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Research Article

Dynamic Performance Evaluation of Decentralized Load Frequency Controllers for Interconnected Thermal Power System with Parallel AC-DC Tie-lines: A Comparative Study

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Abstract: The main objective of Load Frequency Control (LFC) is to balance the total system generation against system load losses so that the desired frequency and power interchange with neighboring systems are maintained. Any mismatch between generation and demand causes the system frequency to deviate from its nominal value. Thus high frequency deviation may lead to system collapse. This necessitates a very fast and accurate controller to maintain the nominal system frequency. This study presents an analysis on dynamic performance of two-area thermal power system interconnected via parallel AC-DC tie-lines when subjected to load disturbances. The dc link is used as system interconnection in parallel with ac tie-line. The dc link is considered to be operating in constant current control mode and the power flow deviation through dc link is modeled based on frequency deviation at rectifier end. This study also deals with the application of various controllers namely Proportional plus Integral (PI) Controller, Dual Mode Controller, Fuzzy Logic Controller and Particle Swarm Optimization (PSO) tuned PI Controller for load frequency control of an interconnected power system with AC-DC tie-lines. The above controllers are simulated using MATLAB and their performance is analyzed. Outcome of the analysis shows the superiority of PSO tuned PI Controller over the other control methods.

Keywords: AC-DC tie-lines, dual mode controller, fuzzy logic controller, interconnected power system, load-frequency control, PI controller, PSO

INTRODUCTION

The Load Frequency Control (LFC) problem is of vital importance for power engineers because of the large size and complexity of interconnected systems. Unpredictable changes in the load demand occur continuously in interconnected power systems. These changes in load always cause a mismatch between power generation and consumption, which adversely affects the quality 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 transient errors in the frequency and the scheduled tie line power and ensuring zero steady state errors of these two quantities. The main desirable features of decentralized LFC are the following:

- It should provide better transient response and improved stability margin.
- The Area Control Error (ACE) should be zero at steady state, i.e., frequency and tie line power deviation should be zero under steady state.
- The control law should be independent of disturbance.
- Each area controller should use its own 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 (Shayeghi *et al*., 2009a) is focused on interconnected power systems considering the area interconnection with ac tie-lines only. However, there has been a tremendous growth of the HVDC transmission system due to economic, environmental and performance advantages over the other alternatives. Hence, it has been applied widely in operating a dc link in parallel with an ac link (Padiyar, 1990; Brecur and Hanth, 1988; Nasser and Vanslcky, 1995; Ganapathy and Velusami, 2010) interconnecting control areas to get an improved system dynamic performance with greater stability margins under small disturbances in the system (Kumar and Ibraheem, 2004). Only scantily information is available on LFC of interconnected power systems connected via HVDC link in parallel with ac link. Therefore, this study

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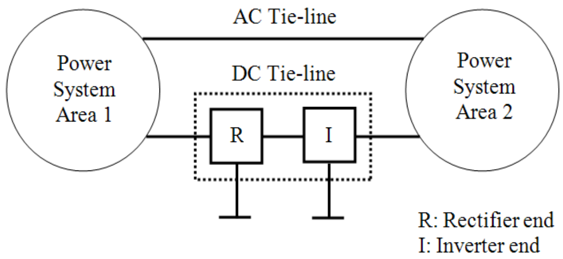

Fig. 1: Two area interconnected power system with parallel AC-DC tie-lines

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 Fig. 1.

There are different intelligent controllers in the literature that have been used in the LFC of isolated as well as interconnected power systems (Mathur and Ghosh, 2006). 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 (Elgerd and Fosha, 1970). 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 (Chidambaram and Velusami, 2005).

Hence in this study the application of various controllers like PI Controller (Mathur and Ghosh, 2006), Dual Mode Controller (Chidambaram and Velusami, 2006; Chidambaram and Velusami, 2007), Fuzzy Logic Controller (Talaq and Al-Basri, 1999; El-Sherbiny *et al*., 2002; Yeşil *et al*., 2004; Sheikh *et al*., 2008; Adel, 2002) and PSO tuned PI Controller (Shayeghi *et al*., 2008) for load frequency control of an interconnected power system with AC-DC tie-lines are analyzed using MATLAB and the dynamic response of each controller is compared with conventional PI controller based on peak overshoot and settling time.

