENT OBJECTIVE FUNCTIONS

OBJ. FUNCTION/ CONTROLLER		J1	J2	J3
PI Controller	KP	-0.2055	-0.4801	-0.4199
	KI	0.3983	0.3112	0.2901

The Table-II shown that the values of eigenvalues, minimum damping ratio and settling time (2%) along with different error criteria of the system. It is clear from Table II that PI controller and ITAE objective function (J1) ITAE value is obtained with PS (ITAE= 1.5941) compared to ITAE value with BFOA (ITAE=1.7975) and GA (ITAE=2.7475) optimization algorithm. It is also evidence that by considering the objective function J_2 which is a combination of ITAE and damping ratios gives improved value of minimum damping ratio $\zeta = 0.2274$ and minimum value of ITAE of 1.2014 using PS algorithm as compared with BFOA and GA based optimization technique of the same controller and same power system. The settling time of frequency deviation and tie line power also give better value as compared to BFOA and GA and J1 objective function using PS algorithm of PI controller of the power system. Similarly in the case of objective function (J3) gives the minimum damping ration $\zeta = 0.2306$,ITAE value of 0.8834 and settling time of frequency deviation and tie line power give better performance as compared with objective function J1 and J2 taken of the same power system using PS optimization techniques and also better than the published results of BFOA and GA techniques. This analysis shows that the performance of the system under study is highly improvised with PI controller with objective function J3 using Pattern Search optimization technique of the two-area power system.

TABLE II:
EIGEN VALUES, MINIMUM DAMPING RATIO AND ERROR CRITERIA OF THE SYSTEM UNDER STUDY

PARAMETERS		J_1	J_2	J_3	GA [18]	BFOA [18]
System modes		-12.9911	-12.9885	-11.110	-13.1203	-13.01
		-13.024	-12.998	-11.7431	-13.1043	-12.9601
		-0.534± 2.9823i	-0.733± 2.7967i	-0.6901± 2.7661i	-0.5605± 3.1716i	-0.7037± 2.8983i
		-1.0123± 1.7781i	-0.8511± 1.1144i	-1.0401± 1.2281i	-1.1751± 1.9112i	-1.0637 ± 1.3221i
		-0.9022 ± 0.2801i	-0.7111± 0.4991i	-0.7234± 0.2401i	-1.1967± 0.4454 i	-0.733± 0.3477i
		-0.7660	-1.2597	-0.79885	-0.4288	-0.7958
Damping ratio (ζ)		0.1490	0.2274	0.2306	0.174	0.2359
Ts (sec)	Δf_1	8.48	6.79	5.12	10.59	5.52
	Δf_2	8.56	6.88	5.89	11.39	7.09
	ΔP_{Tie}	6.59	4.85	6.55	9.37	6.35
ITAE		1.5941	1.2014	0.8834	2.7475	1.7975

5.2 Dynamic Response Analysis

The simulation of dynamics response analysis can be studies by taking the three types of step load perturbation (Case-A, Case-B and Case-C) is considered in the proposed power system model. The time domain analysis is carried out for step change in load at various locations with variable parameters. The responses of frequency deviation and tie line power of PI controller employing three objective functions J_1, J_2, J_3 are represented by a dashed line, dash-dot line and solid line respectively.

Case A: Step increase of load in area-1

In this case to study the dynamic performance of PI controller, at time t= 0 sec, a step increase of 0.1 p.u step load changes in area-1 of the power system and its dynamic responses of frequency deviations and tie line power are obtained as shown in Fig. 4-6.

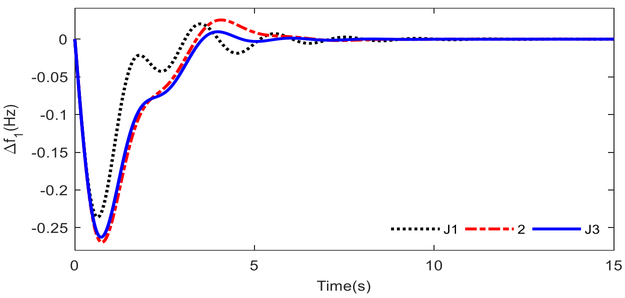


Fig.4. Variation of frequency in area 1 for Case-A

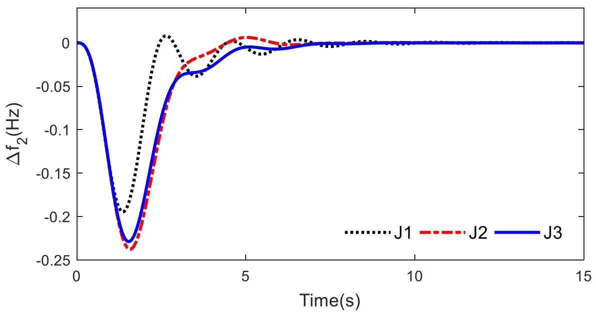


Fig.5. Variation of frequency in area 2 for Case-A

It is clear that a good dynamic performance can be observed by using PS based PI controller with objective function(J_3) in the two-area power system having minimal value of settling time and overshoot as compared to same structure and same PI controller using the objective function (J1 & J2).

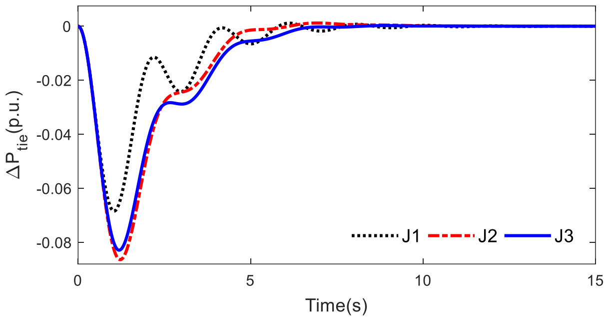


Fig.6. Variation of tie line power for Case-A

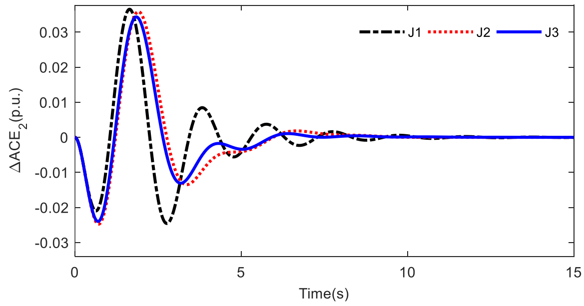


Fig.7. Variation of area control error-2 for Case-A

Case B: Step increase of load in area-2

The Fig.7-9 shows the dynamic performance of the system under studies corresponding to 0.1 p.u. step increase in demand at time t=0sec in area-2 only. It is clear from the Fig. 7-9 shows that it gives the satisfactory performance of controller even with the variation in load disturbance in different location of area. The objective function of J_3 in PI controller of the system the frequencies deviation of area-1 and area-2 and tie line power is gives the better performances with minimal value of oscillation and settling time.

