J. Inst. Eng. India Ser. B (December 2016) 97(4):509–515
DOI 10.1007/s40031-015-0191-7

ORIGINAL CONTRIBUTION

Genetic Algorithm based Decentralized PI Type Controller: Load Frequency Control

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Received: 7 September 2013 / Accepted: 2 March 2015 / Published online: 18 May 2016

Abstract This work presents a design of decentralized PI type Linear Quadratic (LQ) controller based on genetic algorithm (GA). The proposed design technique allows considerable flexibility in defining the control objectives and it does not consider any knowledge of the system matrices and moreover it avoids the solution of algebraic Riccati equation. To illustrate the results of this work, a load–frequency control problem is considered. Simulation results reveal that the proposed scheme based on GA is an alternative and attractive approach to solve load–frequency control problem from both performance and design point of views.

Keywords Proportional plus integral controller · Genetic algorithm · Linear quadratic controller · Step distribution · Decentralized load–frequency control

Introduction

The basic objective of load frequency control (LFC) problem is to restore the balance between load and generation by keeping the frequency deviations within the specified limits and it has become more of a technical challenge [1, 2]. A class of research workers paid a remarkable attention on modern approaches mainly due to their robustness characteristics and less sensitivity to changes in system parameters and external disturbances [3–5]. In [5], a new load frequency design structure and a new PID tuning method is introduced to show the effective performance robustness than the conventional PID when the parameters of the system change.

On the other hand, to control a large dimensional system, decentralized controllers are preferred due to infeasible information communication between subsystems and this, in turn, yields complexity to implement a centralized controller. One main feature that distinguishes decentralized control from centralized control design is the treatment of interconnections between subsystems. In decentralized control design, the effect of interaction terms needs to be considered to the control effort so that the overall system still possesses the certain desirable performance. There has been continuing interest in designing load–frequency controllers with better performance to maintain the frequency and to keep tie-line power flows within pre-specified values, using various decentralized and centralized control methods [6–8]. Another popular design technique to solve LFC problem is based on sliding mode control (SMC) approach. The SMC scheme is basically a nonlinear control strategy that can improve the performance of the LFC problem substantially under parametric uncertainties as well as the changes in the load demand [9, 10]. Most of the works on LFC reported in literature have not considered the problems associated with the communication delay and this issue, in true sense, is valid under traditional dedicated communication links. In recent years, a class of research worker has shown keen interests to solve the LFC problem in presence of communication delays using Lyapunov–Krasovskii functional approach in linear matrix inequality (LMI) framework [11, 12].

One of the powerful optimization techniques that is used more commonly in literature for tuning classical PI

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controller parameters is genetic algorithm (GA) and it does not require any knowledge of mathematical model of the system. It requires specification of the objective function and the tuning parameters are assigned with bounds. GA is an optimisation search algorithm based on evolution mechanism and it has wide spread field of practical applications that are mainly due to its ease of coding and it does not rely on a detailed mathematical model of the system to be optimized [13]. A simple robust controller for solution of LFC problem against uncertainties is designed based on GA optimization technique in LMI framework and it can be found in [14, 15].

The main objective of this work is to design proportional plus integral (PI) type linear quadratic (LQ) controller using GA in decentralized framework. In decentralized controller design, each subsystem controller has only access to its own associated measurements and control inputs. It is known as completely decentralized control structure and the results of this work are compared with the conventional centralized PI type LQ controller.

Problem Formulation

Centralized PI Type LQ Controller Based on GA

Consider a linear time invariant system that is described by the following pair of state equations

$$\dot{X}(t) = AX(t) + BU(t) + \Gamma d(t) \tag{1}$$

$$Y(t) = CX(t) \tag{2}$$

where $A \in \Re \times \Re^{n\times n}$, $B \in \Re \times \Re^{n\times m}$, $C \in \Re \times \Re^{p\times n}$, $\Gamma \in \Re \times \Re^{n\times m}$, and $d(t) \in \Re^{m\times 1}$ is a constant disturbance vector. It is assumed that the pair (A, B) and the pair (A, C) are completely controllable and observable.