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 (Ramar and Velusami, 1989):

$$\dot{X} = Ax + Bu + \Gamma d \quad (1)$$

$$v = Cx \quad (2)$$

$$y = Hx \quad (3)$$

where,

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

$$n = \sum_{i=1}^{N} n_i + (N-1), \qquad n = \text{ state vector} \quad (4)$$

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

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

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

$y = [y_1 \ldots\ldots y_N]^T$, $2N$-measurable output vector

A = The system matrix
B = The input distribution matrix
Γ = The disturbance distribution matrix
C = The control output distribution matrix
H = The measurable output distribution matrix
x = The state vector
u = The control vector
d = The disturbance vector consisting of load changes

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 Eq. (5) is augmented with new state variables defined as the integral of ACE_i ($\int v_i dt$) $i = 1, 2, \ldots, N$.

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

$$\dot{\bar{X}} = \bar{A}\bar{x} + \bar{B}u + \bar{\Gamma}d \quad (5)$$

$$\bar{x} = \begin{bmatrix} \int v\,dt \\ x \end{bmatrix} \begin{matrix} \}N \\ \}n \end{matrix}$$

and $\bar{A} = \begin{bmatrix} 0 & C \\ 0 & A \end{bmatrix}$ $\quad \bar{B} = \begin{bmatrix} 0 \\ B \end{bmatrix}$ and $\bar{\Gamma} = \begin{bmatrix} 0 \\ \Gamma \end{bmatrix}$

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

$$\bar{y} = \bar{H}\bar{x} \quad (6)$$

where,

$$\bar{y} = \left[\bar{y}_1 \ldots\ldots \bar{y}_N \right]^T$$

$$\bar{H} = \left[\bar{H}_1 \ldots\ldots \bar{H}_N \right]^T$$

and

$$\bar{H} = \begin{bmatrix} 0 & 1 & . & . & . & 0 \\ 0 & 0 & . & . & . & H_i \end{bmatrix}$$

The constant matrix $\bar{H}_i (i = 1, 2, \ldots\ldots, N)$ is of dimension 2x (N + n). Hence the matrix $\bar{H}$ is of dimension 2N x (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 $\begin{bmatrix} 0 & C \\ B & A \end{bmatrix}$ is of rank ($N + n$).

The problem now is to design the decentralized feedback control law:

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

To meet the objectives stated in previous section.

The control law Eq. (7) may be written in-terms of v_i as:

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

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

DESIGN OF DECENTRALIZED OUTPUT FEEDBACK CONTROLLER

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

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:

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

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

To obtain the optimal decentralized controller output feedback gain k_i (i = 1, 2, …., 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, $W_i = diag\left\{ w_{i1,} w_{i2,} w_{i3} \right\}$ and $X_{ei}^T = \left\{ \Delta F_i \; \Delta P_{aci} \; \Delta P_{dci} \right\}$

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…] x_i-dimensional vector of area i. Now, the objective 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 equal. Similarly, the decentralized proportional controller feedback gains (k_{12} = …k_{i2} = …k_{N2} = k_p) of the N identical areas are also assumed as equal.

Design of decentralized proportional controller using output feedback: In the absence of the integral control one can sharply increase 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 sharply as a function of the gain, which is highly undesirable. Thus, the integral controller gain cannot be increased to a large value because it leads to instability in the transient region (Ogatta, 1970). Therefore, the design of decentralized proportional controller using output feedback is considered first.

The optimum proportional controller feedback gain k_p is obtained by plotting the cost curve for various values 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 throughout. The proportional controller cost curve is shown in Fig. 2.