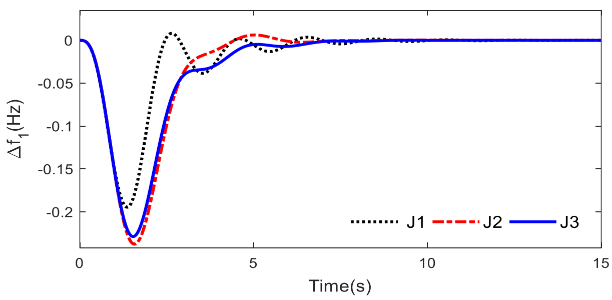


Fig.8. Variation of frequency in area 1 for Case-B

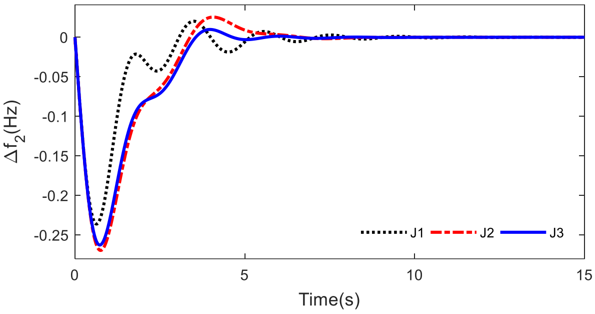


Fig.9. Variation of frequency in area 2 for Case-B

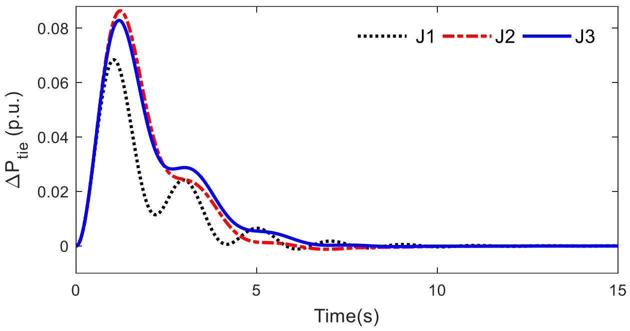


Fig.10. Variation of tie line power for Case-B

Case C: Step load change in area-1 and area-2

The performances of PS optimized PI controller is further investigated by taking 0.1 p.u step increase in load of area 1 as well as 0.1 pu step increase in load of area 2 is simultaneously in both areas of the system. The Fig. 10-12 shows the dynamic response of the system under studies. This indicates that objective function J_3 helps in achieving a better dynamic performance as compared to others (J1 and J2) of the same system model with same controller.

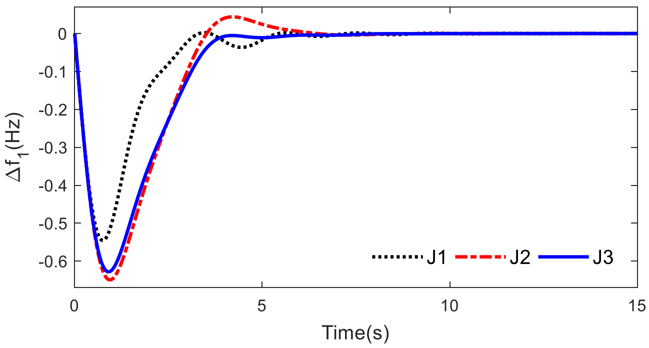
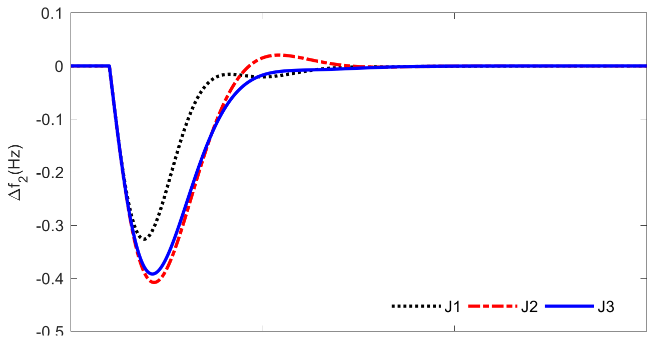


Fig.11. Variation of frequency of area-1 for Case-C



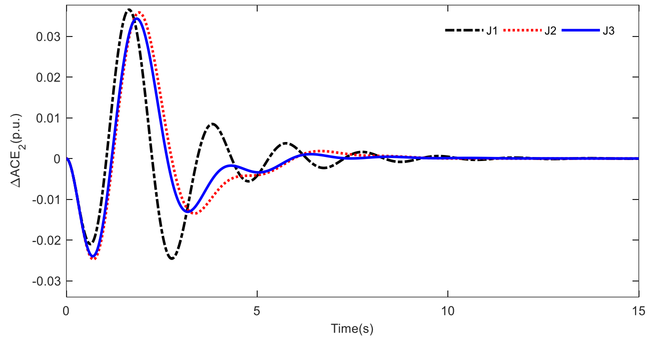


Fig.12. Variation of area control error-2 for Case-C

5.3 The Variation of Parameters

The robustness of PI controller can be assessing by variation of the parameters T_{12} and T_g are applied to test in the proposed model of the power system and in this case-D the objective function J_3 is used as it is giving better performance as compared to J1 and J2. The parameters T_g and T_{12} are increased by 50 % and decreased by 50% and the frequency variation of area-1 as shown in Fig.13-14. It is clear from Figs. 13-14 that the proposed control strategy provides a robust control in the range ± 50% satisfactorily. It is also tested the robustness of the control in the ranges between -50% to +50% including -25% to +25% of the variation of parameter T_{12} and the Fig.15 shows the variation of frequency in area-1 gives satisfactory performances.

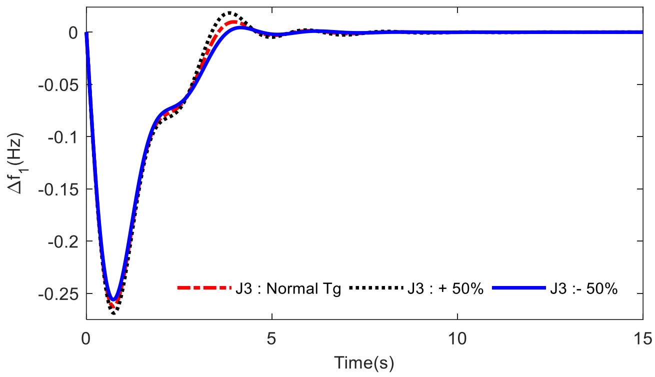


Fig.13.frequency deviation of area-1 for change in nominal load

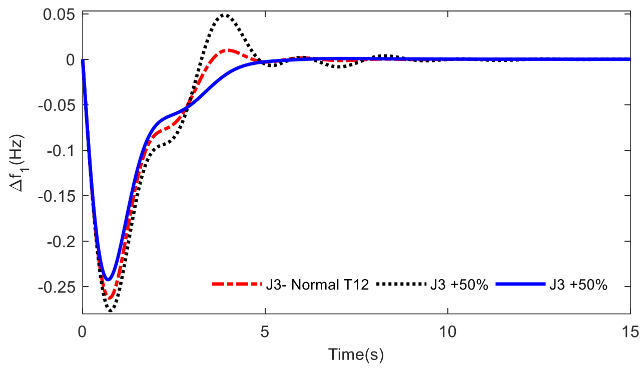


Fig.14.Frequency deviation in area-1 for change in nominal load

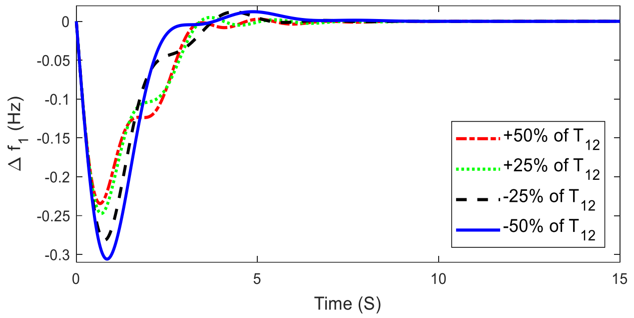


Fig.15.Frequency deviation in area-1 for change T_{12}

5.4 Analysis of Two Area Power System in Presence of Governor Dead Band

In this analysis, the simulation model of two area power system as shown in Fig-1 having remain same structure but only modification of the model is that a physical constraint of governor dead band considered in this system [9,22-23]. In the new power system model in presence of the governor dead-band non-linearity which is affect the dynamic performance of oscillation of power system. Some researcher has been attempted the effect of power oscillation in presence of this non linearity [9] and the transfer function Gg can be represented as follows

