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Two Degrees of Freedom Controller for Load Frequency Control with Communication Delay using Hybrid Strategy

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***Abstract*—** Two degrees of freedom controller is designed for two area load frequency control system with communication delay. The communication delay complicates the design and implementation of the controller to achieve robust performance of the system. The conventional PI controller is used for command tracking whose parameters are tuned using Genetic Algorithm (GA) and a state feedback controller is designed using linear matrix inequality (LMI). A unified Smith predictor (USP) approach is used to convert delayed plant to an augmented plant and LMI based state feedback controller is designed for augmented plant. Despite of delay stable dynamic performance is ensured using above hybrid strategy of GA-LMI.

Keywords- *Communication delay, unified Smith predictor, linear matrix inequality, Genetic Algorithm, load frequency control.*

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I. INTRODUCTION

Load frequency control with integral controller achieves good tracking with zero steady state error and a fast dynamic response but if a disturbance of increase in load occurs in the control area then it provides no control over the relative loading of various generating stations [1]. So, independent control is required and two degrees of freedom control is proposed. Moreover, if two or more areas are connected via tie lines, time delay is introduced due to communication network. Many controllers were introduced by various authors to control change in frequency – proportional and integral (PI) controller, proportional-integral and derivative (PID) controller [2-10], Fractional order PID (FOPID) controller [11], decentralized controller [12-15], artificial neural network (ANN) controller [16], fuzzy logic controller [17-19], neuro-fuzzy controller [20], LQR controller [21], internal model control scheme (IMC) [22-23]. The second issue of time delay is very significant as it complicates the design and implementation of the controller and also it creates instability in the system. To deal with time delay, authors used PI controller, converted the problem to state output feedback control and solved it using Linear Matrix Inequalities (LMI) [24-27]. The Smith predictor (SP) is an effective method to compensate delay [28-30].But, SP can only be applied to known stable systems. Traditional SP gives poor robustness. To improve robustness, many authors came with many modifications in SP [31-33]. In modified Smith predictor (MSP), the delay term e^{-Ah} is non-computable for systems having fast stable eigen values. In this paper, USP [34] is considered which overcome the above mentioned problems. USP is very effective in designing the controller as it combines the advantageous features of both the SP and MSP. Time delayed two area LFC model with PI controller is converted to augmented plant using USP and a state feedback controller is designed using LMI. The integral parameter of PI controller is tuned using GA.

This paper is organized as follows: Section 2 represents two area LFC model with time delay. USP approach is explained in section 3. Section 4 presents H_∞ controller in LMI approach. Simulation results using optimization are presented in section 5 and section 6 concludes the paper.

II. TWO AREA LFC PLANT

Extended power system can be divided into number of load frequency control areas interconnected via tie lines [1]. To understand the concept of communication delay, two area load frequency control (LFC) model [1] is modified to include delays introduced from communication networks. Fig. 1 describes two area LFC model connected by a single tie line. Each area has an equivalent governor and turbo generator. w_1 and w_2 are load demand inputs and delta f_1 and delta f_2 are frequency deviations. Notations with suffix1 represent area 1 and with suffix 2 represent area 2. The symbols represented by state variables and other variables in Fig. 1 are given in table 1. The dynamics of the models are represented by (1) to (9).

$$\dot{x}_1(t) = -\frac{1}{T_{p1}}x_1(t) + \frac{K_{P1}}{T_{P1}}x_2(t) - \frac{K_{P1}}{T_{P1}}x_5(t) - \frac{K_{P1}}{T_{P1}}w_1(t) \quad (1)$$

$$\dot{x}_2(t) = -\frac{1}{T_{ch1}}x_2(t) + \frac{1}{T_{ch2}}x_3(t) \quad (2)$$

$$\dot{x}_3(t) = -\frac{1}{R_1T_{g1}}x_1(t) - \frac{1}{T_{g1}}x_3(t) - \frac{1}{T_{g1}}x_4(t-h_1) + \frac{1}{T_{g1}}u_1(t) \quad (3)$$