Given the models (1) and (2), the problem is to find the control vector $U(t)$, $t \geq 0$, so as to ensure that the system output satisfies the condition

$$Lt_{t\to\infty}[Y(t) - Y_{\text{ref}}] = [0] \tag{3}$$

where Y_{ref} is the desired output or reference output. This is well known description of trajectory tracking problem and convenient form of solution of (3) is possible through linear quadratic regulator (LQR) theory if the following modifications are first made. This requires us to introduce the new process variable Z(t) defined by

$$Z(t) = \int_o^t [Y(t) - Y_{\text{ref}}(t)]dt \tag{4}$$

It is then required to adjoin $Z(t)$ to the vector $x(t)$ so as to get the following augmented system state equation as

$$\begin{bmatrix} \dot{X}(t) \\ \dot{Z}(t) \end{bmatrix} = \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix} \begin{bmatrix} X(t) \\ Z(t) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} U(t) + \begin{bmatrix} \Gamma & 0 \\ 0 & -I \end{bmatrix} \begin{bmatrix} d \\ Y_{\text{ref}}(t) \end{bmatrix}$$

$$\dot{X}_a(t) = A_a X_a(t) + B_a U(t) + \Gamma_a d_a \tag{5}$$

Now, by using the conventional optimal control technique, a performance index with respect to the nominal augmented system dynamics is constructed as

$$J_a(t) = \int_0^\infty \left[X_a^T(t) Q_a X_a(t) + U^T(t) R U(t)\right] dt \tag{6}$$

It is assumed that the (A_a, B_a) is controllable pair and the optimal control law is given as

$$U(t) = -R^{-1} B_a^T P_a X_a(t) = -\begin{bmatrix} K_P & K_I \end{bmatrix} \begin{bmatrix} X(t) \\ Z(t) \end{bmatrix} \tag{7}$$

where P_a is the solution of the following ARE

$$P_a A_a + A_a^T P_a - P_a B_a R^{-1} B_a^T P_a + Q_a = [0] \tag{8}$$

In the LQ optimal regulator problem, the weighting matrices Q_a and R are usually regarded as tuning parameters that involve in the performance index of the augmented system (5). GA is applied to search the controller gains K_P and K_I for the PI type LQ controller and the corresponding proportional and integral controller structures are shown below:

$$K_P = \begin{bmatrix} k_{11} & k_{12} & . & . & . & k_{1n} \\ k_{21} & k_{22} & . & . & . & k_{2n} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ k_{m1} & k_{m2} & . & . & . & k_{mn} \end{bmatrix}_{m\times n}$$

$$K_I = \begin{bmatrix} k_{i11} & k_{i12} & \dots & k_{i1p} \\ k_{i21} & k_{i22} & \dots & k_{i2p} \\ . & . & . & . \\ . & . & . & . \\ k_{im1} & k_{im2} & \dots & k_{imp} \end{bmatrix}_{m\times p}$$

Two types of genes are shown below:

1. Proportional part of control genes

k_{11}	k_{12}	.	.	k_{1n}	k_{21}	k_{22}	.	k_{m1}	.	k_{mn}

2. Integral part of control genes

k_{i11}	k_{i12}	.	.	k_{i1p}	k_{i21}	k_{i22}	.	k_{im1}	.	k_{imp}

Procedure stated below is applied to tune the PI-type LQ controller parameters based on GA. In the genetic search, a finite length binary string represents each controller parameter and then these finite binary strings are connected in a head-to-tail manner to form a single binary string. Possible solutions are coded or represented by a number of binary strings. Another important function to be considered on the GA is the fitness function. In the present work the controller gains are tuned by minimizing the quadratic performance index, J_x using GA.

