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Genetic algorithm tuned IP controller for Load Frequency Control of interconnected power systems with HVDC links

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Abstract: A new design of decentralized Load Frequency Controller for interconnected thermal non-reheat power systems with AC-DC parallel tie-lines based on Genetic Algorithm (GA) tuned Integral and Proportional (IP) controller is proposed in this paper. A HVDC link is connected in parallel with an existing AC tie-line to stabilize the frequency oscillations of the AC tie-line system. Any optimum controller selected for load frequency control of interconnected power systems should not only stabilize the power system but also reduce the system frequency and tie line power oscillations and settling time of the output responses. In practice Load Frequency Control (LFC) systems use simple Proportional Integral (PI) or Integral (I) controller. The controller parameters are usually tuned based on classical or trial-and-error approaches. But they are incapable of obtaining good dynamic performance for various load change scenarios in multi-area power system. For this reason, in this paper GA tuned IP controller is used. A two area interconnected thermal non-reheat power system is considered to demonstrate the validity of the proposed controller. The simulation results show that the proposed controller provides better dynamic responses with minimal frequency and tie-line power deviations, quick settling time and guarantees closed-loop stability margin.

Key word: genetic algorithm, Load Frequency Control, IP controller, AC-DC tie-lines, interconnected thermal non-reheat power systems

1. Introduction

The load frequency control (LFC) problem is of very important for power engineers because of the large size and complication of interconnected systems. Irregular changes in the load demand take place continuously in interconnected power systems. These changes in load always cause an inequality between power generation and utilization, which harmfully affects the excellence of generated power in several ways. Among these, the frequency deviation and the deviation in scheduled tie line power are the most important. Therefore, the objective of LFC in interconnected power systems is twofold: minimizing the momentary errors in the frequency and the planned tie line power and ensuring zero steady state errors of these two quantities. The main enviable features of decentralized LFC are the following:

(i) It should afford improved transient response and enhanced stability margin.

(ii)At steady state, the Area Control Error (ACE) should be zero, i.e. frequency and tie line power deviation should be zero under steady state.

(iii) The control law should be autonomous of disturbance.

(iv) Each area controller should employ its individual area output information.

Many control strategies for LFC of power systems have been proposed and investigated by many researchers over the past several years. Majority of the works carried out earlier [1] is focused on interconnected power systems considering the area interconnection with ac tie-lines only. Remote generation and system interconnections lead to a search for efficient power transmission at increasing power levels. The increase in voltage levels is not always feasible. The problems of AC transmission particularly in long distance transmission, has led to the development of DC transmission. There has been a tremendous growth of the HVDC transmission system due to economics of power transmission, technical performance and reliability. Hence, it has been applied widely in operating a DC link in parallel with an AC link [2-5] interconnecting control areas to get an improved system dynamic performance with greater stability margins under small disturbances in the system [6]. Only scantily information is available on LFC of interconnected power systems connected via HVDC link in parallel with ac link. Therefore, this paper considers LFC of an interconnected power system with a DC tie-line in parallel with an ac tie-line. Incremental DC power flow is considered as an additional state variable in the LFC strategy. The two-area interconnected power system with parallel AC-DC tie-lines is shown in Figure 1.

There are different intelligent controllers in the literature that have been used in the LFC of isolated as well as interconnected power systems [7]. The optimum parameter values of the conventional proportional plus integral (PI) controller have been obtained in the literature by minimizing the Integral of the Squared Error (ISE) criterion [8]. Controllers designed on the basis of ISE criterion are often of practical significance because of the minimization of control effort. But the system has poor relative stability. Hence, to obtain the decentralized controllers with improved stability margin, they are designed on the basis of Maximum Stability Margin (MSM) criterion using Lyapunov method. However, controllers designed on the basis of MSM criterion do not possess the inherent good properties of the controller designed on the basis of ISE criterion even though there is improvement in stability [9].

Hence in this paper the GA tuned IP controller [10] is used for load frequency control of an interconnected non-reheat thermal power system with AC-DC tie-lines. This system is analyzed using MATLAB and the dynamic response of GA tuned IP controller is compared with conventional PI controller and IP controller based on peak overshoot and settling time.

2. Statement of the problem

The state variable equation of the minimum realization model of ‘N’ area interconnected power system with AC-DC parallel tie-lines may be expressed as [11]