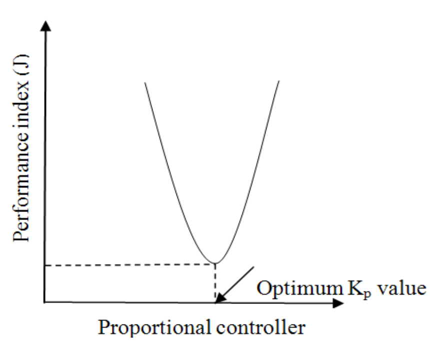

Fig. 2: Cost curve of proportional controller

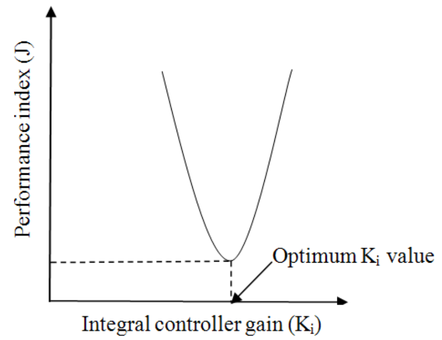

Fig. 3: Cost curve of integral controller

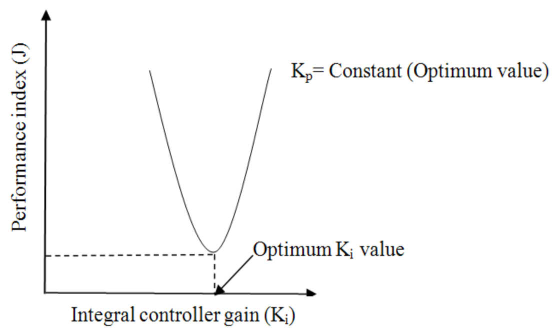

Fig. 4: Cost curve of PI controller

Design of decentralized integral controller with output feedback: Following the procedure discussed in the previous subsection, 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 Fig. 3.

Design of decentralized proportional plus integral controller with output feedback: Following the procedure discussed in the previous two subsections, 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 $k_p = k_{p(optimum)}$. The optimal k_i, corresponding to minimum J_i, is obtained from the cost curve. The PI controller cost curve is shown in Fig. 4.

Design of decentralized biased dual mode controller with output feedback: The controller designed on the basis of the ISE criterion provides a reduction of rise time to limit the effect of large initial errors, a reduction of peak overshoot and a reduction of settling time to limit the effect of small errors lasting for a long time. Further, this criterion is often of practical significance because of the minimization of control effort, but the controller designed on the basis of the ISE criterion tends to show a rapid decrease in the large initial error. Hence, the response is fast and oscillatory. Thus, the system has poor relative stability. Hence, to obtain decentralized controllers with improved stability margin and satisfactory performance, a new controller design should be developed based the ISE design criterion.

The problem is to design the decentralized output feedback dual mode control law (Chidambaram and Velusami, 2006; Chidambaram and Velusami, 2007; Carpentier, 1985):

$$u_i = -k_{i1} \int v_i dt \quad for \; |v_i| \leq \; \varepsilon \tag{11}$$

and

$$u_i = -k_{i2} v_i \quad for \; |v_i| \; > \; \varepsilon \tag{12}$$

The block diagram of the dual mode controller of area i is shown in Fig. 5. The dual mode controller operates by switching between a proportional controller mode or an integral controller mode depending upon the magnitude of the output signal v_i. ε>0 is some constant indicating the specified limit of the output error signal.