$$G_g = \frac{0.8 - \frac{0.2}{\pi} s}{1 + sT_g}$$

The proposed modified simulation model is run in same procedure as in the previous analysis under condition of a step load disturbance of 0.1p.u considered in the area-1 of the system. The optimization processes are continuing with minimum 50 times run and the best global value of objective function becomes as final value obtained in PI and PID controller parameters. The best values of control parameters of the proposed power system by considering the objective function (J3) are obtained as shown in Table-III.

TABLE III
CONTROLLER PARAMETERS IN THE MODIFIED POWER SYSTEM IN PRESENCE OF GOVERNOR DEAD BAND NON-LINEARITY

TUNING PARAMTERS			J3	J3
PI Controller	KP	Proportional Gain	-0.3221	-0.4743
	KI	Integral Gain	0.2974	0.3104
PID Controller	KP	Proportional Gain	0.6954	0.2286
	KI	Integral Gain	0.8701	0.8835
	KD	Derivative Gain	0.6943	0.5261

The corresponding performance indexes settling time, maximum overshoots and maximum undershoot of frequency deviations and tie lie power with the above varied system conditions are given in Table IV. To study the dynamic performance of the proposed modified model in presence of governor dead band non linearity by considering the three step load disturbances as in case-1, case-2 and case-3 just like in absence of governor dead band of the same system.

TABLE IV:
THE SETTLING TIME, OVERSHOOT AND UNDERSHOOT OF FREQUENCY AND TIE LINE POWER DEVIATION OF PI AND PID CONTROLLER

PARAMETERS		PI CONTROLLER	PID CONTROLLER	PI CONTROLLER	PID CONTROLLER	PI CONTROLLER	PID CONTROLLER
J3		Case-1		Case-2		Case-3	
T_S (sec)	Δf_1	21.5	6.9	22.1	7.2	21.5	9.1
	Δf_2	22.1	6.7	22.5	7.1	20.5	9.2
	ΔP_{Tie}	23.5	7.1	24.2	8.5	20.6	9.2
Max. Overshoots (MOS)	Δf_1	0.010	0.003	0.005	0.001	0.004	0.001
	Δf_2	0.006	0.002	0.010	0.002	0.008	0.002
	ΔP_{Tie}	0.001	0.000	0.008	0.003	0.0083	0.0025
Max. Undershoots (MUs)(-ve)	Δf_1	0.032	0.018	0.031	0.011	0.035	0.009
	Δf_2	0.031	0.011	0.031	0.017	0.032	0.016
	ΔP_{Tie}	0.008	0.003	0.001	0	0.005	0

Case-1: Step increase in load in area-1

To studies the dynamic performances of the PI and PID controller of the proposed new power system model in presence of governor dead band non linearity which employing PS algorithm using the best objective function (J_3) as compared to objective function of J1 and J2. As in Case-1, a step increase in load is same as in Case-A taken in the previous analysis and the system dynamic responses of PI/PID controller are shown in Figs. 16-21. It is clear that system responses in PID controller better performance as compared to PI controller of the same system in term of settling time, overshoot and undershoot of frequency deviations and tie line power the system