$$\dot{X} = Ax + Bu + \Gamma d, \tag{1}$$

$$v = Cx, \tag{2}$$

$$y = Hx. \tag{3}$$

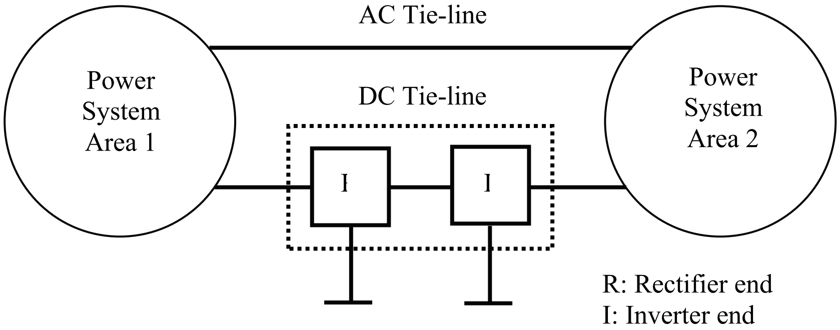

Fig. 1. Two area interconnected power system with parallel AC-DC tie-lines

Where

$$x = \left[x_1^T \; \Delta P_{aci} \; \Delta P_{dci} \; \ldots\ldots x_{(N-1)} \; \Delta P_{ac(N-1)} \; \Delta P_{dc(N-1)} \ldots\ldots \; x_N^T\right]^T,$$

$$n = \sum_{i=1}^{N} n_i + (N-1), \quad n = \text{state vector},$$

$$u = [u_1 \ldots\ldots u_N]^T = [\Delta P_{c1} \ldots\ldots \Delta P_{cN}]^T, \quad N - \text{control vector}, \tag{4}$$

$$d = [d_1 \ldots\ldots d_N]^T = [\Delta P_{d1} \ldots\ldots \Delta P_{dN}]^T, \quad N - \text{disturbavce input vector}$$

$$v = [v_1 \ldots\ldots v_N]^T, \quad N - \text{control output vector},$$

$$y = [y_1 \ldots\ldots y_N]^T, \quad 2N - \text{measurable output vector}.$$

A is the system matrix, B is the input distribution matrix, Γ is the disturbance distribution matrix, C is the control output distribution matrix, H is the measurable output distribution matrix, x is the state vector, u is the control vector and d is the disturbance vector consisting of load changes.

3. Decentralized output feedback control scheme

It is known that, by incorporating an integral controller, the steady state requirements can be achieved. In order to introduce integral function in the controller, the system Equation (5) is augmented with new state variables defined as the integral of ACE_i

$$(\int v_i dt) \quad i = 1, 2, \ldots, N.$$

The augmented system of the order $N + n$ may be described as

$$\dot{\overline{X}} = \overline{A}\,\overline{x} + \overline{B}u + \overline{\Gamma}d, \tag{5}$$

$$\overline{x} = \begin{bmatrix} \int vdt \\ x \end{bmatrix}\begin{matrix} \}N \\ \}n \end{matrix} \quad \text{and} \quad \overline{A} = \begin{bmatrix} 0 & C \\ 0 & A \end{bmatrix} \quad \overline{B} = \begin{bmatrix} 0 \\ B \end{bmatrix} \quad \text{and} \quad \overline{\Gamma} = \begin{bmatrix} 0 \\ \Gamma \end{bmatrix}.$$

As the newly added state variables $(\int v_i dt) \quad i = 1, 2, \ldots, N.$ will also be available for feedback in each area, the new measurable output vector y may be written as

$$\overline{y} = \overline{H}\,\overline{x}, \tag{6}$$

where

$$\overline{y} = [\overline{y}_1 \ldots\ldots \overline{y}_N]^T \quad \overline{H} = \left[\overline{H}_1 \ldots\ldots \overline{H}_N\right]^T, \text{ and } \overline{H} = \begin{bmatrix} 0 \; 1 \ldots & 0 \\ 0 \; 0 \ldots & H_i \end{bmatrix}.$$

The constant matrix $\overline{H}_i (i = 1, 2, \ldots, N$ is of dimension $2 \times (N + n)$. Hence the matrix $\overline{H}$ is of dimension $2N \times (N + n)$. For the design of a decentralized controller, the augmented system should be controllable and should not have unstable fixed modes. It can be easily shown that the augmented system will be controllable if and only if the system is controllable and the matrix

$$\begin{bmatrix} 0 & C \\ B & A \end{bmatrix} \text{ is of rank } (N + n).$$

The problem now is to design the decentralized feedback control law

$$u_i = -k_i^T \overline{y}_i \quad i = 1, 2, \ldots, N \tag{7}$$

to meet the objectives stated in previous section.

The control law Equation (7) may be written in-terms of proportional and integral controller as

$$u_i = -k_{i1} \int v_i dt - k_{i2} v_i, \quad i = 1, 2, \ldots, N. \tag{8}$$

where $k_i^T = [k_{i1} \; k_{i2}]$ is a two dimensional integral and proportional feedback gain vector.

4. Decentralized output feedback controller

The various techniques to obtain the decentralized output feedback controller are discussed in this section.

4.1. Design of decentralized output feedback controller using Integral Squared Error criterion (ISE)

Decentralized optimal proportional plus integral controller using output feedback for interconnected power systems are designed by applying the ISE criterion.