$$J_x(t) = \int_0^\infty \left[X_a^T(t) Q_a X_a(t) + U^T(t) R_a U(t)\right] dt \tag{9}$$

where, Q_a and R_a are state and input weighting matrices. GAs works directly, with strings (chromosomes) of characters representing the parameter set. Each of the strings represents one possible solution to the problem and is decoded so that the character strings yield the controller parameters. The parameters are then used to implement PI type LQ controller and also used in a system model to evaluate the objective (J_x) function and a fitness function is described as

$$J_f = \frac{1}{1 + J_x} \tag{10}$$

This fitness value is rewarded based on the quality of the solution represented by strings. A new population of strings or a new generation is produced by employing the three operators (selection, crossover, and mutation) and the new strings are again decoded, evaluated and transferred using the basic operators. The process continues until a convergence is achieved or a suitable solution is found.

Design of Decentralized PI Type LQ Controller

A dynamic model of large power system can be described by the interconnection of N-subsystems as

$$\dot{X}_i(t) = A_{ii}X_i(t) + B_iU_i(t) + \sum_{\substack{j=1 \\ j \neq i}}^{N} A_{ij}X_j(t) + \Gamma_i d_i(t) \tag{11}$$

$$Y_i(t) = C_{ii}X_i(t) \text{ for } i = 1, 2, \ldots, N \tag{12}$$

where $X_i(n_i \times 1)$, $A_{ii}(n_i \times n_i)$, $B_i(n_i \times m_i)$, $C_i(p_i \times n_i)$, $\Gamma_i(n_i \times m_i)$ and $d_i(m_i \times 1)$. It is assumed that the pair (A_{ii}, B_i) is controllable. Note that the state interaction term $\sum_{\substack{j=1 \\ j \neq i}}^{N} A_{ij}X_j$ in (11) arising from the other subsystems and this term will be treated as a disturbance term acting to the ith subsystem and the earlier two equations can be rewritten as

$$\dot{X}_i(t) = A_{ii}X_i(t) + B_iU_i(t) + \bar{\Gamma}_i\bar{d}_i, \; Y_i(t) = C_{ii}X_i(t) \text{ for } i = 1, 2, \ldots, N \tag{13}$$

Once again the main objective is find a control vector $U_i(t)$ for the ith subsystem, $t \geq 0$, so as to ensure that the system output satisfies the following condition.

$$Lt_{t \to \infty}[Y(t) - Y_{\text{ref}}] = [0] \tag{14}$$

Following the same procedure as described by the Eqs. (4) to (8), one can obtain the control law for the ith subsystem which is described as

$$\begin{aligned} U_i(t) &= -R_i^{-1}B_{ia}^T P_{ia} X_{ia}(t) \\ &= -K_{pi}X_i(t) - K_{Ii}\int_0^t [Y_i(t) - Y_{i,\text{ref}}(t)]dt \end{aligned} \tag{15}$$

The ith subsystem control law designed based on conventional PI type LQR using (15) does not provide any guarantee for stability of the composite system. This is due to the reason that the ith subsystem state interaction terms are not taken into consideration while designing the control law $U_i(t)$. However, a stable decentralized controller for the ith subsystem can be obtained by adopting the GA and the corresponding ith subsystem performance index and fitness function are considered as

$$J_{ix}(t) = \int_0^\infty \left[X_{ia}^T(t)\, Q_{ia}\, X_{ia}(t) + U_i^T(t)\, R_{ia}\, U_i(t)\right] dt \tag{16}$$

$$J_{if} = \frac{1}{1 + J_{ix}} \tag{17}$$

In a decentralized control scheme, the feedback control law in each area is computed using the measurements of each area only. This implies that no interchange of state interaction information among areas is necessary for the purpose of LFC. The advantage of this control scheme is apparently provides cost savings in data communications and reduces the scope of the monitoring network. In order to implement decentralized control schemes for LFC problem, the following control structures have been used. For PI type decentralized controller (state feedback + integral output error feedback).