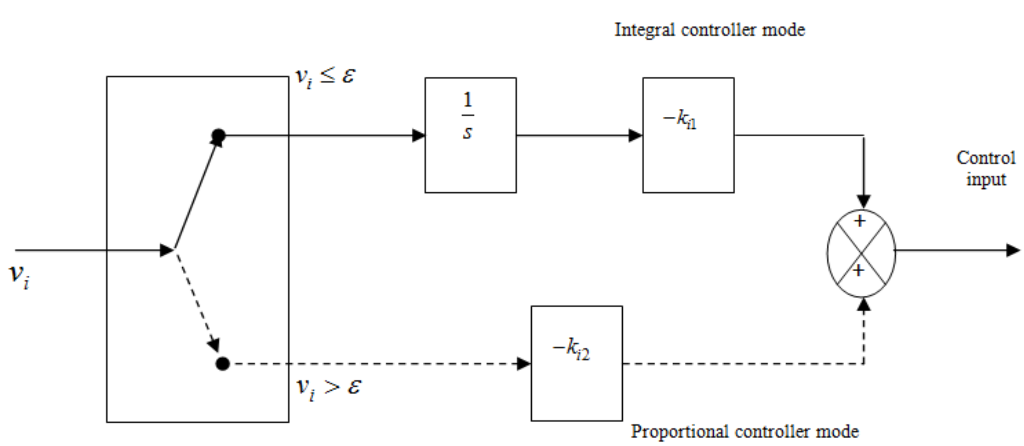

Fig. 5: Block diagram of a dual mode controller of area i

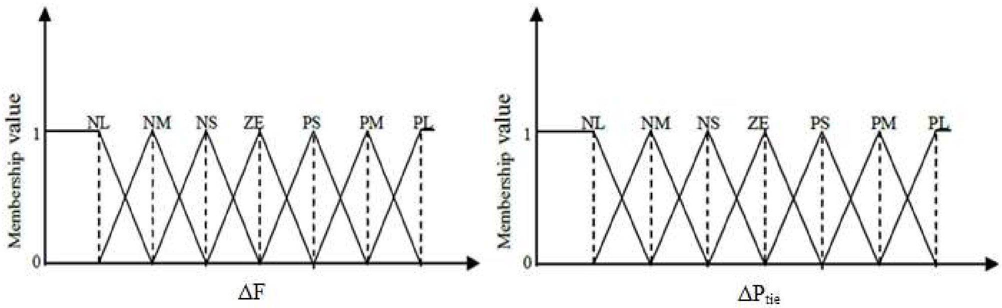

Fig. 6: Input membership functions of fuzzy controller

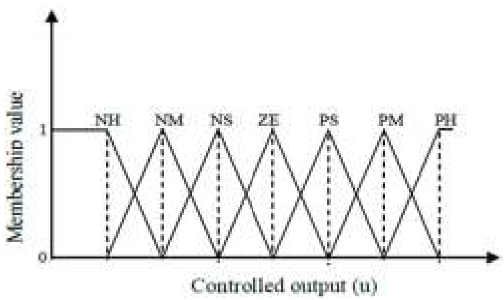

Fig. 7: Output membership functions of fuzzy controller

Table 1: Fuzzy rule matrix

	ΔF						
ΔP_{tie}	NL	NM	NS	ZE	PS	PM	PL
NL	NH	NH	NM	NH	NM	NS	ZE
NM	NH	NM	NS	NM	NS	ZE	PS
NS	NH	NM	NS	NS	ZE	PS	PM
ZE	NH	NM	NS	ZE	PS	PM	PH
PS	NM	NS	ZE	PS	PS	PM	PH
PM	NS	ZE	PS	PM	PS	PM	PH
PL	ZE	PS	PM	PH	PM	PS	PH

Design of decentralized output feedback controller using fuzzy logic: The design of LFC can be normally divided into three areas namely allocation of area inputs, determination of rules and defuzzifying of output into a real value. The method of fuzzification has found increasing application in power system. In this Fuzzy Logic Controller (FLC), Membership Function (MF) specifies the degree to which a given input belongs to a set. In the case of FLC, seven membership functions in triangular shape have been chosen for the inputs of ΔF_i, ΔP_{tiei} and output (u). The linguistic descriptions of input membership functions are Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Large (PL). The output membership functions are Negative High (NH), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive High (PH). The fuzzy membership functions for inputs and output are shown in Fig. 6 and 7. The union maximum operation has been selected for the fuzzy implication. For the two-input fuzzy system, it is generally expressed as:

$$\mu_{Ai(x1)\cup Ai(x2)} = \max\left\{\mu_{Ai(x1)}, \mu_{Ai(x2)}\right\} \tag{13}$$

where, $A_i\,(x1)$ and $A_i\,(x2)$ and are input fuzzy sets. The rule base of the fuzzy controller relates the premise ΔF and ΔP_{tie} to consequent u. The structure of the control rules of the fuzzy controller with two inputs and one output is expressed as:

$$If\left(\Delta F \;\; is \;\; NM \;\; or \;\; \Delta P_{tie} \;\; is \;\; NS\right) \;\; then \;\; control \;\; signal \;\; u \;\; is \;\; NH$$

Table 1 lists 49 linguistic fuzzy rules for the fuzzy controller. The centroid difuzzification has been made to find the crisp value of output. The centroid difuzzification is defined as:

$$U^{Crisp} = \frac{\sum_{i=1}^{n} u_i \;\; \mu(u_i)}{\sum_{i=1}^{n} \mu(u_i)} \tag{14}$$

where,

U^{Crisp} = The output of the fuzzy controller

u_i = The centre of the membership function of the consequent of the i^{th} rule

μ = The membership value for the rule's premise

n = The total number of fuzzy rules

Design of decentralized output feedback controller using Particle Swarm Optimization (PSO): In a PSO system (Shayeghi *et al*., 2009b; Gaing, 2004; Coello *et al*., 2004; Shayeghi *et al*., 2008; Clerc and Kennedy, 2002), multiple candidate solutions coexist and collaborate simultaneously. Each solution candidate, called a "particle", flies in the problem space (similar to the search process for food of a bird swarm) looking for the optimal position. A particle with time adjusts its position to its own experience, while adjusting to the experience of neighboring particles. If a particle discovers a promising new solution, all the other particles will move closer to it, exploring the region more thoroughly in the process. This new approach features many advantages; it is simple, fast and can be coded in few lines. Also its strong requirement is minimal. Moreover, this approach is advantageous over evolutionary and genetic algorithm in many ways. First, PSO has memory, i.e., every particle remembers its best solution (global best). Another advantage of PSO is that the initial population of PSO is maintained and so there is no need for applying operators to the population, a process that is time-and memory-storage-consuming. In addition, PSO is based on constructive co-operation between particles, in contrast with the genetic algorithms, which are based on the survival of the fittest.