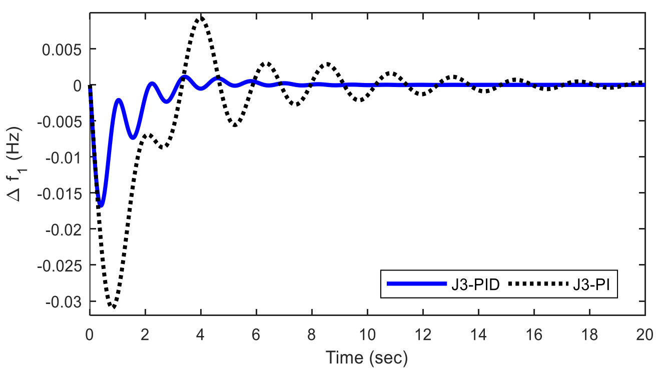


Fig.16. Variation of frequency in area-1 in presence of physical constraint

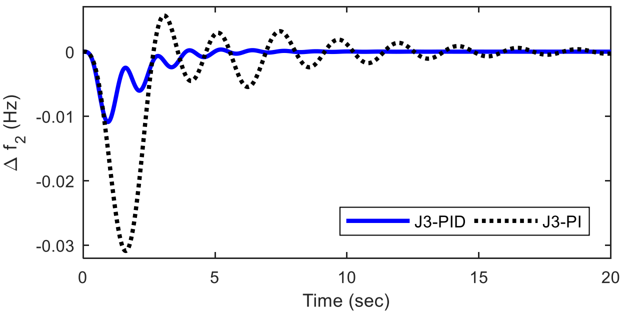


Fig.17. Variation of frequency in area-2 in presence of physical constraint

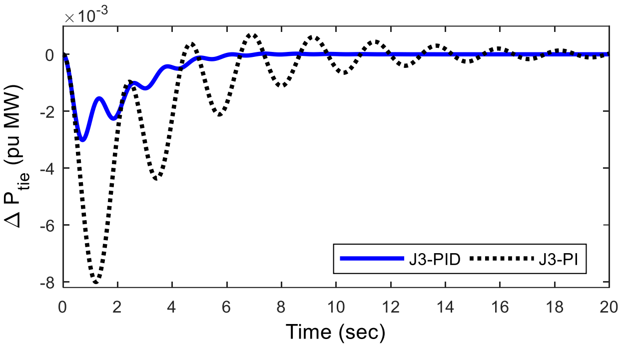


Fig.18. Variation of Tie line power with governor dead band physical constraint

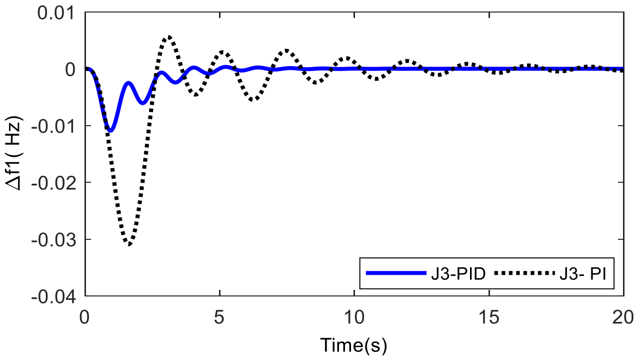


Fig.19. Variation in frequency as in Case-2 in presence of physical constraint

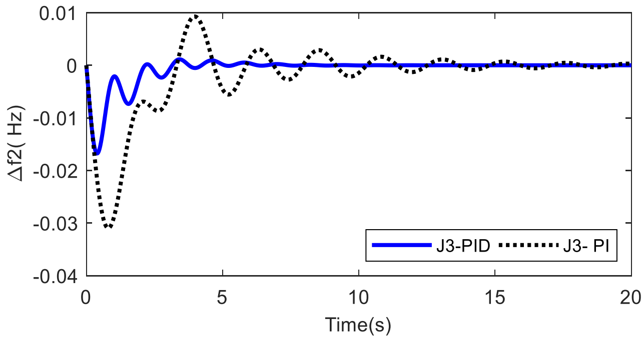


Fig.20. Variation in frequency as in Case-2 in presence of physical constraint

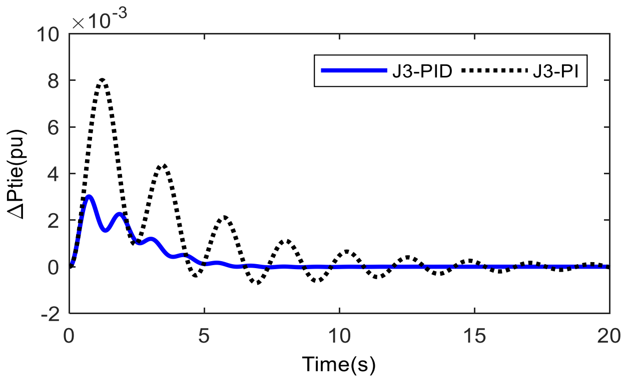


Fig.21. Variation in tie line power as in Case-2 with governor dead band physical constraint

*Case 3: Step load change in area-1 and area-**2***

In this Case 3, the performance of PI and PID controller can be studies under the disturbances same as in Case-C of the proposed power system. The system responses under this condition are shown in Figs. 22-24 which are clear that the proposed controllers are robust and perform satisfactorily performances in PID controller as compared to PI controller subjected to load disturbance changes in both areas simultaneously.

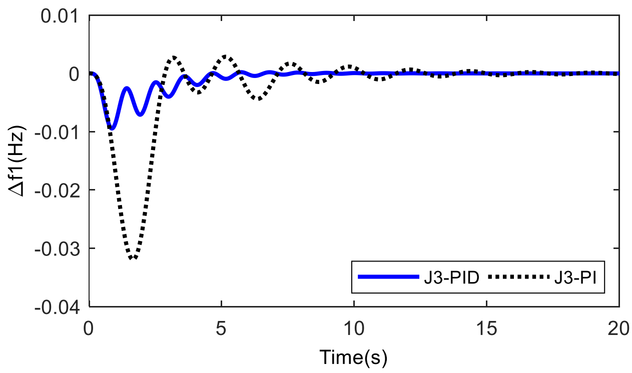


Fig.22. Variation of frequency as in Case-3 with governor dead band physical constraint

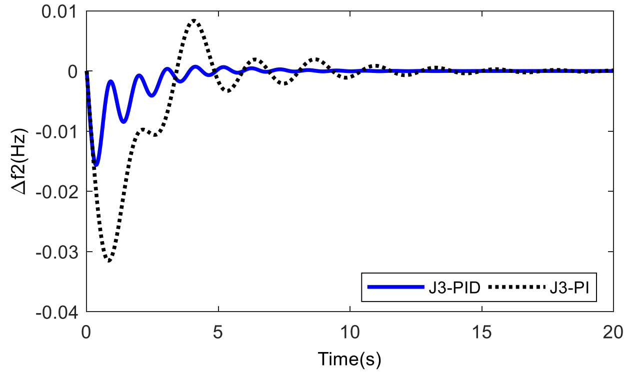


Fig.23 Variation of frequency as in Case-3 with governor dead band physical constraint

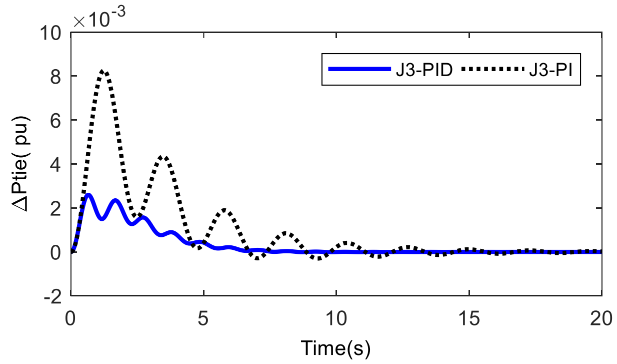


Fig.24. Variation of tie line power as in Case-3 with governor dead band physical constraint

5.5 Sensitivity Analysis

It is further investigated the sensitivity analysis under extensive changes in operation condition and also change in system parameters to test the robustness of the proposed new power system in presence of physical constraint of governor dead band. In this analysis only operating loading condition changes from nominal value to ±50 % and ±25% in step of the power system of PI and PID controller. The PI and PID controller parameter obtained under +50%, -50%, +25% and -25% of nominal loading by using PS optimization algorithm with objective function is considered in presence of perturbation same as in Case-1. The optimized controller of PI and PID parameters are obtained as in the given Table-V. The Figure 25-36 shows that the system responses of PID controller gives better performances as compared to PI controller of the same system under operating loading condition changes from nominal value to ±50 % and ±25% in step of the proposed power system. The table-VI shows depict undershoot, overshoot and settling time of $\Delta f_1, \Delta f_2$ and ΔP_{tie} for PI and PID controllers of the proposed power system. It is clear that settling time, overshoot and undershoot is improved better in PID controller as compared to PI controller of the same power system.

TABLE V
OPTIMIZED CONTROLLER PARAMETERS UNDER FOUR NOMINAL LOADING CONDITIONS

TUNING CONTROL PARAMETERS		+25%	+50%	-25%	-50%
PI	KP	-0.4972	-0.4761	-0.4654	-0.4568
	KI	0.2344	0.1974	0.1257	0.1258
PID	KP	0.2361	0.6012	0.1750	0.3442
	KI	0.576	0.8833	0.9031	0.8865
	KD	0.5601	0.7453	0.4972	0.5672