$$\dot{x}_4(t) = k_1B_1x_1(t) + k_1x_5(t) \quad (4)$$

$$\dot{x}_5(t) = 2\pi T_1x_1(t) - 2\pi T_1x_6(t) \quad (5)$$

$$\dot{x}_6(t) = -\frac{1}{T_{p1}}x_6(t) + \frac{K_{P1}}{T_{P1}}x_7(t) + \frac{K_{P1}}{T_{P1}}x_5(t) - \frac{K_{P1}}{T_{P1}}w_2(t) \quad (6)$$

$$\dot{x}_7(t) = -\frac{1}{T_{ch1}}x_7(t) + \frac{1}{T_{ch2}}x_8(t) \quad (7)$$

$$\dot{x}_8(t) = -\frac{1}{R_1T_{g1}}x_6(t) - \frac{1}{T_{g1}}x_8(t) - \frac{1}{T_{g1}}x_9(t-h_2) + \frac{1}{T_{g1}}u_2(t) \quad (8)$$

$$\dot{x}_9(T) = k_1B_1x_6(t) + k_1x_5(t) \quad (9)$$

(1) – (9) can be represented by state space form as

$$\dot{x}(t) = Ax(t) + A_{d1}x(t-h_1) + A_{d2}x(t-h_2) + Bu(t) + Fw(t) \quad (10)$$

$$y(t) = Cx(t) \quad (11)$$

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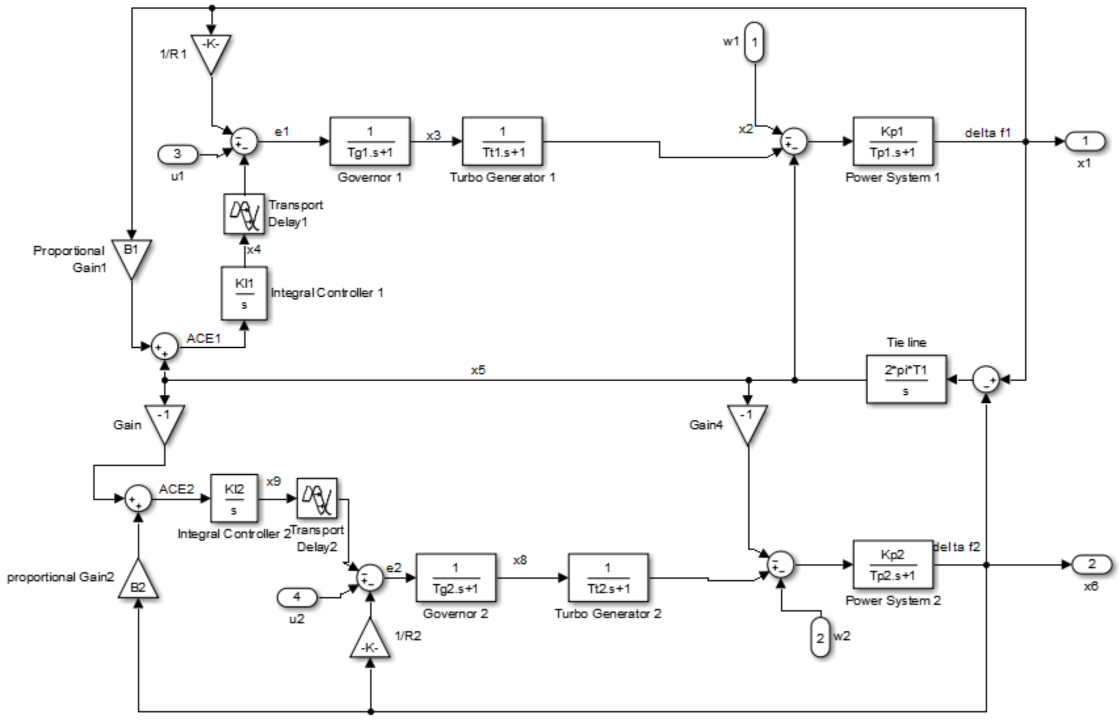