The closed loop augmented system with the decentralized controllers may be represented as

$$\dot{\overline{X}} = \left(\overline{A} - \sum_{i=1}^{N} \overline{b}_i k_i^T \overline{H}_i \right) \overline{x} + \overline{\Gamma} d, \tag{9}$$

where $\overline{b}_i$ is the column vector of $\overline{B}$

To obtain the optimal decentralized controller output feedback gain $k_i (i = 1, 2, \ldots, N)$, the following quadratic performance index is considered.

$$J_i = \int_0^t \left(X_{ei}^T W_i X_{ei} \right) dt \quad i = 1, 2, \ldots, N, \tag{10}$$

where $W_i = diag\{w_{i1}, w_{i2}, w_{i3}\}$ and $X_{ei}^T = \{\Delta F_i \ \Delta P_{aci} \ \Delta P_{dci}\}$ w_{i1}, w_{i2} and w_{i3} are weighting factors for the frequency deviation, AC tie-line power deviation and DC tie-line power deviation respectively of area i. $\Delta F_i = G_i x_i$, where $G_i = [1\ 0\ \ldots] x_i$ – dimensional vector of area i. Now, the aim is to design the proportional and integral controller feedback gains using decentralized output feedback. This design assumes that the interconnected power system consists of N identical areas. Therefore, the decentralized integral feedback gains (k_{11} = ... k_{i1} = ... k_{N1} = k_i) of N identical areas are considered as identical. Similarly, the decentralized proportional controller feedback gains (k_{12} = ... k_{i2} = ... k_{N2} = k_p) of the N identical areas are also assumed as identical.

4.1.1. Design of decentralized proportional controller with output feedback

In the nonappearance of the integral control, one can piercingly raise the gain of the closed loop system and thereby improve the system response. If the feedback gain of the integral controller is sufficiently high, overshoot will occur, increasing piercingly as a function of the gain, which is extremely detrimental. Thus, the integral controller gain cannot be increased to a large value because it leads to unsteadiness in the transient region [12]. Therefore, decentralized proportional controller using output feedback is designed first. The best possible proportional controller feedback gain k_p is obtained by plotting the cost curve for various values of k_p against the cost function of area i, J_i The cost function of area i, J_i is obtained by simulating the closed loop system for various values of k_p and keeping k_i equal to zero right through. The proportional controller cost curve is shown in Figure 2.

4.1.2. Design of decentralized integral controller with output feedback

Following the procedure discussed in the Section 4.1.1, the integral controller is designed. The cost function of area i, J_i is obtained by simulating the closed loop system for various values of k_i and keeping k_p equal to zero throughout. The optimum integral controller feedback gain k_i is obtained from the cost curve. The integral controller cost curve is shown in Figure 3.

4.1.3. Design of decentralized proportional plus integral controller with output feedback

Following the procedure discussed in Section 4.1.1 and 4.1.2, the proportional plus integral controller is designed. The cost function of area i, J_i is obtained by simulating the closed loop system for various values of k_i and keeping $k_p = k_{p(\text{optimum})}$. The optimal k_i, corresponding to minimum J_i, is obtained from the cost curve. The PI controller cost curve is shown in Figure 4.

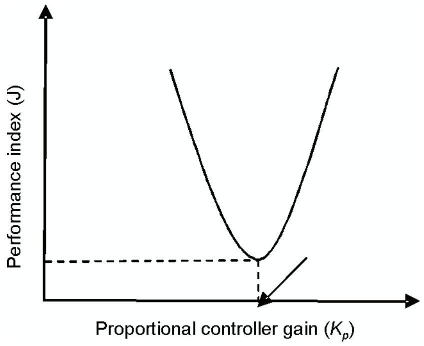

Fig. 2. Cost curve of proportional controller

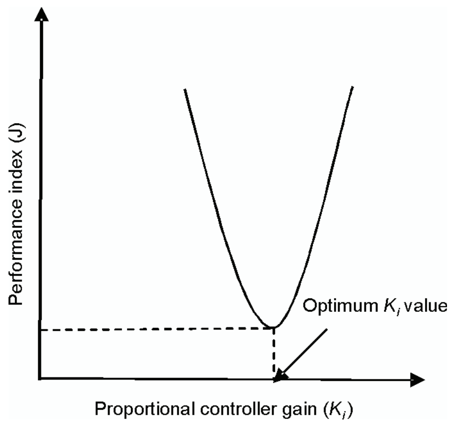

Fig. 3. Cost curve of integral controller

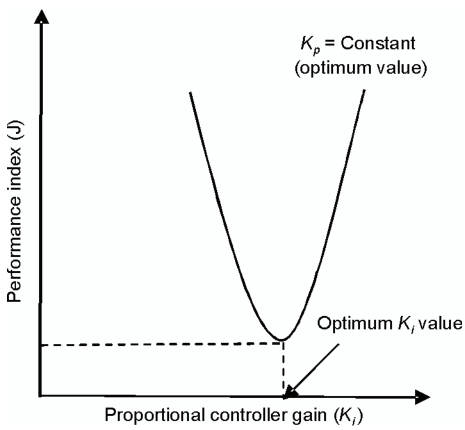

Fig. 4. Cost curve of PI controller

4.2. Design of decentralized output feedback IP controller

The controller considered on the source of the ISE criterion provides a decrease of rise time to limit the outcome of large primary errors, a lessening of peak overshoot and a fall of settling time to limit the effect of small errors lasting for a long time. Further, this criterion is often of practical consequence because of the minimization of control exertion, but the controller designed on the source of the ISE criterion tends to confirm a quick decrease in the large primary error. Hence, the response is quick and oscillatory. Therefore, the relative stability of the system is poor. Hence, to obtain decentralized controllers with enhanced stability boundary and acceptable performance, a new controller design namely IP controller is developed based on ISE design criterion.