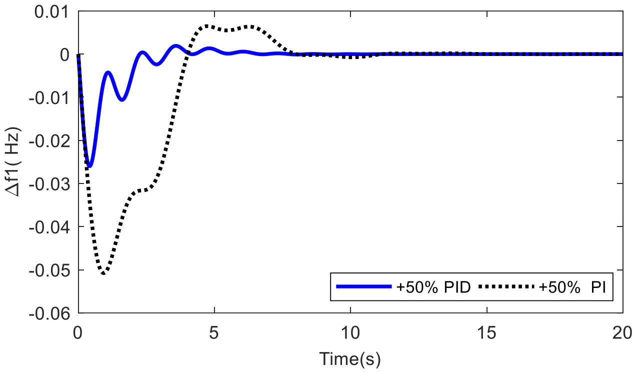


Fig.25. Deviation of frequency in area-1 for condition same as Case-1

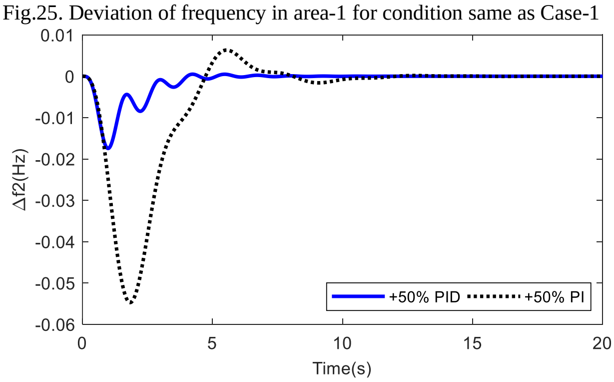


Fig.26. Change in frequency in area-2 for the condition same as Case-1

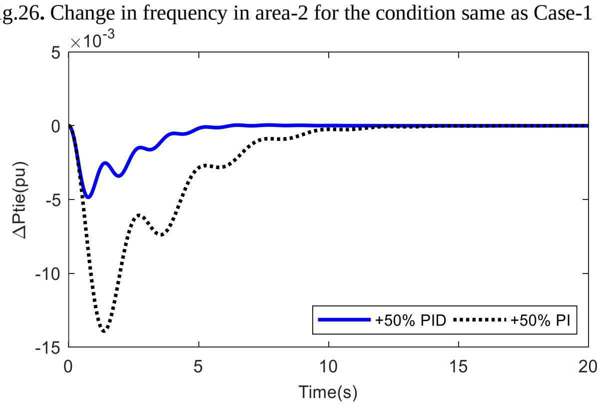


Fig.27. Change in tie line power for the condition same as Case-1

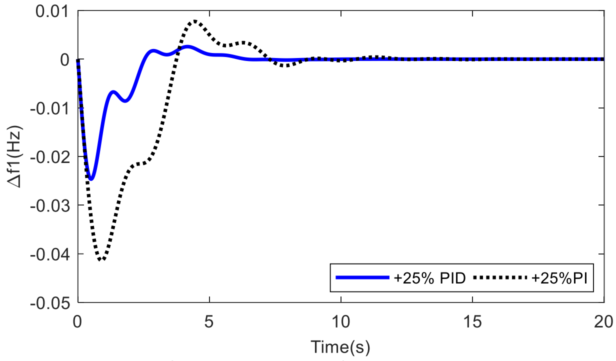


Fig.28. Variation in frequency in area-1 for the condition same as Case-1

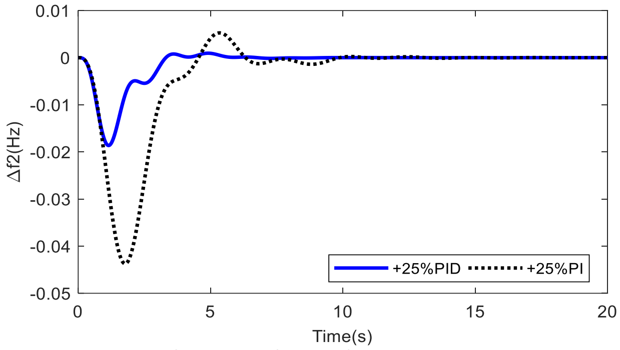


Fig.29. Variation in frequency of area-2 for the condition same as Case-1

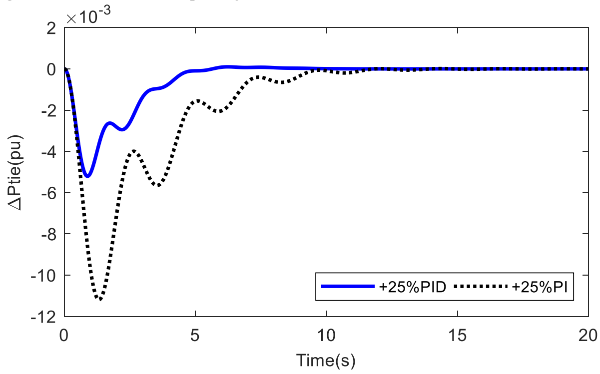


Fig.30. Variation in tie line power for the condition same as Case-1

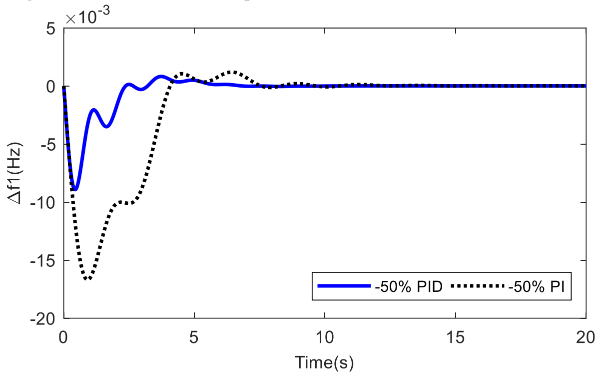


Fig.31. Variation in frequency of area-1 for the condition same as Case-1

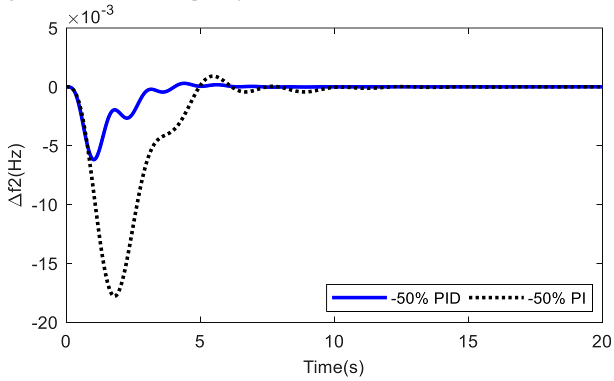


Fig.32. Variation in frequency of area-2 for the condition same as Case-1

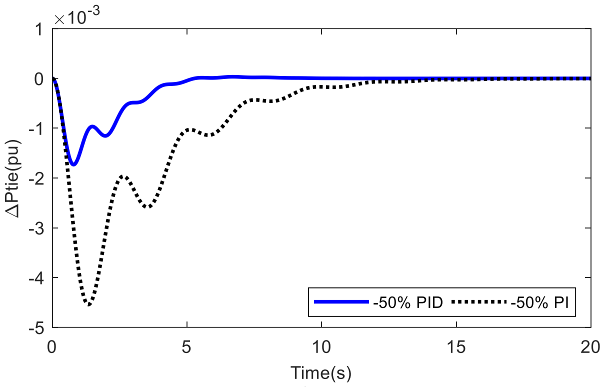


Fig.33. Change in tie line power for the condition same as Case-1

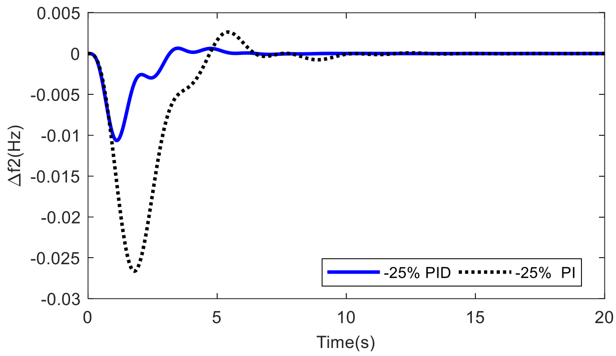


Fig.35. Change in frequency of area-2 for the condition same as Case-1

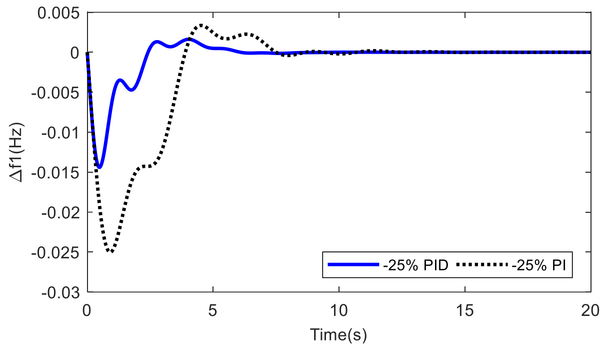


Fig.34. Change in frequency of area-1 for the condition same as Case-1

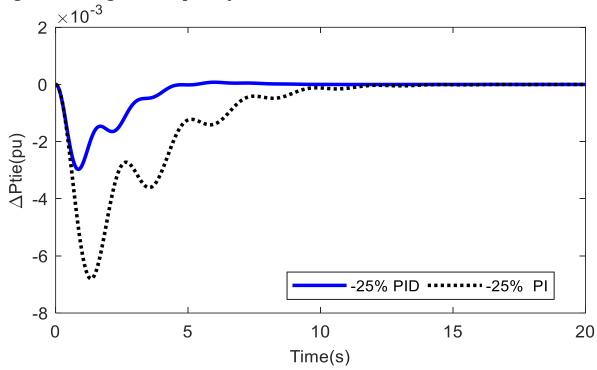


Fig.36. Change in tie line power for the condition same as Case-1

TABLE VI:
DEPICTS UNDERSHOOT, OVERSHOOT AND SETTLING TIME OF $\Delta f_1, \Delta f_2$ And ΔP_{tie} FOR PI AND PID CONTROLLERS

PARAMETERS		+25%	+50%	-25%	-50%	+25%	+50%	-25%	-50%
J3		PI Controller				PID Controller			
T_S (sec)	Δf_1	12.7	11	12.1	12.4	8.1	7.2	8.1	7.5
	Δf_2	13.1	13	11.9	12.3	7.3	7.7	7.0	7.1
	ΔP_{Tie}	14.2	13.8	14.1	15.8	7.7	7.1	8.2	7.9
Max. Overshoots (MOS)	Δf_1	0.008	0.008	0.004	0.004	0.003	0.005	0.002	0.002
	Δf_2	0.005	0.007	0.003	0.002	0.001	0.002	0.001	0.001
	ΔP_{Tie}	0.001	0.014	0.000	0.000	0.002	0.001	0.001	0.001
Max. Under shoots (MUs)(-ve)	Δf_1	0.041	0.051	0.025	0.017	0.024	0.025	0.013	0.008
	Δf_2	0.045	0.057	0.027	0.018	0.018	0.018	0.011	0.0065
	ΔP_{Tie}	0.0112	0.014	0.007	0.004	0.005	0.004	0.003	0.001

5.6 Extension to Multi-area Multi-source Power System