Fig. 1 Two Area Load Frequency Control Model with Communication Delay

Table 1 Symbols used in two area LFC model

Symbols	Representation
$x_1=\Delta f_1$	Frequency deviation in area 1
$x_2=\Delta Pm_1$	Mechanical power output of generator in area 1
$x_3=\Delta Pv_1$	Governor valve position in area 1
$x_4=\Delta E_1$	Area control error (ACE) in area 1
$x_5=\Delta P_{12}$	Tie-line power flow from area 1 to area 2
$x_6=\Delta f_2$	Frequency deviation in area 2
$x_7=\Delta Pm_2$	Mechanical power output of generator in area 2
$x_8=\Delta Pv_2$	Governor valve position in area 2
$x_9=\Delta E_2$	Area control error (ACE) in area 2
$[u_1,u_2]=[\Delta P_{c1},\Delta P_{c2}]$	Change in speed changer setting in area 1 and 2
$[w_1,w_2]=[\Delta P_{d1}, \Delta P_{d2}]$	Change in load demand
B	Proportional gain of PI controller
K	Integral gain of PI controller
T_g	Integral gain of PI controller
T_{ch}	Governor time constant
T_p	Power system time constant
R	Speed droops
T	Stiffness coefficient

where,

$$A=\begin{bmatrix} -\frac{1}{T_{P1}} & \frac{K_{P1}}{T_{P1}} & 0 & 0 & -\frac{K_{P1}}{T_{P1}} & 0 & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{ch1}} & \frac{1}{T_{ch1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{R_1T_{g1}} & 0 & -\frac{1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 & 0 \\ k_1B_1 & 0 & 0 & 0 & k_1 & 0 & 0 & 0 & 0 \\ 2\pi T_1 & 0 & 0 & 0 & 0 & -2\pi T_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{K_{P2}}{T_{P2}} & -\frac{1}{T_{P2}} & \frac{K_{P2}}{T_{P2}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_{ch2}} & \frac{1}{T_{ch2}} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{1}{R_2T_{g2}} & 0 & -\frac{1}{T_{g2}} & 0 \\ 0 & 0 & 0 & 0 & k_2 & k_2B_2 & 0 & 0 & 0 \end{bmatrix}$$

$$A_{d1}=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{g1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

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$$A_{d2}=\begin{bmatrix}0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0&-\frac{1}{T_{g2}}\\0&0&0&0&0&0&0&0&0\end{bmatrix}$$

$$B^T=\begin{bmatrix}0&0&\frac{1}{T_{g1}}&0&0&0&0&0&0\\0&0&0&0&0&0&0&\frac{1}{T_{g2}}&0\end{bmatrix}$$

$$F^T=\begin{bmatrix}-\frac{K_{P1}}{T_{P1}}&0&0&0&0&0&0&0&0\\0&0&0&0&0&-\frac{K_{P2}}{T_{P2}}&0&0&0\end{bmatrix}$$

$$C=\begin{bmatrix}1&0&0&0&0&0&0&0&0\\0&0&0&0&0&1&0&0&0\end{bmatrix}$$

III. UNIFIED SMITH PREDICTOR

SP and MSP were introduced to deal the time delay systems but due to numerical problems for delay with fast stable eigen values systems USP was proposed by Zhong and Weiss [34]. It does not require matrix exponential computation for fast stable poles. The system can be represented in transfer function as

$$G(s)=P(s)e^{-sh} \qquad (12)$$

where, $P(s)$ is delay free part of the two input (w, u) two output (z, y) plant and $\tau>0$ is the delay in the plant as represented in Fig. 2. $K(s)$ is a stabilizing controller for $G(s)$.