Algorithm for PSO: Steps of PSO as implemented for optimization are:

Step 1: Initialize an array of particles with random positions and their associated velocities to satisfy the inequality constraints.
Step 2: Check for the satisfaction of the equality constraints and modify the solution if required.
Step 3: Evaluate the fitness function of each particle.
Step 4: Compare the current value of the fitness function with the particles previous best value (pbest). If the current fitness value is less, then assign the current fitness value to pbest and assign the current coordinates (positions) to pbestx.
Step 5: Determine the current global minimum fitness value among the current positions.
Step 6: Compare the current global minimum with the previous global minimum (gbest). If the current global minimum is better than gbest, then assign the current global minimum to gbest and assign the current coordinates (positions) to gbestx.
Step 7: Change the velocities.
Step 8: Move each particle to the new position and return to step 2.
Step 9: Repeat steps 2-8 until a stop criterion is satisfied or the maximum number of iterations is reached.

PSO algorithm definition: The PSO definition is presented as follows:

- Each individual particle i has the following properties:
  x_i = A current position in search space
  v_i = A current velocity in search space
  y_i = A personal best position in search space
- The personal best position 'p_i' corresponds to the position in search space, where particle 'i' presents the smallest error as determined by the objective function 'f', assuming a minimization task
- The global best position denoted by 'g' represents the position yielding the lowest error among all the p_i 's

Equations (15) and (16) define how the personal and global best values are updated at time 'k' respectively. It is assumed that the swarm consists of 's' particles. Thus, $i \in 1, 2, \ldots, s$:

$$p_i^{k+1} = \begin{cases} p_i^k & if \ f(p_i^k) \le (x_i^{k+1}) \\ X_i^{k+1} & if \ f(p_i^k) > (x_i^{k+1}) \end{cases} \quad (15)$$

$$g^k \in \left\{ p_1^k, p_2^k, \ldots, p_s^k \right\} \ \left| f(g^k) \right. = \min \left\{ f(p_1^k), f(p_2^k), \ldots, f(p_s^k) \right\} \quad (16)$$

In each iteration, every particle in the swarm is updated using the steps 4 and 5. Two pseudo random sequences r_1~U (0, 1) and r_2~U (0, 1) are used to affect the stochastic nature of the algorithm:

$$v_i^{k+1} = w \times v_i^k + c_1 \times rand()_1 \times (p_i^k - x_i^k) + c_2 \times rand()_2 \times (g^k - x_i^k) \quad (17)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (18)$$

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \times iter \quad (19)$$

$$v_{\max} = k \times x_{\max} \qquad 0.1 \le k \le 1 \quad (20)$$

where,

v_i^k = Velocity of i^{th} particle at k^{th} iteration
v_i^{k+1} = Velocity of i^{th} particle at $(k + 1)^{th}$ iteration
w = Inertia weigh
x_i^k = Position of the i^{th} particle in the k^{th} iteration
x_i^{k+1} = Position of the i^{th} particle in the $(k + 1)^{th}$ iteration
$c_1 = c_2$ = Positive constant = 2
$iter$, $iter_{\max}$ = Iteration number and maximum iteration number
$rand(\,)_1$, $rand(\,)_2$ = Random number selected between 0 and 1

Evolutionary operators such as selection, crossover and mutation have been applied into the PSO. By applying selection operation in PSO, the particles with the best performance are copied into the next generation; therefore, PSO can always keep the best performed particles. By applying crossover operation, information can be exchanged or swapped between two particles so that they can fly to the new search area as in evolutionary programming and genetic algorithms. Among the three evolutionary operators, the mutation operators are the most commonly applied evolutionary operators in PSO. The purpose of applying mutation to PSO is to increase the diversity of the population and the ability to have the PSO to escape the local minima.