The study is further extended to a multi-area multi source power of transfer function model interconnected by transmission line as shown in Fig. 4. Each area comprises reheat thermal, hydro and gas generating units. The nominal parameters of the system are given in reference [24]. The PI and PID controllers considered in each unit of the anticipated model of the multi area power system. The objective function J2 and J3 of the two-area power system is same objective function considered in multi area multi source power system. The control inputs of each unit of the power system U_T, U_H and U_G with PID structure are obtained as:

$$U_T = K_{P1}AEC_1 + K_{I1}\int AEC_1 + K_{D1}\frac{dAEC_1}{dt} \quad (16)$$

$$U_H = K_{P2}AEC_1 + K_{I2}\int AEC_1 + K_{D2}\frac{dAEC_1}{dt} \quad (17)$$

$$U_G = K_{P3}AEC_1 + K_{I3}\int AEC_1 + K_{D3}\frac{dAEC_1}{dt} \quad (18)$$

The optimization was repeated 50 times using tuned PS algorithm and the best final solution among the 50 runs is chosen as proposed PI and PID controller parameters. The best final tuning controller parameters corresponding to the minimum objective function as shown in Table VII. The performance index in terms of settling time, peak overshoot, minimum damping ratio and ITAE value for under objective functions J2 with PID and J3 with PI and PID controllers of the power system are shown in Table VIII under 1% step load perturbation in area-1 of the system.

To study the dynamic performance of the system under 1% step load perturbation (SLP) in area 1 is considered at time t = 0 sec. The system dynamic performances of as shown in Fig 37-39 for the objective function J3 of PI/PID controller compared with the objective J2 of PID controller under this condition. It is clear that from the Fig 37-39 that settling time, overshoot of frequency deviation ΔF_1, ΔF_2 and tie line power ΔP_{tie} are improved better in case of objective function (J3) used in PID controller as compared the objective function (J2) of same PID controller of the same power system. It is also demonstrated that both J2 and J3 objective function based PID controller is superior performance as compared to J3 of PI controller in term of overshoot and settling time of frequency and tie line power.