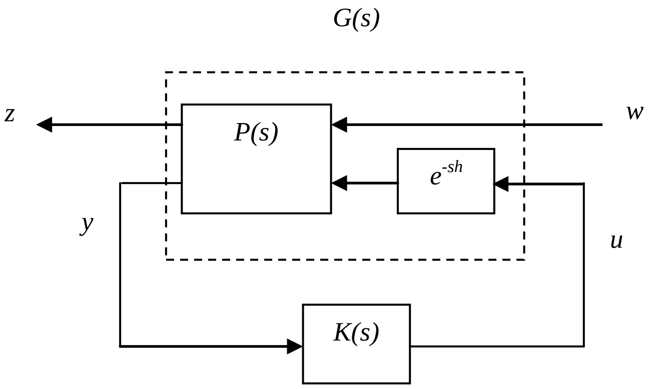

Fig. 2 Control system comprising time delayed plant G and controller K

$$P(s)=\begin{bmatrix}A_1&\vdots&e^{A_1h}F&B\\\cdots\cdots&\vdots&\cdots\cdots\cdots&\cdots\\C&\vdots&0&0\\Ce^{-A_1h}&\vdots&0&0\end{bmatrix} \qquad (13)$$

Where $A_1=A+A_{d1}+A_{d2}$. In the proposed technique delay free part is decomposed in stable and unstable parts $P(s)=P_s(s)+P_u(s)$. Transformed augmented delay free plant is given as

$$P_{22}(s)=\begin{bmatrix}V^{-1}A_1V&\vdots&V^{-1}B\\\cdots\cdots\cdots&\vdots&\cdots\cdots\\CV&\vdots&0\end{bmatrix}=\begin{bmatrix}A_u&0&\vdots&B_u\\0&A_s&\vdots&B_s\\\cdots\cdots\cdots&&\vdots&\cdots\cdots\\C_u&C_s&\vdots&0\end{bmatrix} \qquad (14)$$

Where, the transformation matrix $V$is chosen such that $J=V^{-1}A_1V$ is in the Jordan canonical form. In Matlab, this is obtained by *[V, D]=eig(A₁)*. The transformation matrix V and the diagonal eigen values matrix D are converted from complex diagonal form to real block diagonal form using $[V,D]=cdf2rdf(V,D)$. A_u and A_s are the stable and unstable parts of A_1 after transforming into Jordan canonical form. This decomposition is made by spilting the complex plane along with a vertical line $Re(s)=\alpha$ with $\alpha<0$. The value of α is chosen as the maximum negative real part of poorly damped poles. Then the eigenvalues of A_u are all eigenvalues $\lambda$of A_1 with $Re(\lambda)>\alpha$, while A_s has remaining eigen values of A_1. The generalized plant $\tilde{P}(s)$ shown in Fig. 3 using USP is realized as

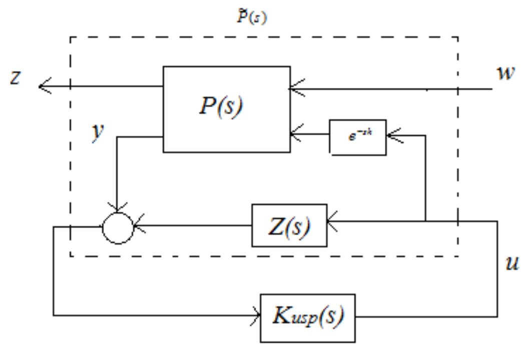

Fig. 3 $\tilde{P}(s)$ consisting of plant $G(s)$ together with USP and controller K has been decomposed into USP $Z(s)$ and compensator $K_{usp}(s)$, so that $K=K_{usp}(1-ZK_{usp})^{-1}$

$$\tilde{P}=\begin{bmatrix}A_1&0&\vdots&E_h^{-1}F&B\\0&A_s&\vdots&\begin{bmatrix}0&e^{A_sh}-I_s\end{bmatrix}V^{-1}F&0\\\cdots\cdots\cdots&&\vdots&\cdots\cdots\cdots\cdots&\\C&CV\begin{bmatrix}0\\I_s\end{bmatrix}&\vdots&0&0\\CE_h&0&\vdots&0&0\end{bmatrix} \qquad (15)$$

$$=\begin{bmatrix}P_a&\vdots&P_f&P_b\\\cdots&\vdots&\cdots\cdots\cdots&\\P_{c1}&\vdots&0&\\P_{c2}&\vdots&&\end{bmatrix}$$

$$E_h = V\begin{bmatrix} e^{-A_u h} & 0 \\ 0 & I_s \end{bmatrix} V^{-1} \qquad (16)$$