APPLICATION TO A TWO-AREA POWER SYSTEM

Mathematical model: The decentralized controller design is applied to an interconnected two-area thermal power system with AC-DC parallel tie-lines as shown in Fig. 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:

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

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} c_1^T & 1 & 1 & 0 \\ 0 & -\alpha_{12} & -\alpha_{12} & c_2^T \end{bmatrix} \begin{bmatrix} x_1 \\ \Delta P_{ac1} \\ \Delta P_{dc1} \\ x_2 \end{bmatrix} \tag{22}$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_1 & 1 & 1 & 0 \\ 0 & 1 & 1 & h_2 \end{bmatrix} \begin{bmatrix} x_1 \\ \Delta P_{ac1} \\ \Delta P_{dc1} \\ x_2 \end{bmatrix} \tag{23}$$

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

$$x_1 = \begin{bmatrix} \Delta F_1 & \Delta P_{g1} & \Delta X_{el} \end{bmatrix}^T ; \; x_2 = \begin{bmatrix} \Delta F_2 & \Delta P_{g2} & \Delta X_{e2} \end{bmatrix}^T$$

$$u_1 = \Delta P_{c1} \; ; \; u_2 = \Delta P_{c2}$$

$$d_1 = \Delta P_{d1} \; ; \; d_2 = \Delta P_{d2}$$

$$v_1 = ACE_1 \; ; \; v_2 = ACE_2$$

$$y_1 = \begin{bmatrix} \Delta F_1 & \Delta P_{ac1} & \Delta P_{dc1} \end{bmatrix}^T$$

$$y_2 = \begin{bmatrix} \Delta F_2 & \Delta P_{ac2} & \Delta P_{dc2} \end{bmatrix}^T$$

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 the controller design section.

Design of decentralized output feedback controller using ISE criterion: Decentralized optimum proportional and integral controllers using output feedback are designed by considering the quadratic

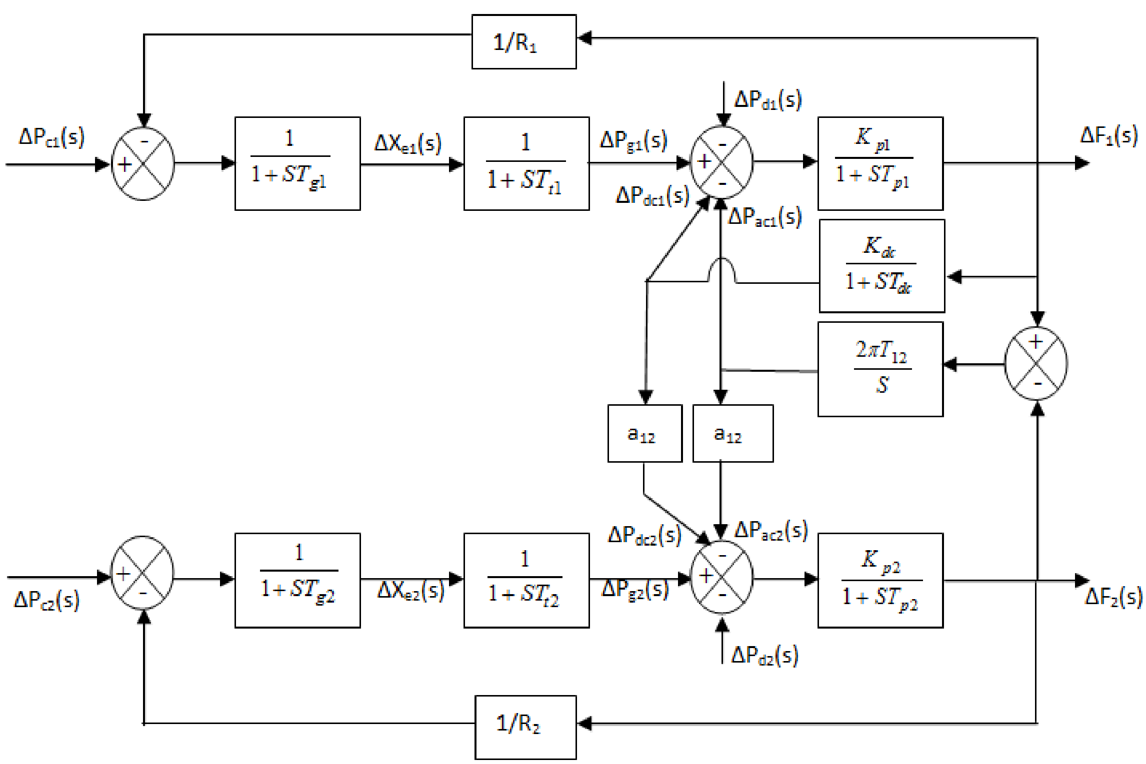

Fig. 8: Block diagram of a two area interconnected thermal power system with AC-DC parallel tie-lines