$K_P = \mathrm{diag}\left(K_{p1} \quad K_{p2} \quad \cdots \quad K_{pm} \right), \ K_I = \mathrm{diag}\left(K_{I1} \quad K_{I2} \quad \cdots \quad K_{Im} \right)$

For each subsystem, there are two types of genes, known as proportional control genes and integral control genes, as shown in form of chromosome ($i = 1, 2, \ldots, N$):

1. Proportional controller gene

$k_{p,i,1}$	$k_{p,i,2}$	…	$k_{p,i,ni}$

2. Integral controller gene

$k_{I,i,1}$	$k_{I,i,2}$	…	$k_{I,i,pi}$

Simulation Results

Figure 1 shows a multi-area LFC scheme, all generating power units in each station area are approximated by an equivalent linearized state-space model.

The effectiveness of the proposed PI type LQ controller algorithm based on GA is illustrated by considering two-input/two-output power system model and it is described by the following pair of equations [16].

$$\dot{X}(t) = AX(t) + BU(t) + \Gamma d(t); \quad Y(t) = CX(t) \tag{18}$$

where,
$X(t) = \left[\Delta f_1 \quad \Delta P_{g1} \quad \Delta X_{g1} \quad \Delta P_{tie} \quad \Delta f_2 \quad \Delta P_{g2} \quad \Delta X_{g2} \right]^T$

ΔP_{tie} is the tie-line incremental power, ΔP_{g1} and ΔP_{g2} are the turbine-generator outputs, ΔX_{g1} and ΔX_{g2} are the outputs of the governors, $\Delta f_1$and Δf_2 are the incremental changes in frequency. $d(t) =$ step-change in the load demand. The area control error in area-1 (ACE_1) is $y_1 = \Delta f_1 + \Delta P_{tie}$ and the area control error in area-2 (ACE_2) is $y_2 = \Delta f_2 - \Delta P_{tie}$. Furthermore, $U = \left[\Delta P_{c1} \quad \Delta P_{c2} \right]^T =$ control vector and $\Delta P_d = \left[\Delta P_{d1} \quad \Delta P_{d2} \right]^T =$ disturbance vector. The nominal system matrices are as follows:

$$A = \begin{bmatrix} -0.05 & 6 & 0 & -6 & 0 & 0 & 0 \\ 0 & -3.33 & 3.33 & 0 & 0 & 0 & 0 \\ -5.2063 & 0 & -12.5 & 0 & 0 & 0 & 0 \\ 0.545 & 0 & 0 & 0 & -0.545 & 0 & 0 \\ 0 & 0 & 0 & 6 & -0.05 & 6 & 0 \\ 0 & 0 & 0 & 0 & 0 & -3.33 & 3.33 \\ 0 & 0 & 0 & 0 & -5.2063 & 0 & -12.5 \end{bmatrix},$$

$$B^T = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 12.5 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 12.5 \end{bmatrix}$$

$$\Gamma^T = \begin{bmatrix} -6.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & -6.0 & 0.0 & 0.0 \end{bmatrix},$$

$$C = \begin{bmatrix} 1.0 & 0.0 & 0.0 & 1.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & -1.0 & 1.0 & 0.0 & 0.0 \end{bmatrix}$$

In LFC problem, it is necessary to maintain the system frequency and the inter-area tie-line power as close as possible to the scheduled value through control action. The following initial data have been considered in order to study the performance effectiveness of the proposed GA based load–frequency controller. Initial data for centralized PI type LQ controller:

$$X(0) = \left[0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \right]^T, \quad \Delta P_d = \left[0.1 \quad 0 \right]^T; \quad Y_{\mathrm{ref}} = \left[0 \quad 0 \right]^T$$