And I_s is an identity matrix having same dimensions as A_s.

$$Z(s) = P_{22}^{aug}(s) - P_{22}(s)e^{-sh} \qquad (17)$$

Where, $$P_{22}^{aug}(s) = \begin{bmatrix} A_1 & \vdots & B \\ \cdots & \vdots & \cdots \\ CE_h & \vdots & 0 \end{bmatrix} \qquad (18)$$

The performance of controller K_{usp} with generalized plant $\tilde{P}$ is same as performance of controller K with original time delayed plant. The controller K_{usp} is designed as state feedback controller.

$$u(t) = K_{usp}x(t) \qquad (19)$$

The transfer function between disturbance *w(t)* and unmeasured output *z(t)* is

$$T_{zw} = P_{c1}\left(sI - (P_a + P_b.K_{usp})\right)^{-1} P_f \qquad (20)$$

Where, '*s*' is the Laplace operator. The design of $H\infty$ controller stabilizes the system if the infinity norm of T_{zw} is bounded by γ.

$$\|T_{zw}\|_\infty \le \gamma, \qquad \gamma > 0 \qquad (21)$$

IV. H_∞ CONTROLLER DESIGN USING LINEAR MATRIX INEQUALITY

There exists a state feedback controller that stabilizes the system (10) if a symmetric and positive definite matrix *S>0*, an arbitrary matrix *Q* and a positive scalar *γ* satisfies the following LMI:

$$\begin{bmatrix} P_aS + S^TP_a^T + P_bQ + Q^TP_b^T & SP_{c2}^T & P_b \\ P_{c2}S^T & -\gamma I & 0 \\ P_b^T & 0 & -\gamma I \end{bmatrix} < 0 \qquad (22)$$

After minimizing γ subjected to the above LMI constraints, the controller is computed by $K = QS^{-1}$.

V. SIMULATION

The parameters of GA used to tune integral controller are:
size of population: 20
number of generation: 100
mutation rate: 0.05

To show the effectiveness of the proposed USP, the simulation results of two area LFC with communication delay are compared with PI controller and LMI control of time delay system [24]. The system shown in Fig. 1 is modeled with two generators represented by a single equivalent generator in area 1 and four generators represented by a single equivalent generator in area 2. The plant parameters in p.u. for the proposed technique and k_1 and k_2 for the comparative purpose are given below:

Area – 1
T_{ch1} = 0.3s, T_{g1} = 0.1s, R_1 = 0.05, D_1 = 1, M_1 = 10, k_1=0.7, τ_1=0.1, $T_{p1} = \frac{M_1}{D_1}$, $K_{p1} = \frac{1}{D_1}$ and $B_1 = \frac{2}{R_1} + D_1$

Area-2
T_{ch2} = 0.17s, T_{g2} = 0.4s, R_2 = 0.05, D_2 = 1.5, M_2 = 12, k_2=0.69, τ_2=0.6, $T_{p2} = \frac{M_2}{D_2}$, $K_{p2} = \frac{1}{D_2}$ and $B_2 = \frac{4}{R_2} + D_2$

The system represented by (10) and (11) with *u(t)* = 0 includes an local PI controller. For 5% change in the load demand *w(t)* and time delay in both control areas results are shown in Fig. 4, 5 and 6. Fig. 4 shows that time delayed plant is unstable with conventional PI controller with the specified integral gains. Fig. 5 shows the responses with the technique of state feedback controller design by LMI [24] and Fig. 6 with the proposed USP technique. Results show that with the proposed techniques frequency deviation dies out earlier and also overshoots are less. The parameters of the integral controller obtained by optimization are k_1=0.7358 and k_2=0.7559. With the proposed technique K_{usp} is given by (23) and with [24] technique controller *K* is given by (24).