Table 2: Fuzzy sets and its range

Fuzzy sets	Range
NL/NH	(-1 -1 -0.6 -0.4)
NM	(-0.6 -0.4 -0.2)
NS	(-0.4 -0.2 0)
ZE	(-0.2 0 0.2)
PS	(0 0.2 0.4)
PM	(0.2 0.4 0.6)
PL/PH	(0.4 0.6 1 1)

performance index of area 1. The proportional controller cost curve is obtained as discussed in the controller design section by choosing the weighting factors w_{i1} and w_{i2} 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 the controller design section. The optimum integral feedback controller gain k_i = 0.23 is obtained from the cost curve.

Design of decentralized biased dual mode controller with output feedback: As discussed in the controller design section, the decentralized biased dual mode controllers are obtained. The decentralized optimum performance index criterion biased dual mode controller feedback gains k_p = 0.5799 and k_i = 0.9999 are obtained by choosing ε = 0.013.

Design of decentralized biased controller with output feedback using fuzzy logic: As discussed in the controller design section, the decentralized biased fuzzy logic controllers are obtained. In the case of FLC, seven membership functions in triangular shape have been chosen for the inputs of ΔF_i, ΔP_{tiei} and output (u). The fuzzy sets and its range for two area interconnected power system with parallel AC-DC tie-lines are shown in Table 2.

Design of decentralized output feedback controller using PSO: As discussed in the controller design section the optimum values of PSO tuned proportional plus integral controller are obtained as k_p = 0.1536 and k_i = 0.0388. The PSO control parameters are chosen as:

Population size	: 50
Maximum no. of iteration	: 50
$w_{\max}$ and $w_{\min}$	: 0.9 and 0.1
Acceleration constants c_1 and c_2	: 0.12 and 1.2
Scaling factor	: 0.01

SIMULATION RESULTS AND OBSERVATIONS

The decentralized controller with output feedback is designed using various controllers, namely PI controller, Dual mode controller, Fuzzy Logic controller and PSO tuned PI controller and implemented in the interconnected two area thermal power system. The system is simulated with various controllers for 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 Fig. 9 to 11. It is observed that the transient performance is improved significantly with quick settling time with the proposed controllers. Further, the comparison of system performance, Table 3, provides the maximum peak overshoot of frequency and tie line power deviations, settling time and cost function of the two area interconnected power systems with the various biased controllers. It is observed from the figures and the table that the PSO tuned PI controller have less frequency and tie line power oscillations, greater improvement in