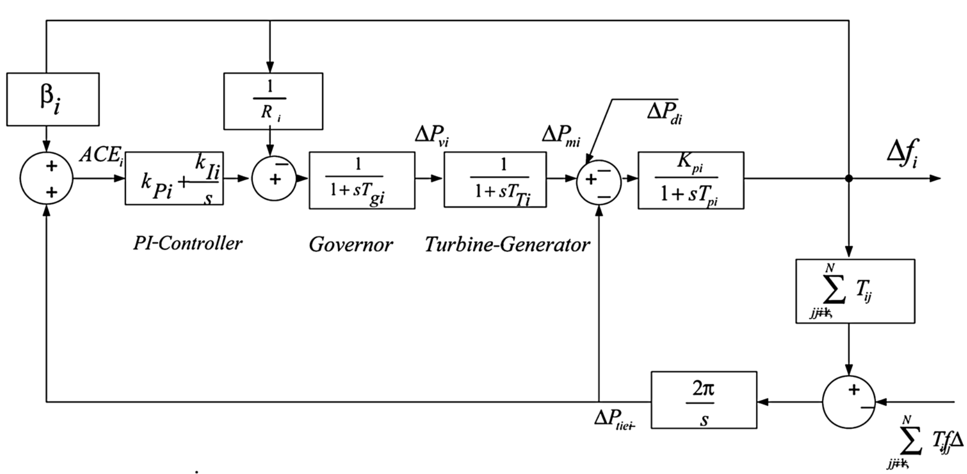

Fig. 1 Dynamic model of the ith control are in multi-area scheme

Table 1 Parameter settings for GA based centralized PI type LQ controller

Description	Control genes (P-part)	Control genes (I-part)
Population size	40	40
Number of generation	80	80
Range	[−2, 2]	[−2, 2]
Crossover point	3	1
Crossover probability	1	1
Mutation probability	0.1	0.1
Number of controller parameters	14	4
Bit length for each parameter	8	8

Table 2 Parameter settings for decentralized PI type LQ controller based on GAs

Description	Control genes (P-part)	Control genes (I-part)
Population size	40	40
Number of generation	60	60
Range	[−2, 2]	[−2, 2]
Crossover point	3	1
Crossover probability	1	1
Mutation probability	0.1	0.1
Number of controller parameters	7	2
Bit length for each parameter	8	8

For conventional PI type LQ: $Q_a = I_{9\times9}$; $R_a = I_{2\times2}$
For centralized GA based PI type LQ controller: $Q_a = I_{9\times9}$; $R_a = I_{2\times2}$

Centralized and decentralized PI type LQ controllers are designed by setting the following GA parameters and they are presented in Tables 1 and 2. Using the earlier data, the following controller gains are obtained:

Conventional PI type LQ controller parameters (obtained after solving conventional ARE)

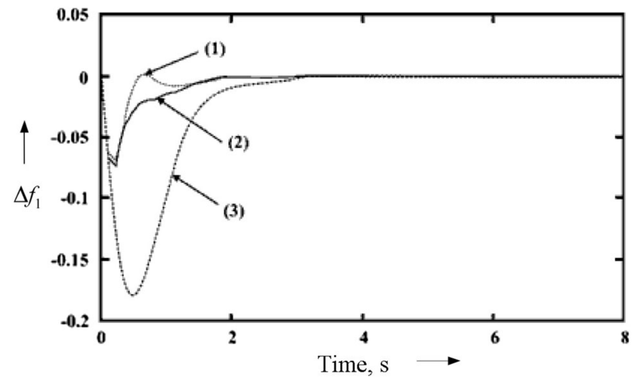

Fig. 2 Frequency deviation for 10 % step change in load demand. (*1*) GA based centralized PI type LQ controller; (*2*) GA based decentralized PI type LQ controller; (*3*) conventional centralized PI type LQ controller