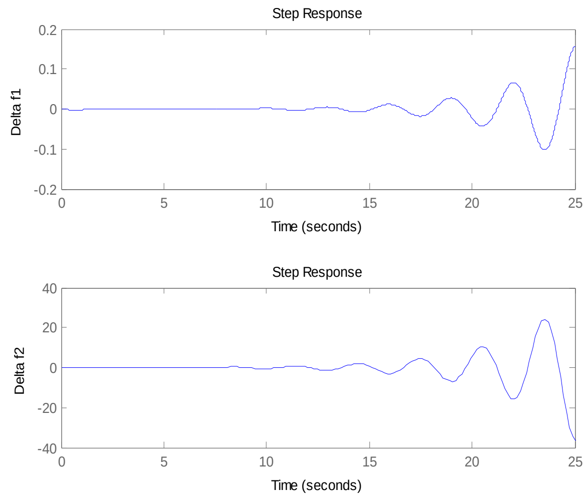

Fig. 4 Frequency deviation using conventional PI controller with 5% load change in area2

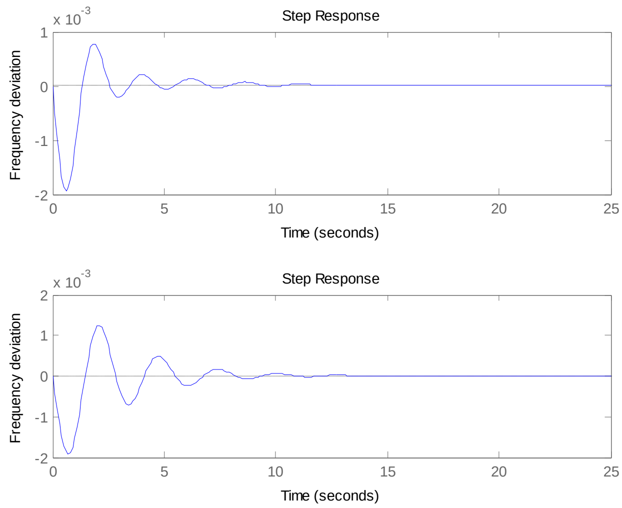

Fig. 5 Frequency deviations using state feedback LMI controller as in [135] with 5% load change in area2

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$$K_{usp} = \begin{bmatrix} -13.5971 & -0.8011 & -0.6249 & -0.2269 & 1.2749 & -0.2314 & 0.0850 & 0.0897 & 0.0851 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -2.0167 & 0.1630 & 0.1912 & 0.1548 & -3.2017 & -85.5454 & -1.5352 & -2.0625 & -1.5925 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (23)$$

$$K = \begin{bmatrix} -16.3022 & -0.3319 & -0.0917 & -1.5967 & -0.1824 & 0.4176 & -0.0224 & -0.1252 & -0.1959 \\ -0.4749 & -0.0208 & -0.0099 & 0.4723 & -0.3316 & -22.6162 & -0.2747 & -0.4027 & -1.1464 \end{bmatrix} \quad (24)$$

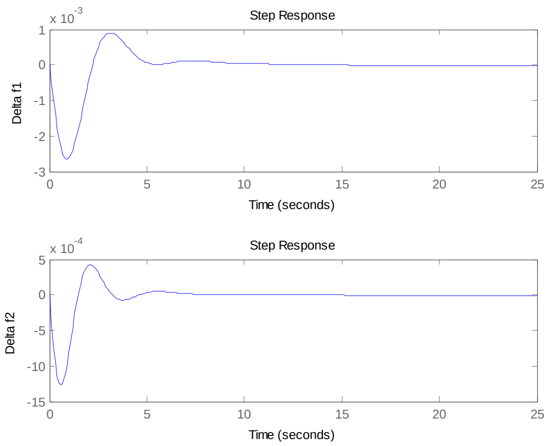

Fig. 6 Frequency deviations using hybrid technique with 5% load change in area2

VI. Conclusion

The Unified Smith Predictor is introduced to deal the problems of communication delay in multiple area load frequency control. An LMI based approach is proposed to design H_∞ controller for load disturbance rejection and GA is used to tune the integral parameter of PI controller in the plant. Simulations and comparative study show the validation of the proposed technique. Damping characteristics are comparable to the technique proposed by Yu and Tomsovic [24].

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