4.2.1. IP controller

In this paper IP type controllers are considered for LFC problem. Figure 5 shows the structure of IP controller. It has some clear differences with PI controller. In the case of IP controller, at the step input, the output of the controller varies slowly and its magnitude is smaller than the magnitude of PI controller at the same step input [10]. Also as shown in Figure 6, If the outputs of the both controllers are limited as the same value by physical constraints, then compared to the bandwidth of PI controller the bandwidth of IP controller can be extended without the saturation of the controller output [10]. In the Figure 5, U_i is the input to the controller and $U_{i,ref}$ is the reference input to the Controller.

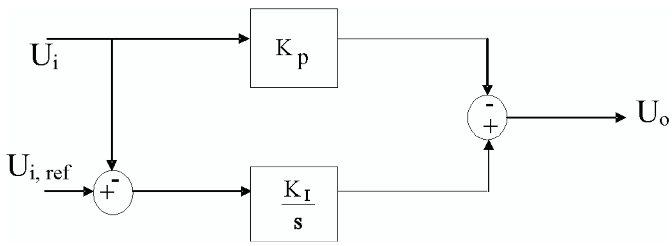

Fig. 5. Structure of IP controller

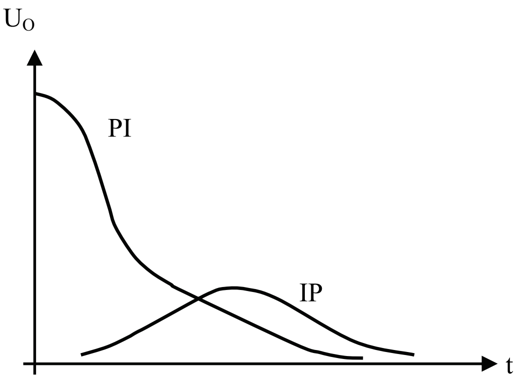

Fig. 6. Output of IP and PI controllers with the same damping coefficient ($\xi = 1$) and the same band width at the same step input signal command

In the Figure 6, U_o is the input to the controller if PI and IP Controllers are considered separately for the same input.

4.2.2. Optimization of controller gain setting using genetic algorithm

Genetic algorithm (GA) is one of the optimization methods based on heredity and evolution. This algorithm is one of the statistic searching methods and as it mentioned before due to the fact that load frequency control involves with inconstant loads and we face to a non-liner problem, real coded GA can be considered as an appropriate method for reaching optimal gains with fast response to system [13].

In designing the controller, cost function can be assumed as minimization of Integral of Square Error(ISE) for step response of load deviation.

Now the objective function is

$$F_{cost} = \int_0^t ACE_i^2 \; dt, \text{ for } i = 1, 2. \tag{11}$$

In GA algorithm considering the cost function a fitness function is considered for each string of values, so that in the next stage the initial population will be chosen in a way that we can use the probability of roulette for this choice.

The suggested fitness function for creating the initial population can be written as

$$F_{Fitness} = \frac{1}{1 + F_{\cos t}}. \tag{12}$$

Consequently the roulette is divided in according to the quantities of fitness function of each real coded string and with each circulation one string for creating a new generation is selected. Then the act of creating a new generation is done by the genetic operators such as cross-over and mutation. Afterward the fitness quantity for each one of the newly created strings is calculated and strings with more fitness are chosen as the next generation. Absolutely the strings with high fitness values are more probable to be transferred to the next generation. This process will be continued until the best answer in successive repetitions has minimum variance to unit (So J will have minimum variance to zero) and the best solution does not change for a prespecified interval of generations. The resulted string shows the information of the final optimized gains. The flow chart shown in Figure 7 illustrates basic steps in genetic algorithm used for load frequency control.

5. Application to a two-area power system

5.1. Mathematical model

The decentralized controller design is applied to an interconnected two-area non-reheat thermal power system with AC-DC parallel tie-lines as shown in Figure 8. Data for the system is given in Appendix. The state variable equation of an interconnected thermal power system with AC-DC parallel tie-lines may be written as