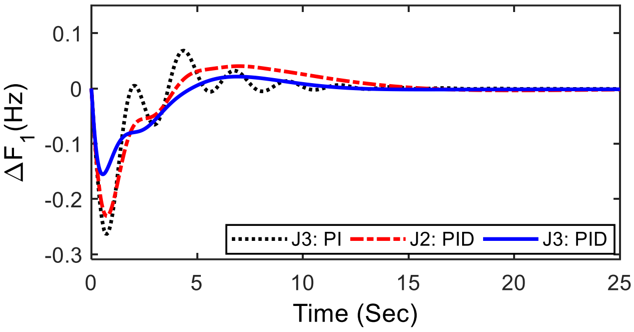


Fig. 37. Change in frequency of area-1 for 10 % change in area-1

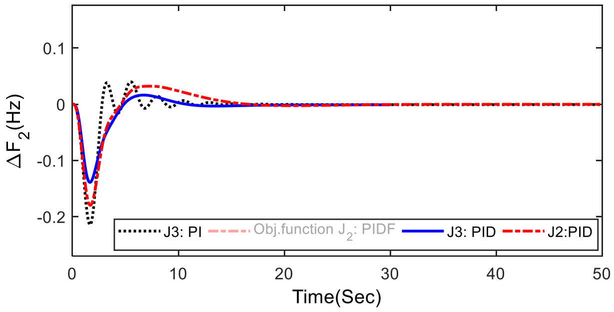


Fig. 38. Change in frequency of area-2 for 10 % change in area-1

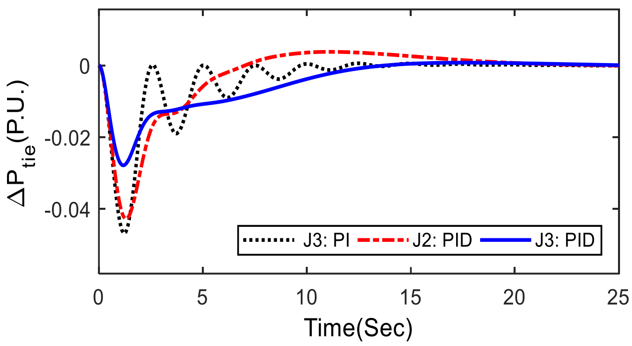


Fig. 39. Change in tie line power for 10 % change in area-1

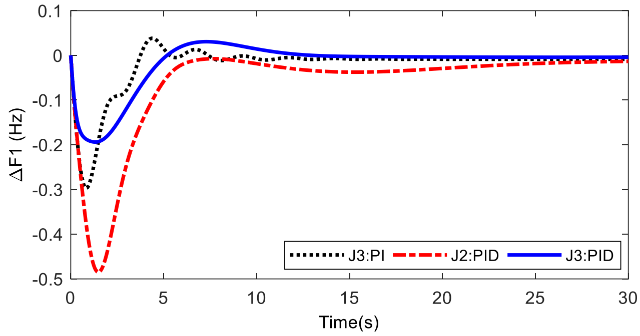


Fig. 40. Change in frequency of area-1 for 10 % change in area-2

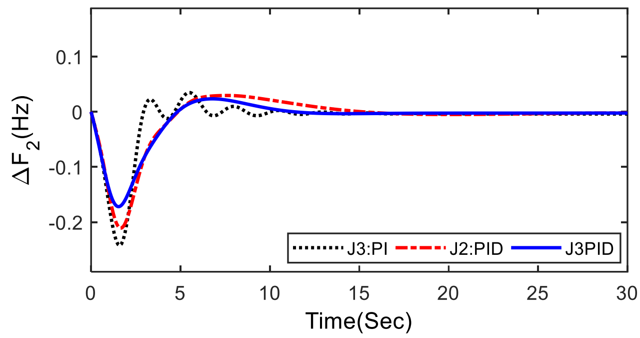


Fig. 41. Change in frequency of area-2 for 10 % change in area-2

Similarly, the dynamic responses of frequency and tie line power deviation responses of the system for a 1% step load perturbation (SLP) in area 2 occurring at time t = 0 sec are shown in Figs. 40-42.

TABLE-VII: PI(J3) AND PID(J3) CONTROLLER PARAMETERS OF MULTI AREA MULTI SOURCE POWER SYSTEM.

Controller/Objective function Parameter	PI (J_3)	PID (J_2)	PID (J_3)
KP1	-1.8611	-1.7251	-1.6845
KP2	1.7566	-0.6001	0.1976
KP3	-0.1011	-0.6218	-1.5679
KP4	-1.4680	-1.3679	1.1053
KP5	1.9015	-0.1007	0.8104
KP6	0.5994	-0.1984	-0.5890
KI1	-0.7896	-1.1102	-0.7991
KI2	1.1002	-1.1924	-1.0236
KI3	-1.8721	-1.1145	-1.6047
KI4	-0.2912	-1.5993	-0.4912
KI5	1.0717	-0.8967	1.5381
KI6	-1.0123	-1.1893	-1.1503
KD1	-	-0.2986	-1.7825
KD2	-	-1.8891	-0.0227
KD3	-	-1.1178	-1.5172
KD4	-	-0.8911	-0.3873
KD5	-	0.4113	-1.5704
KD6	-	-1.3762	-1.1946

TABLE 6: PERFORMANCE INDEX WITH DIFFERENT OBJECTIVE FUNCTIONS AND CONTROLLER STRUCTURE

Performance index Controller/Objective function	T_S(sec)			Peak Overshoot			ζ	ITAE
	ΔF_1	ΔF_2	ΔP_{tie}	ΔF_1	ΔF_2	ΔP_{tie}		
PI: *J3*	17.5	21.4	23.6	0.0714	0.0642	0.0037	0.4581	5.1204
PID: *J2*	16	19	21.5	0.0468	0.0538	0.0045	0.1784	6.8362
PID: *J3*	13	16.5	19.7	0.3105	0.0351	0.0005	0.1233	3.4728

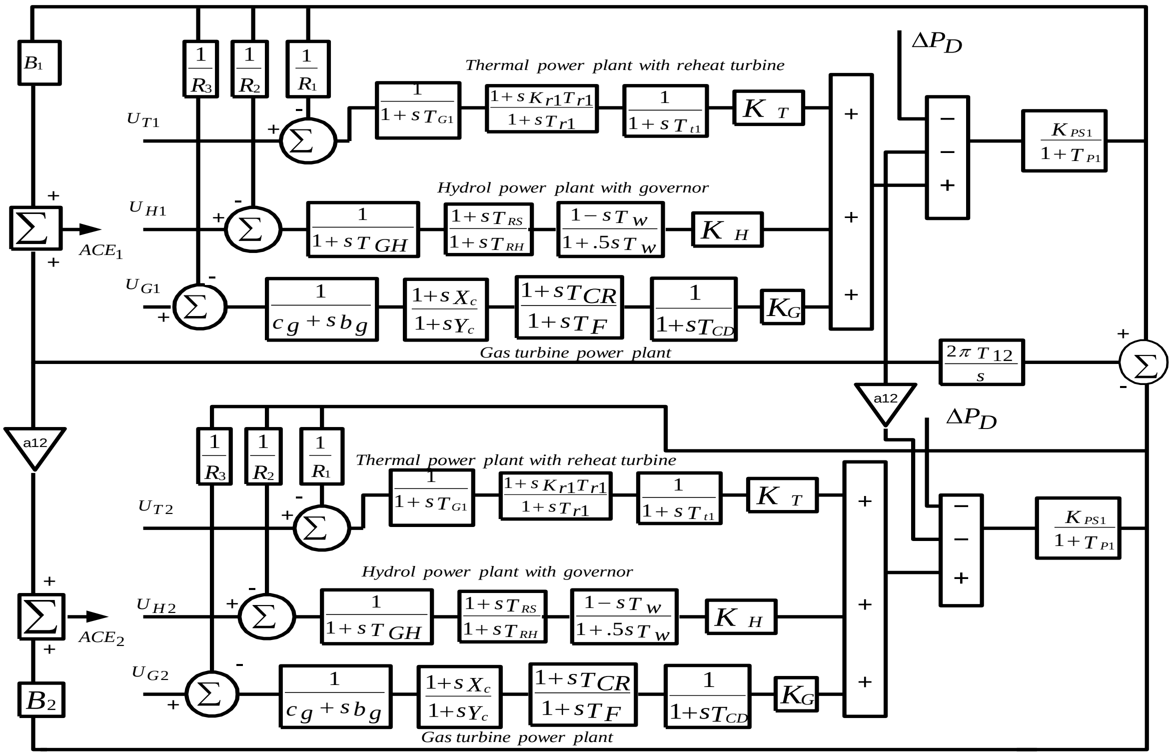


Fig.23. Multi Machine Multi sources two area power system

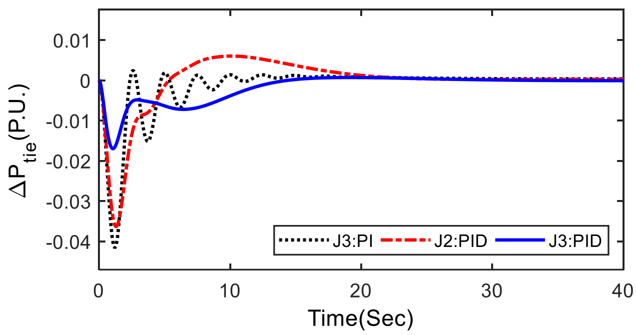


Fig. 42. Change in tie line power for 10 % change in area-2

Similarly, the dynamic frequency and tie line power deviation responses of the system for a 1% step load perturbation (SLP) in area 2 occurring at t = 0 sec are shown in Figs. 40-42. It is clear from Figs. 40-42 that settling time and overshoot of frequency deviation ΔF_1 and ΔF_2, tie line power ΔP_{tie} gives the better transient performance in objective function (J3) used with PID controller as compared to objective function (J2) used of same PID controller but however the objective function used in J2 and J3 in PID controller better performance as compared to objective function(J3) used in PI controller of the same multi machine power system.