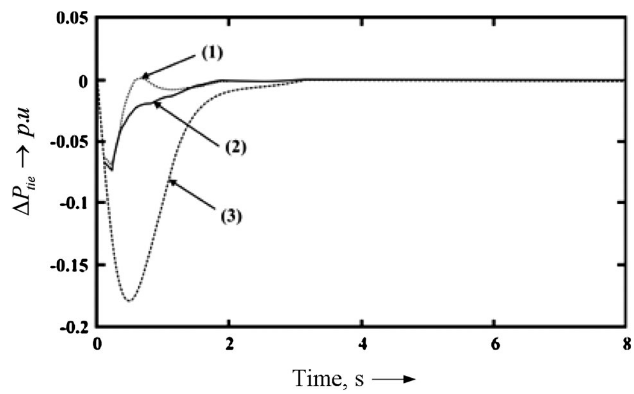

Fig. 3 Frequency tie-line power for 10 % step change in load demand. (*1*) GA based centralized PI type LQ controller; (*2*) GA based decentralized PI type LQ controller; (*3*) conventional centralized PI type LQ controller

$$K_P = \begin{bmatrix} 0.9954 & 1.6243 & 0.6927 & -1.3433 & 0.0821 & 0.0538 & 0.0085 \\ 0.0821 & 0.0538 & 0.0085 & 1.3433 & 0.9954 & 1.6243 & 0.6927 \end{bmatrix} \quad K_I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

GA based centralized PI type LQ controller parameters

$$K_P = \begin{bmatrix} 1.7176 & 1.0274 & -1.3411 & -0.9333 & -0.1960 & -1.8117 & 0.3686 \\ -0.2431 & -0.3843 & -0.2745 & 1.0901 & 1.5294 & 1.5764 & 0.4000 \end{bmatrix} \quad K_I = \begin{bmatrix} 1.843137 & 0.070588 \\ -0.462745 & 1.435294 \end{bmatrix}$$

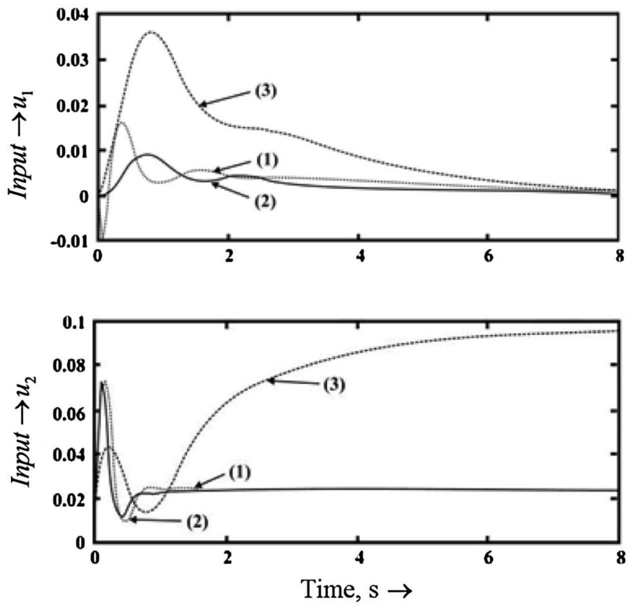

Fig. 4 Control signals. (*1*) GA based centralized PI type LQ control signal; (*2*) GA based decentralized PI type LQ control signal; (*3*) conventional centralized PI type LQ control signal