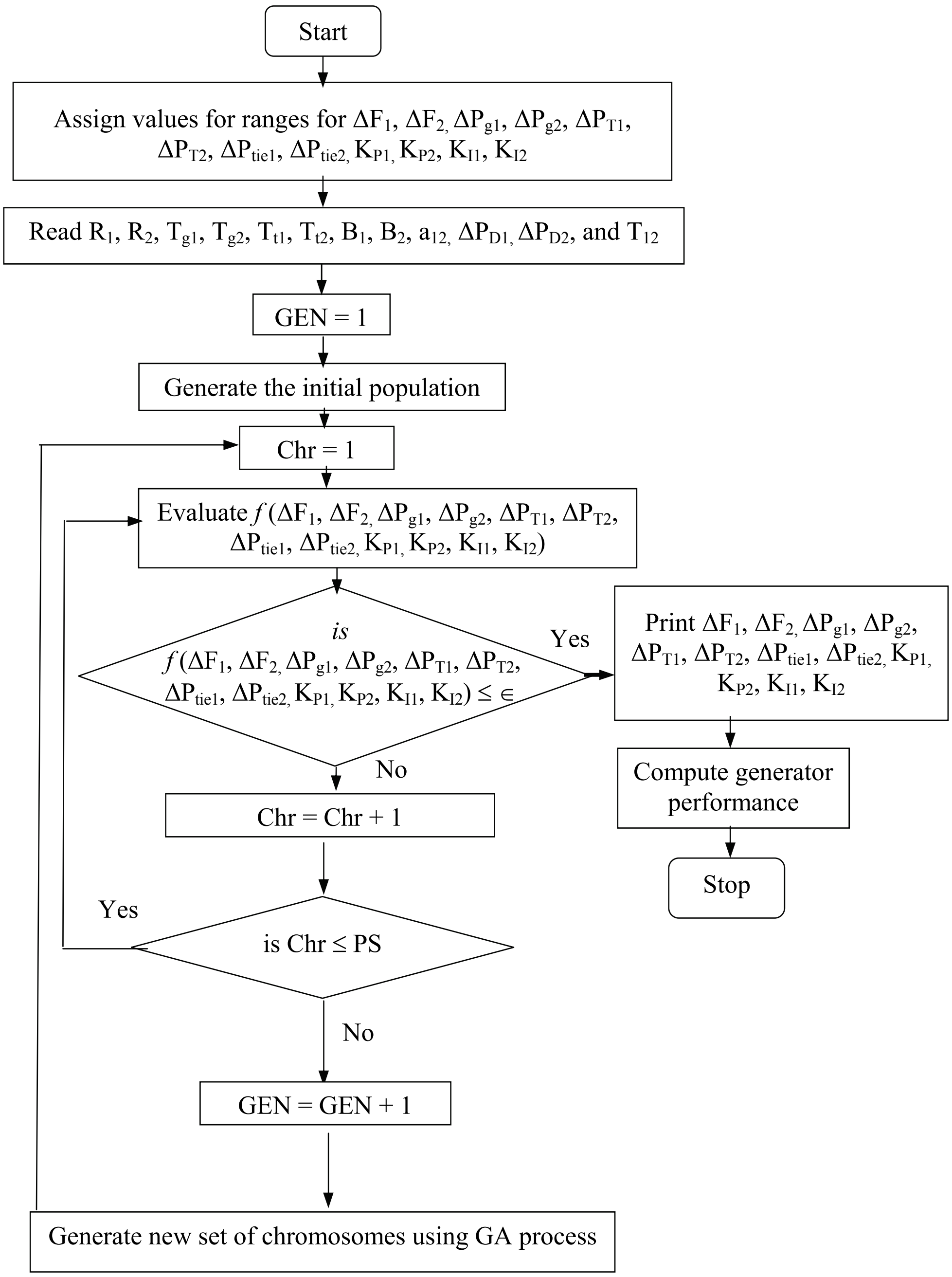

Fig. 7. Flow chart for minimization of area control error using GA
(PS – population size; Chr – chromosomes; GEN – generation; ∊ – tolerance)