6. Conclusion

This article depicts the advantages of employing a pattern search algorithm technique to optimize proportional-integral controller used in AGC of an interconnected two area power system. The proper tuning of the parameters of PI controller with heuristic optimization techniques involves to choose of suitable objective function of given power system. Various types of objective functions employing ITAE, damping ratio of dominant eigenvalues and settling time with appropriate weight coefficients are used to improve the robustness of the chosen controller. The improved dynamic performance is seen using new objective functions in the proposed control strategy. The advantage of this designed approach can be found on comparison of the results of PI controller with BFOA, GA under different perturbation of change in step load of the system. The proposed approach is further extended by considering the physical constraints of governor dead band in the power system. It is clear that by physical constraint nonlinearity included the system becomes a more accurate power system and the change in performance index is quite prominent from the analysis. We also investigated the sensitivity analysis, demonstrated to show the robustness of the system and we observed that in presence of governor dead band nonlinearity with PID tuning controller superior performance is achieved compared to PI controller under different range of nominal loading condition (±25% and ±50%) of the system. Lastly, it is further extended to multi-area multi-source power system to check the effectiveness of the analysis of the system and it is observed that transient performance in objective function (J3) used with PID controller is achieved compared to objective function (J2) used of same PID controller but however the objective function used in J2 and J3 in PID controller better performance as compared to objective function(J3) used in PI controller of the same multi machine power system.

APPENDIX.

Parameters of power System model for two area system.	Values
B_1, B_2	$B_1 = B_2$ =0.045 p.u. MW/Hz
R_1, R_2	R1=R2=2.4 Hz/p.u
T_{G1}, T_{G2}	$T_{G1} = T_{G2}$ =0.08(s)
T_{T1}, T_{T2}	$T_{T1} = T_{T2}$ =0.3(s)
K_{PS1}, K_{PS2}	$K_{PS1} = K_{PS2}$ =120 Hz/p.u. MW
T_{PS1}, T_{PS2}	$T_{PS1} = T_{PS2}$ =20(s)
T_{12}	T_{12} =0.545 pu
a_{12}	a_{12} =-1

References

[1] N. Jaleeli, L. S. VanSlyck, D. N. Ewart, L. H. Fink and A. G. Hoffmann, "Understanding automatic generation control," in IEEE Transactions on Power Systems, vol. 7, no. 3, pp. 1106-1122, Aug. 1992

[2] P. Kundur, Power System Stability and control, TMH, 8th reprint 2009.

[3] O.I. Elgerd, Electric energy systems theory. An introduction. New Delhi: Tata McGraw-Hill; 1983

[4] C. E. Fosha and O. I. Elgerd, "The Megawatt-Frequency Control Problem: A New Approach Via Optimal Control Theory," in IEEE Transactions on Power Apparatus and Systems, vol. PAS-89, no. 4, pp. 563-577, April 1970

[5] D.K. Chaturvedi, P.S. Satsangi, P.K. Kalra, Load frequency control: a generalized neural network approach, Elect. Power Energy Syst. 21 (6) (1999) 405–415.

[6] H.L. Zeynelgil, A. Demiroren, N.S. Sengor, The application of ANN technique to automatic generation control for multi-area power system, Electr. Power Energy Syst. 24 (5) (2002) 345–354.

[7] S.R. Khuntia, S. Panda, Simulation study for automatic generation control of a multi-area power system by ANFIS approach, Applied Soft Computing, 12 (1) (2012) 333-341.

[8] Junfeng Zhao, Jian Li and Cuirong Huang, Multi-objective Optimization Model of Hydrodynamic Sliding Bearing Based on MOPSO with Linear Weighting Method, IAENG International Journal of Computer Science, Volume 48, Issue 3: September 2021

[9] Gonggui Chen, Xilai Zhao, Yi Xiang, Xianjun Zeng and Hongyu Long,Research on Multi-objective Active Power Optimization Simulation of Novel Improved Whale Optimization Algorithm, IAENG International Journal of Applied Mathematics, Volume 51, Issue 3: September 2021.

[10] S.P. Ghosal, Optimization of PID gains by particle swarm optimization in fuzzy based automatic generation control, Electr. Power Syst. Res. 72 (3) (2004) 203–212.

[11] H. Gozde, M.C. Taplamacioglu. Automatic generation control application with craziness based particle swarm optimization in a thermal power system, Int. J. Elect. Power Energy Syst. 33 pp.8–16,2011

[12] Mostafa, Mohamed & Attia, Mahmoud & Mekhamer, S. & Mostafa, Mahmoud, "Application of Different Optimization Techniques to Load Frequency Control with WECS in a Multi Area System", Electric Power Components and Systems, 2018

[13] S. Mishra, "Maiden application of bacterial foraging-based optimization technique in multiarea automatic generation control," *2012* IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 2012

[14] J. Nanda, S. Mishra, L.C. Saikia, Maiden application of bacterial foraging-based optimization technique in multiarea automatic generation control, IEEE Trans. Power Syst. 24 (2) (2009) 602–609.

[15] S. Panda, Multi-objective PID controller tuning for a FACTS-based damping stabilizer using non-dominated sorting genetic algorithm-II, Int. J. Elect. Power & Energy Systs., 33 (2011) 1296-1308.

[16] H. Golpîra, H. Bevrani and H. Golpîra, Application of GA optimization for automatic generation control design in an interconnected power system, Energy Conversion and Management 52 (2011) 2247–2255.

[17] Elmenfy, Tawfiq A Genetic Algorithm for Optimum Design of PID Controller in Load Frequency Control", 2012 World academy of Science, Engineering and Technology, Vol 6

[18] E.S. Ali, S.M. Abd-Elazim, Bacteria foraging optimization algorithm-based load frequency controller for interconnected power system, Elect. Power and Energy Syst. 33 (2011) 633–638

[19] Rout UK, Sahu RK, Panda S. Design and analysis of differential evolution algorithm based automatic generation control for interconnected power system, Ain Shams Eng J (2012).

[20] M. F. AlHajri and M. E. El-Hawary, "Pattern search optimization applied to convex and non-convex economic dispatch," 2007 IEEE International Conference on Systems, Man and Cybernetics, Montreal, QC, Canada, 2007, pp. 2674-2678,

[21] K. Ogatta, Modern control engineering. NJ, USA: Prentice Hall; 1990

[22] Saikia LC, Nanda J, Mishra S. Performance comparison of several classical controllers in AGC for multi-area interconnected thermal system. Int J Electr Power Energy Syst 2011; 33:394–401.

[23] Panda S, Yegireddy NK, Automatic generation control of multi-area power system using multi-objective non-dominated sorting genetic algorithm-II, Int J Electr Power Energy Syst 2013:53:54-63.

[24] Parmar K.P.S., Majhi S., Kothari DP., Improvement of Dynamic Performance of LFC of the Two Area Power System: An Analysis using MATLAB, Int. Journal of Comp App. 40(10) (2012) 28-32

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