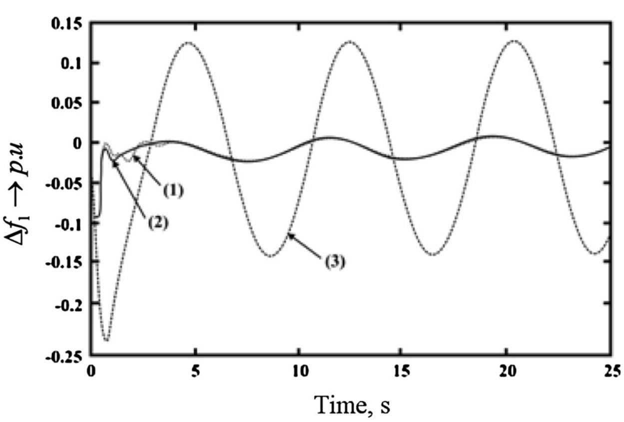

Fig. 5 Frequency deviation for time-varying load demand. (*1*) GA based centralized PI type LQ controller; (*2*) GA based decentralized PI type LQ controller; (*3*) conventional centralized PI type LQ controller

It may be noted that the gains obtained in GA are quite different from the conventional PI type LQ controller gains. The same initial data are being considered to obtain the decentralized PI type LQ controller gains based on GAs.

For GA based decentralized PI type LQ Controller:

$Q_{1a} = I_{5\times5};\ R_{1a} = I_{1\times1}\ ,\ Q_{2a} = I_{4\times4};\ R_{2a} = I_{1\times1}$

Subsystem-1 controller gains:

$K_{P1} = [\,1.6827 \quad 0.5568 \quad 1.7803 \quad 1.7490\,],$
$K_{I1} = [1.8431]$

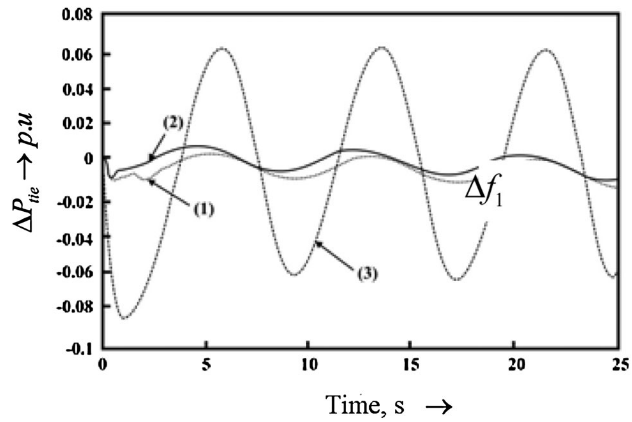

Fig. 6 Tie-line deviation for time-varying load demand. (*1*) GA based centralized PI type LQ controller; (*2*) GA based decentralized PI type LQ controller; (*3*) conventional centralized PI type LQ controller

Subsystem-2 controller gains:

$K_{P2} = [\,1.2941 \quad 1.3411 \quad 0.0235\,], K_{I2} = [1.3725]$

Simulation results for centralized and decentralized controllers based on GA and LQR are compared and they are presented in Figs. 1, 2, 3, 4 and 5 under constant and time varying load disturbances. Figures 1 and 2 show system response under constant load disturbance in area-1 and the corresponding control signals are presented in Fig. 3. It has been also studied on the effectiveness of the proposed controller for the time varying load disturbances in addition to 10% step change in the load demand and the simulated results as presented in Figs. 4 and 5. The tie-line power for time varying load demand is plotted in Fig. 6. Simulation results show that the proposed controller performance is considerably better than the conventional one even in presence of time varying load disturbances. It is observed that the deviations in frequency and tie-line power in both areas approach near to zero as time progress tends to infinity.

Conclusion

This work demonstrates the design of centralized/decentralized PI type LQ controller based on GA without solving an algebraic Riccati equation. The proposed design technique allows considerable flexibility in defining the control objectives and it does not consider any knowledge of the system matrices. Figures 1, 2, 3, 4 and 5 show that the proposed GA based PI type LQ controller performs substantially better than that of a conventional PI type LQ-controller and the proposed technique reduces the steady-state error in frequency and tie-line power deviations even in the presence of time varying load disturbances. The distinct advantage offered by the proposed technique provides a precise reference frequency tracking and time-varying disturbance attenuation under a wide range of area-load disturbances.

Conflict of Interest None.

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