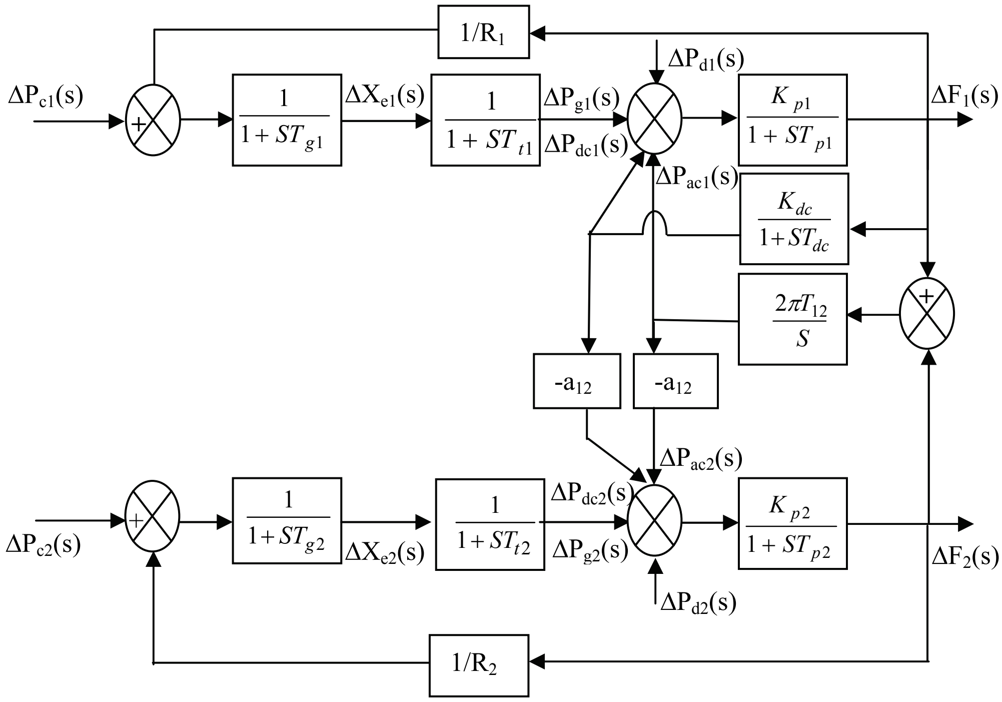

Fig. 8. Block diagram of a two area interconnected thermal power system with AC-DC parallel tie-lines

$$\begin{bmatrix} \dot{x}_1 \\ \Delta\dot{P}_{ac1} \\ \Delta\dot{P}_{dc1} \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & a_{t1} & a_{t1} & 0 \\ m_{12}^T & 0 & 0 & m_{21}^T \\ z_{12}^T & 0 & -\rho_{t2} & 0 \\ 0 & -\alpha_{12}a_{t2} & -\alpha_{12}a_{t2} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ \Delta P_{ac1} \\ \Delta P_{dc1} \\ x_2 \end{bmatrix} + \begin{bmatrix} b_1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & b_2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} \tau_1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & \tau_2 \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}, \tag{13}$$

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} c_1^T & 1 & 1 & 0 \\ 0 & -\alpha_{12} & -\alpha_{12} & c_2^T \end{bmatrix} \begin{bmatrix} x_1 \\ \Delta P_{ac1} \\ \Delta P_{dc1} \\ x_2 \end{bmatrix}, \tag{14}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_1 & 1 & 1 & 0 \\ 0 & 1 & 1 & h_2 \end{bmatrix} \begin{bmatrix} x_1 \\ \Delta P_{ac1} \\ \Delta P_{dc1} \\ x_2 \end{bmatrix} \tag{15}$$

The state and other variables of the two-area system are

$$x_1 = [\Delta F_1 \ \Delta P_{g1} \ \Delta X_{e1}]^T; \quad x_2 = [\Delta F_2 \ \Delta P_{g2} \ \Delta X_{e2}]^T$$

$$u_1 = \Delta P_{c1};\ u_2 = \Delta P_{c2}, \quad d_1 = \Delta P_{d1};\ d_2 = \Delta P_{d2},$$

$$v_1 = ACE_1;\ v_2 = ACE_2; \quad y_1 = [\Delta F_1 \ \Delta P_{ac1} \ \Delta P_{dc1}]^T;\ y_2 = [\Delta F_2 \ \Delta P_{ac2} \ \Delta P_{dc2}]^T,$$

where

$$A_{11}=\begin{bmatrix}\frac{-1}{T_{p1}} & \frac{K_{p1}}{T_{p1}} & 0\\ 0 & \frac{-1}{T_{t1}} & \frac{1}{T_{t1}}\\ \frac{-1}{R_1T_{g1}} & 0 & \frac{-1}{T_{g1}}\end{bmatrix}, A_{22}=\begin{bmatrix}\frac{-1}{T_{p2}} & \frac{K_{p2}}{T_{p2}} & 0\\ 0 & \frac{-1}{T_{t2}} & \frac{1}{T_{t2}}\\ \frac{-1}{R_2T_{g2}} & 0 & \frac{-1}{T_{g2}}\end{bmatrix}, a_{t1}=\begin{bmatrix}\frac{-K_{p1}}{T_{p1}} & 0 & 0\end{bmatrix}^T,$$

$$a_{t2}=\begin{bmatrix}\frac{-K_{p2}}{T_{p2}} & 0 & 0\end{bmatrix}^T, m_{12}=[2\pi T_{12}\ \ 0\ \ 0]^T, m_{21}=[-2\pi T_{12}\ \ 0\ \ 0]^T,$$

$$b_1=\begin{bmatrix}0 & 0 & \frac{1}{T_{g1}}\\ 0 & 0 & 0\end{bmatrix}^T, b_2=\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & \frac{1}{T_{g2}}\end{bmatrix}^T, \tau_1=\begin{bmatrix}\frac{K_{p1}}{T_{p1}} & 0 & 0\\ 0 & 0 & 0\end{bmatrix}^T, \tau_2=\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & \frac{-K_{p2}}{T_{p2}}\end{bmatrix}^T,$$

$$c_1=\begin{bmatrix}\beta_1 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}^T, c_2=\begin{bmatrix}0 & 0 & 0\\ \beta_2 & 0 & 0\end{bmatrix}^T, h_1=\begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}^T, h_2=\begin{bmatrix}0 & 0 & 0\\ 1 & 0 & 0\end{bmatrix}^T.$$

5.2. Design of decentralized output feedback controller

As a first step, the augmented system equations are formed. Next, the decentralized output feedback controller using various techniques has to be designed as discussed in Section 4.