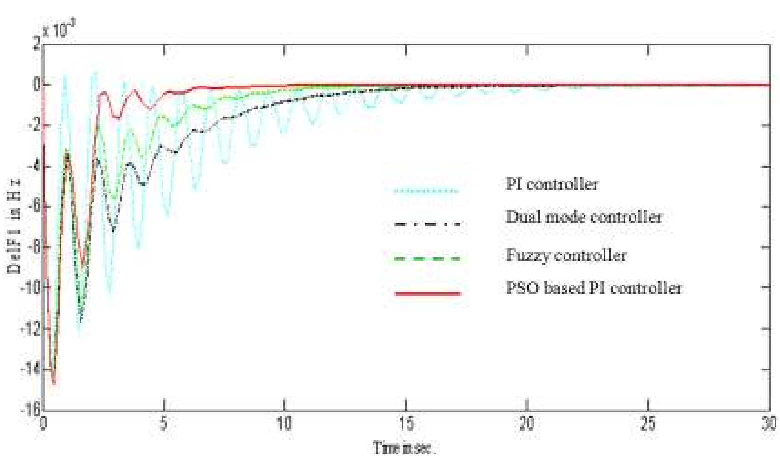

Fig. 9: Frequency deviation in area 1 for 0.01 p.u.MW step load change in area 1

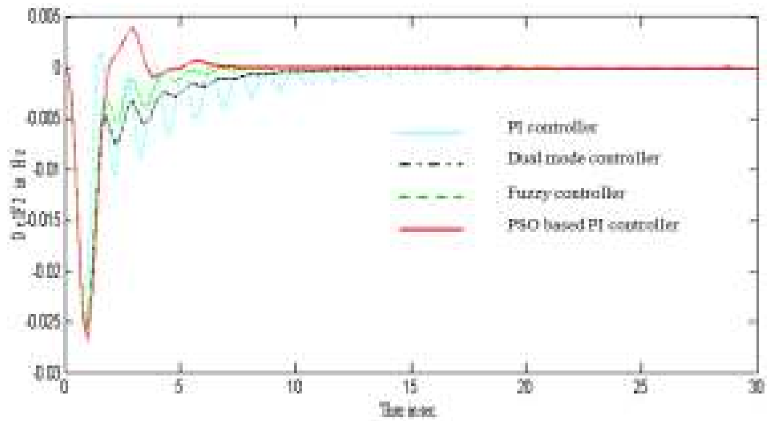

Fig. 10: Frequency deviation in area 2 for 0.01 p.u.MW step load change in area 1

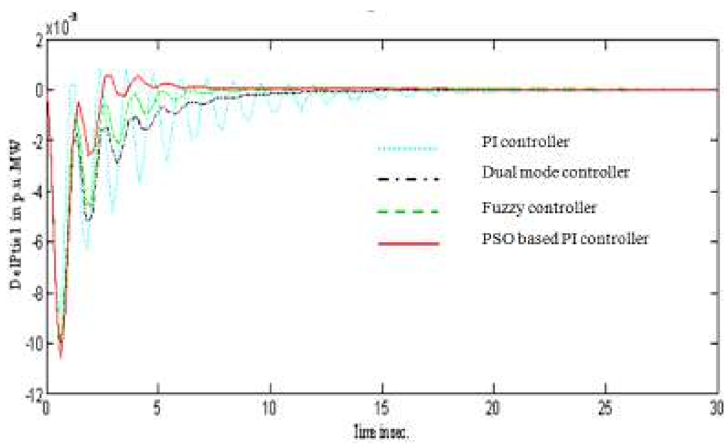

Fig. 11: Tie-line power deviation in area 1 for 0.01 p.u.MW step load change in area 1

Table 3: Comparison of system performance with various biased controllers

			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			
System studied	Area disturbed	Control scheme	ΔF_1	ΔF_2	ΔP_{tie1}	ΔF_1	ΔF_2	ΔP_{tie1}	Cost function value
Two area thermal power system with parallel AC-DC tie lines	Disturbance in area 1	PI controller	-0.0130 +0.0030	-0.0230 +0.0010	-0.0090 +0.0010	>30	>30	>30	3.100
Two area thermal power system with parallel AC-DC tie lines	Disturbance in area 1	Dual mode controller	-0.0140 +0.0000	-0.0255 +0.0000	-0.0100 +0.0000	24	21	21	2.306
Two area thermal power system with parallel AC-DC tie lines	Disturbance in area 1	Fuzzy controller	-0.0140 +0.0000	-0.0255 +0.0000	-0.01000 +0.00001	16	9	10	2.270
Two area thermal power system with parallel AC-DC tie lines	Disturbance in area 1	PSO tuned PI controller	-0.0145 +0.0000	-0.0260 +0.0000	-0.0102 +0.0004	9	8	9	1.960

stability and smaller settling time. Further, the PSO tuned PI controller cost function values is less than the other controller values. Moreover, the PSO tuned PI controller meet all the desirable features of the decentralized LFC problem.

CONCLUSION

In this study various controllers are designed successfully and they are applied to an interconnected two-area thermal power system with AC-DC tie-lines.

The computer simulation results reveal that PSO tuned PI controller provides excellent closed loop stability with high quality transient and steady state responses. It is to be noted PSO tuned PI controller satisfies all the requirements of decentralized LFC stated in introduction. Thus, the overall performance of PSO tuned PI controller is found to be superior to the other controllers.

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_{aci}	:	Incremental change in AC tie line power of area i, p.u.MW
ΔP_{dci}	:	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

APPENDIX

Data for the two area interconnected thermal power system with parallel AC-DC tie- lines:

$R_1 = R_2 = 2.4$ Hz/p.u.MW, $T_{g1} = T_{g2} = 0.08$ sec, $T_{t1} = T_{t2} = 0.3$ 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.

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