5.2.1. Design of decentralized output feedback controller using ISE criterion

Decentralized most favourable proportional and integral controllers using output feedback are designed by considering the quadratic performance index of area 1. The proportional controller cost curve is obtained as discussed in Section 4.1.1 by choosing the weighting factors w_{i1} and w_{i1} as unity. The optimum proportional controller gain k_p = 0.5799 is obtained from the cost curve. Similarly, the integral controller cost curve is obtained as discussed in Section 4.1.2. The optimum integral feedback controller gain k_p = 0.23 is obtained from the cost curve.

5.2.2. Design of decentralized output feedback controller using IP controller

As discussed in Section 4.2.1, the optimum values of GA tuned IP controller are obtained as k_p = 0.2 and k_i = 0.2709.

5.2.3. Design of decentralized output feedback controller using GA tuned IP controller

As discussed in Section 4.2.2, the optimum values of GA tuned IP controller are obtained as k_p = 0.3831 and k_i = 0.2445. The main GA parameters are

– Population size = 150
– No. of generation = 40
– No. of variables = 10

6. Simulation results and observations

The decentralized controller with output feedback is designed using GA tuned IP controller and implemented in the interconnected two area non-reheat thermal power system. The system is simulated with 0.01 p.u.MW step load change in area 1 and the corresponding frequency deviation and tie-line power deviation are plotted with respect to time. For easy comparison, the responses of frequency deviation in area 1(ΔF_1), frequency deviation in area 2 (ΔF_2), AC tie line power deviation in area 1 (ΔP_{ac1}) and DC tie line power deviation (ΔP_{dc1}) of the system are shown along with the responses obtained with the optimal decentralized proportional plus integral controller designed based on ISE criterion in Figs. 9-11. It is observed that the transient performance is improved significantly with quick settling time with the proposed controller. Further, the evaluation of system performance, Table 1, provides the maximum peak overshoot of frequency and tie line power deviations, settling time and cost function of the two area non-reheat interconnected power systems with PI,IP and GA tuned IP controllers.

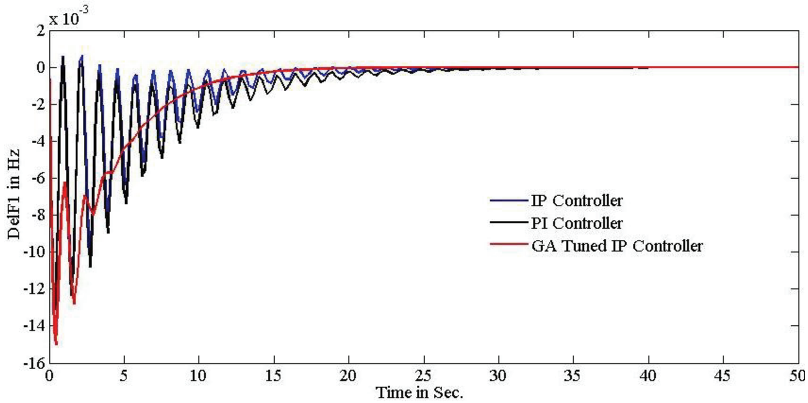

Fig. 9. Frequency deviation in area 1 for 0.01 p.u. MW step load change in area 1

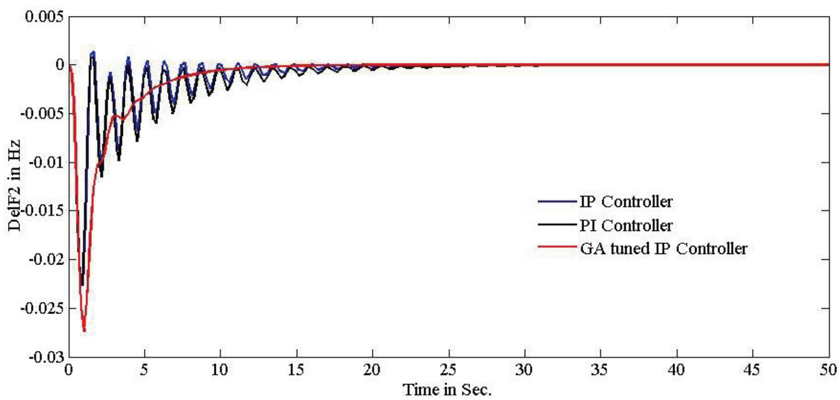

Fig. 10. Frequency deviation in area 2 for 0.01 p.u. MW step load change in area 1

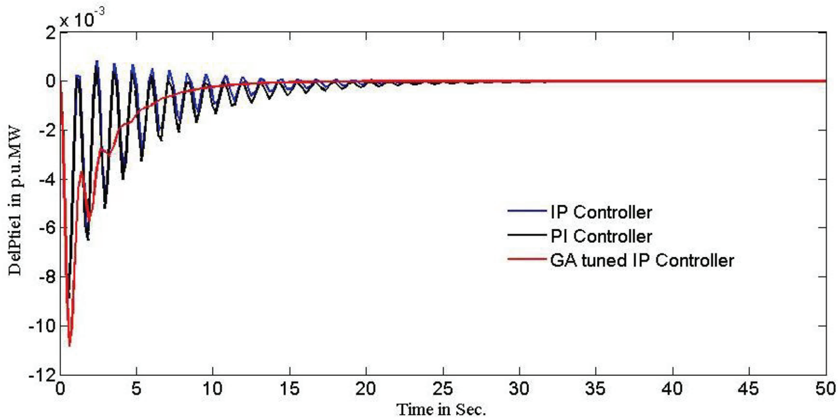

Fig. 11. Tie-line power deviation in area 1 for 0.01 p.u. MW step load change in area 1

Table 1. Comparison of system performance with PI, IP and GA tuned IP controllers

System studied	Area dis-turbed	Control scheme	Maximum peak of frequency deviation in Hz and tie line power deviation in p.u. MW			Settling time of frequency deviation and tie line power deviation in sec.			Optimum Perfor-mance index values
			ΔF_1	ΔF_2	ΔP_{tie1}	ΔF_1	ΔF_2	ΔP_{tie1}	
Two area thermal power system with parallel AC-DC tie lines	Distur-bance in area 1	PI controller	+0.00063 −0.01320	+0.00134 −0.02260	+0.00083 −0.00885	>30	>30	>30	4.540
Two area thermal power system with parallel AC-DC tie lines	Distur-bance in area 1	IP controller	+0.00000 −0.01360	+0.00000 −0.02400	+0.00000 −0.00942	25	21	21	4.288
Two area thermal power system with parallel AC-DC tie lines	Distur-bance in area 1	GA tuned IP controller	+0.00000 −0.01400	+0.00000 −0.02700	+0.00000 −0.01100	14	12	11	3.024

Table 2 shows that the system with GA tuned IP controller has the reduction of 33.39% in performance index values. It is observed from the figures and the tables that GA tuned IP controller has less frequency and tie line power oscillations, greater improvement in stability and smaller settling time. Moreover, the GA tuned IP controller meets all the desirable features of the decentralized LFC problem.

Table 2. Percentage variation in optimum performance index values

Controller used	Percentage variation	Remark
PI Controller	Base case	–
IP controller	5.55%	Reduction
GA tuned IP controller	33.39%	Reduction

7. Conclusion

In this paper the GA tuned IP controller is designed successfully and they are applied to an interconnected two-area non-reheat thermal power system with AC-DC tie-lines. The computer simulation results reveal that GA tuned IP controller provides excellent closed loop stability with high quality transient and steady state responses. It is to be noted GA tuned IP controller satisfies all the requirements of decentralized LFC stated in Section 1. Thus, the overall performance of GA tuned IP controller is found to be superior than the conventional PI controller.

Nomenclature

ACE –	Area Control Error
β_i –	Frequency bias setting of area *i*, p.u. MW/Hz
ΔF_i –	Incremental Frequency deviation of area *i*, Hz
K_i –	Integral Controller Gain
K_p –	Proportional Controller Gain
K_{dc} –	DC link Gain
K_{pi} –	Power System Gain of area *i*, Hz/p.u. MW
ΔP_{ci} –	Incremental change in the speed changer position of area *i*
ΔP_{di} –	Incremental Load Change of area *i*
ΔP_{gi} –	Incremental generation change of area *i*, p.u. MW
ΔP_{ac} –	Incremental change in AC tie line power of area *i*, p.u. MW
ΔP_{dc} –	Incremental change in DC tie line power of area *i*, p.u. MW
R_i –	Speed Regulation due to governor action of area *i*, Hz/p.u. MW
T_{gi} –	Governor time constant of area *i*, sec.
T_{ij} –	Synchronizing coefficient between subsystem *i* and *j*
T_{pi} –	Power system time constant of area *i*, sec.
T_{dc} –	DC link time constant, sec.
T_{ti} –	Turbine time constant of area *i*, sec.
ΔX_{ei} –	Incremental change in governor value position of area *i*

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Appendix

Data for the two area interconnected non-reheat thermal power system with parallel AC-DC tie-lines: Rating of each area = 2000 MW, Base power = 2000 MVA, f = 60 Hz, $R_1 = R_2 = 2.4$ Hz/p.u.MW, $T_{g1} = T_{g2} = 0.08$ sec., Tt1 = T_{t2} = 0.3 sec., $K_{p1} = K_{p2} = 120$ Hz/p.u.MW, $T_{p1} = T_{p2} = 20$ sec., $\beta_1 = \beta_2 = 0.425$ p.u.MW/Hz, $a_{12} = 1$, $2\pi T_{12} = 0.545$ p.u.MW/Hz, $K_{dc} = 1.0$, $T_{dc} = 0.5$ sec.